Neural and behavioural correlates of auditory discrimination and language processing in infants and children

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Neural and behavioural correlates of auditory discrimination and language processing in infants and children

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Abstract

Inconsistency of accounts on auditory and speech processing in early development tends to be attributed to maturational factors in children. However, variability in stimulus and design features used across studies is likely to contribute to this lack of consensus. The mismatch response (MMR), an electrophysiological measure elicited to auditory stimulation, can provide a neural index of speech processing and language development. The current study investigated the design and paradigm features which influence MMR in 5- to 11-month-old infants and 4-to 6-year-old children. Across experiments, trial duration; deviance type; stimulus type and number of simultaneous streams (phonemes and tone pairs) were systematically manipulated. Taking such an approach provided means to gain an understanding of those factors that influence auditory and speech development in infants and young children and address questions of interest to researchers working within the field of neurodevelopmental research. A secondary objective of this thesis was to delineate the relationship between neural and behavioural correlates of language development in the same participants at the time of testing and in a subset of the infants at 2 years.

The results indicated that the 'oddball' auditory deviance elicited the largest MMR, as did tone pairs compared to phonemes. The deviance modulation revealed larger MMR deflections to the oddball than roving or sequential change between deviant and standard stimuli. Furthermore, shorter trial duration produced no difference in MMR intensity, a finding that suggests a slightly shorter stimulus presentation time can be utilised at minimal processing cost. Stimulus modulation confirmed that tone pairs consistently elicited larger MMR than phonemes. Finally, the number of concurrent stimulation streams did not influence MMR to tone pairs but revealed dissociation in processing phonemes between infants and children. Infants discriminated phonetic deviance at the sensory level whereas children exhibited later MMR response, which was associated with attentional focus.

Results of the analyses related to the secondary question revealed a positive association that linked MMR to acoustic contrast and language proficiency in infants. A similar pattern was observed between MMR in infancy and language at 2 years of age, but an opposite trend was found in children. In this age group, the ability to ignore background sounds was linked to more advanced language. Nonetheless, a relationship between MMR to acoustic and language proficiency in children was identified with the potential for auditory processing to predict language outcomes. Recommendations deriving from this work may be of considerable interest to neuroscientists and neuropsychologists who specialise in enabling children achieving their linguistic aptitude. They may also inform the development of clinical interventions targeted at children with language difficulties.

Declaration

I declare that this thesis is a presentation of original work, and I am the sole author. This work has not previously been presented for an award at this or any other university. All sources are acknowledged as references.

Jolanta Golan

Contents

List of Figures

List of Tables

List of Abbreviations

ANOVA	Analysis of Variance
dB	decibel
DTI	Diffusion Tensor Imaging
EEG	Electroencephalography
ERP	Event-Related Potential
fMRI	functional Magnetic Resonance Imaging
Hz	Hertz
ISI	Inter-Stimulus-Interval
ITI	Inter-Trial-Interval
MEG	Magnetoencephalography
MMN	Mismatch Negativity
MMR	Mismatch Response
ms	milliseconds
NIRS	Near-Infrared Spectroscopy
SPL	Sound Pressure Level
TWI	Temporal Window of Integration
vs	versus

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November 2021 Jolanta Golan

Dedication

To my Godchildren Dylan, Josephine and Szymon, to inspire you to achieve your potential and fulfil your dreams and as a proof that any goal you set your mind to is possible.

Your Godmother Jolanta

General Introduction

Background to the Thesis

Changes in brain activity recorded on the scalp with the electroencephalogram (EEG) can provide a reliable index of underlying brain function (Bridwell et al., 2018). Event-related potential components (ERPs) are derived from the continuous EEG recording via signal averaging processes, synchronised to the onset of stimulus processing (Luck, 2004). One of the large ERP components which has been the focus of a large body of research is mismatch response (MMR) beginning with the paper by Näätänen and colleagues (Näätänen, Gaillard & Mäntysalo, 1978). It is elicited in response to the differences between a sequential presentation of stimuli with a proportion of deviants. The recent decades have seen a growing trend towards the exploration of the developmental trajectories of the MMR component (Cheng et al., 2013, 2015; He, Hotson, & Trainor, 2009; Maurer, Bucher, Brem, & Brandeis, 2003b; Partanen, 2013).

While the MMR is generally consistent in adults and is represented by the mismatch negativity (MMN; Kathmann, Frodl-Bauch, & Hegerl, 1999; Näätänen, Paavilainen, Rinne, & Alho, 2007; Schröger, 1998), the main challenge faced by developmental researchers are the rapid changes in amplitude and spatial and temporal distribution of the MMR in early development (Cheour, Alho, et al., 1998; Choudhury & Benasich, 2011; Kushnerenko, Čeponiené, Balan, Fellman, & Näätänen, 2002; Leppänen et al., 2004; Linnavalli, Putkinen, Huotilainen, & Tervaniemi, 2018; Mahajan & McArthur, 2012; Morr, Shafer, Kreuzer, & Kurtzberg, 2002; Shafer, Morr, Kreuzer, & Kurtzberg, 2000; Shafer, Yu, & Wagner, 2015; Trainor, 2010; Trainor et al., 2003; Wunderlich & Cone-Wesson, 2006; Wunderlich, Cone-Wesson, & Shepherd, 2006). There is lack of consensus across the labs in the reports of the direction and timing the amplitude of the component (Guzzetta, Conti, & Mercuri, 2011) and these are likely to reflect the design and methodological differences between the studies. This issue needs considerable critical attention.

There is a growing body of literature that recognises the importance of a systematic approach in assessing the functional attributes and spatial and temporal features of the MMR in adults (Escera, Yago, Polo, & Grau, 2000; Kathmann et al., 1999; Pekkonen, Rinne, & Näätänen, 1995; Schaadt, Pannekamp, & van der Meer, 2014; Schröger, 1998; Tervaniemi et al., 2005), but such stringent scientific methods have not been accentuated in developmental research (with the exception of Volkmer & Schulte-Körne, 2018). To date, research on the methodological factors such as type of change between the standard and deviant stimuli (Putkinen, Niinikuru, Lipsanen, Tervaniemi, & Huotilainen, 2012), the length of individual trials (Benasich et al., 2006; Čeponiené et al., 1998; Choudhury et al., 2015), stimulus type (Čeponiené, Torki, Alku, Koyama, & Townsend, 2008) and influence of the number of streams being presented simultaneously in a single paradigm (Gutschalk & Dykstra, 2014; Sussman & Steinschneider, 2009) on the MMR in children is limited and it remains speculative in infants. Therefore, the first objective of this thesis is to analyse the impact of the aforementioned paradigm features on the MMR in infants and children.

This work may be of interest to developmental neuropsychologists and neurolinguists. The MMR has been linked to speech processing, and as such, it has been implicated at the heart of understanding early language development (Guttorm et al., 2005; Kuhl, 2010). Recent studies on speech processing in infants (Cheng et al., 2013, 2015; Cheour-Luhtanen et al., 1995a; Guttorm, Leppänen, Richardson, &

Lyytinen, 2001; Martynova, Kirjavainen, & Cheour, 2003; Silvia Ortiz-Mantilla, Hämäläinen, & Benasich, 2012; Partanen, Pakarinen, Kujala, & Huotilainen, 2013; Ragó, Honbolygó, Róna, Beke, & Csépe, 2014; Shafer et al., 2015) and children (Čeponiené et al., 2008; Lee et al., 2012; Linnavalli, Putkinen, Huotilainen, & Tervaniemi, 2018a; Lovio, Näätänen, & Kujala, 2010; Shafer, Yu, & Garrido-Nag, 2012; Tallal & Gaab, 2006a) have highlighted the need for exploring the associations between MMR and language in early development.

Furthermore, the MMR has been the subject of considerable discussion in behavioural research on language development (Cantiani et al., 2016b; Chen, Tsao, & Liu, 2015; Cheng et al., 2015; Choudhury & Benasich, 2011; Friedrich, Weber, & Friederici, 2004; Kuhl, 2010). Indeed, the spatial and temporal distribution of the MMR could be contributing to determining language proficiency in infants and children, but few studies have investigated this relationship in a systematic way. Exploring these correlates is the second objective of the thesis.

Scope of the Thesis

The central focus of the thesis are the electing features of the MMR in early development. The studies set out to examine the differential effects of manipulating paradigm features on the MMR and to determine the relationship between MMR and language proficiency in infants and children. The influence of deviance, trial duration, stimulus type and a number of streams in a paradigm on the MMR is investigated in Studies 1, 2 and 5. The aims of Studies 3, 4 and 6 are to ascertain the associations between MMR and language proficiency in infants and children. The purpose of Study 7, which is the final study of the thesis, is to assess the difference in the paradigm manipulations that impact the MMR maximally and to delineate how MMR features compare between infants and children. The final analysis was performed to explore the associations between MMR and behavioural language ability in early development.

The experimental, correlational, and cross-sectional methodological approaches taken in the thesis were selected to provide insights on auditory processing and objective behavioural indicators of language development. The experimental design involved analysing the differential effects of paradigm features on brain activity in infants and children. Data for the studies were thus collected using electroencephalography (EEG), which records changes in electrophysiological activity of the brain in response to specific paradigm design. The responses were averaged, and ERPs to standard stimuli were subtracted from ERPs to deviants to obtain the MMR component. The temporal and spatial distribution between the MMR to paradigm modulations, including the type of change, trial duration, stimulus and number of streams were compared in a within-subject design in both age groups. The details are available in Studies 1, 2 and 5.

The correlational approach involves an assessment of the neural correlates of the MMR obtained in Studies 2 and 5 and behavioural measures of language ability in infants and children. The results of those correlations are available in Studies 3, 4 and 6. Finally, the cross-sectional design of Study 7 is used to assess the differences between MMR to the modulations in infants and children. The final correlational analysis explores the relationship between MMR and language ability across infants' and children's cohorts.

The strength of this work lies in highlighting the importance of careful study design and awareness of how different methodological choices may impact neural response. Furthermore, it makes a significant contribution to research on the neural signatures associated with language in early development.

In conclusion, this thesis aims to answer two overarching research questions:

1. How do paradigm features such as deviance, trial duration and stimulus type, along with a number of streams in a paradigm influence the MMR in infants and children?
2. Is there a relationship between MMR obtained in response to the above paradigm features and behavioural language scores in infants and children?

Thesis Overview

The purpose of this work is to verify the differential effects of paradigm design on the MMR and to examine the associations between MMR and language trajectories in early development. The thesis is organised as follows:

General Introduction. This section demonstrates the origins of the debate on the influence of the paradigm features on the MMR in infants and children and on the associations between the MMR and language early development. The need, importance and uniqueness of the problem are highlighted. The summary validates the causality and social responsibility, which have led to forming the current research questions.

Chapter 1. Literature review. The following review of the findings to date sets out the current problem against the backdrop of psychological research. The characteristics of the MMR and the paradigm designs evoking the component are outlined. Finally, the observed associations between the MMR and auditory and specifically language development are revealed. The section concludes by demonstrating the aims of the project and general hypotheses for the subsequent studies.

Chapter 2. General Methods. The methodology includes the ethics application process and the general design and procedure, as well as the sample characteristics. The electrophysiological and the behavioural measures are described, followed by the description of the data processing and analysis strategy.

Chapter 3. Study 1. The differential effects of the trial duration, deviance and stimulus type on the MMR are examined in 5-10-month-old infants.

Chapter 4. Study 2. The effect of stream modulation on the linguistic and non-linguistic MMR is investigated in 5-11-month-old infants.

Chapter 5. Study 3. The relationship between the linguistic and non-linguistic MMR in the streaming and control single stream design and language ability in 5-11-month-old infants is evaluated.

Chapter 6. Study 4. The predictive value of the linguistic and non-linguistic MMR in the streaming and control single stream design in infancy on language ability at 2 years is verified.

Chapter 7. Study 5. The effect of stream modulation on the linguistic and non-linguistic MMR is investigated in 4-6-year-old children.

Chapter 8. Study 6. The relationship between the linguistic and non-linguistic MMR in the streaming and control single stream design and language ability is explored in 4-6-year-old children.

Chapter 9. Study 7. Linguistic and non-linguistic MMR in the streaming and control single stream design in 5-11-month-old infants and 4-6-year-old children are compared, and the associations between MMR and language ability in early development evaluated.

Chapter 10. General Discussion. The findings from all seven studies are summarised and interpreted. The importance of the MMR in language development is assessed and the new emerging questions highlighted. The contributions of the thesis to broader research are contemplated, limitations recognised, and possible future directions suggested. Finally, in the General Conclusions section, the broader scientific impact of the research is reviewed and summarised.

Chapter 1. Literature review.

The review commences by providing a historical overview of research on auditory development, focusing specifically on the functional neuroanatomy of the auditory network. The review subsequently discusses the behavioural language milestones, followed by development of the language network in the brain. This scientific account forms the foundations for current research on the development of the MMR and techniques to induce and measure its spatial and temporal distribution. Thereupon, research exploring associations between the MMR and language in child development is outlined. Overall, this summary of scientific literature sets out the contextual background to the research questions presented in the Thesis Overview section of General Introduction. The literature review concludes with providing the theoretical framework behind the design and methodology employed in the current project.

1.1 Auditory development in early childhood

The focus of this section is to demonstrate the general auditory network in the brain. It begins with the description of the functional neuroanatomy of the peripheral and then the central auditory regions. The attention is given to the mapping out the primary auditory cortex as the centre of auditory processing.

1.1.1 Functional neuroanatomy of the auditory network.

Peripheral auditory structures.

The auditory system is responsible for the sense of hearing. It is divided into the peripheral auditory system, which registers auditory stimuli from the environment and the central auditory system that in turn specialises in sound processing (Kaya & Elhilali, 2017; Snyder & Alain, 2007). The primary structures are divided into the outer, middle and inner ears. The outer anatomy begins with the pinna, which surrounds the ear canal and helps in locating sounds, while the ear canal amplifies the soundwaves. They are then transferred through the eardrum to be transformed into vibrations in the ossicles and then converted into higher pressure sounds in the cochlea in the inner ear (W. M. Yu & Goodrich, 2014). While in the latter, the sounds are differentiated and categorised based on their frequencies and transferred via auditory nerves to the brain stem and further up to the higher-order auditory processing areas in the brain. The latter part of the auditory system is the focus of the next paragraph.

The central auditory network.

As indicated in Figure 1.1, the central auditory system is not a single component within the brain, but instead, it consists of a network of neural connections (Javitt & Sweet, 2015; Kaas & Hackett, 2010). It begins in the brain stem, where the auditory neurons reach the cochlear and then superior olivary nuclei. From there the signal ascends through midbrain via reticular formations, passing lateral lemnisci and inferior colliculi to thalamic medial geniculate nuclei, which act as the hub for sound processing from across cortical auditory regions, including the primary auditory area (Hackett, 2011).

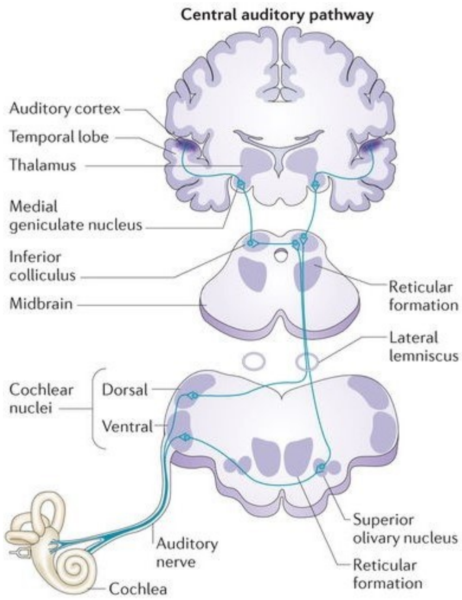

Figure 1.1. A model of the central auditory system (adapted from *Javitt & Sweet, 2015).*

Primary auditory cortex.

The primary auditory cortex is divided into three sections: core, belt, and parabelt (see Figure 1.2). Within these structures auditory signal is processed further and dependent upon their on the contextual features it is transmitted onto the relevant cortical regions (Hackett, 2011; Hackett, Stepniewska, & Kaas, 1999; Javitt & Sweet, 2015). Auditory cortex encompasses several structures along the temporal lobe, but also extends onto the inferior frontal gyri, motor cortex and posteriorly veering towards the angular and occipitotemporal gyri. Features and functions of the processed sound may determine the specific processing region, e.g., processing speech in the temporal areas, but memorising speech or emotions associated with it in the inferior frontal gyri or responding to an alerting shout by moving away from danger triggered in the primary motor cortex. The processed information is fed back to the thalamus.

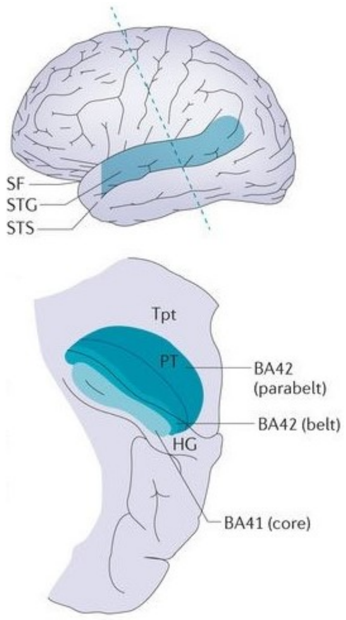

Figure 1.2. Division of the auditory cortex in the temporal lobe (adapted from *Javitt & Sweet, 2015)*. Abbreviations indicate: BA41 - Brodmann's area 41, BA42 - Brodmann's area 42, HG – Heschl's gyrus, PT – planum temporale, SF – Sylvian fissure, STG – superior temporal gyrus, STS – superior temporal sulcus, Tpt – heteromodal temporoparietal region.

1.1.2 Development of the primary auditory functions.

Children develop by communicating with their surroundings. The early foetal signs of typical auditory recognition may be expressed with increased heart rate (Grimwade, Walker, Bartlett, Gordon, & Wood, 1971; Rand & Lahav, 2014; Voegtline, Costigan, Pater, & DiPietro, 2013) change in motor activity (Moon, 2017) or electrophysiological fluctuations (Abrams & Gerhardt, 2000; Cheour-Luhtanen et al., 1995a; Muenssinger et al., 2013; Preissl, Lowery, & Eswaran, 2004; Sakabe, Arayama, & Suzuki, 1969) as a response to external sounds. Neonates turn towards attractive sounds (Leventhal & Lipsitt, 1964; Morrongiello, Fenwick, Hillier, & Chance, 1994; Peck, 1995) and recognise their mother's voice among other speakers in the environment (Hepper, Scott, & Shahidullah, 1993; Lee & Kisilevsky, 2014; Rand & Lahav, 2014a; Winkler et al., 2003). Development of the fundamental auditory processes is mapped out in Figure 1.3.

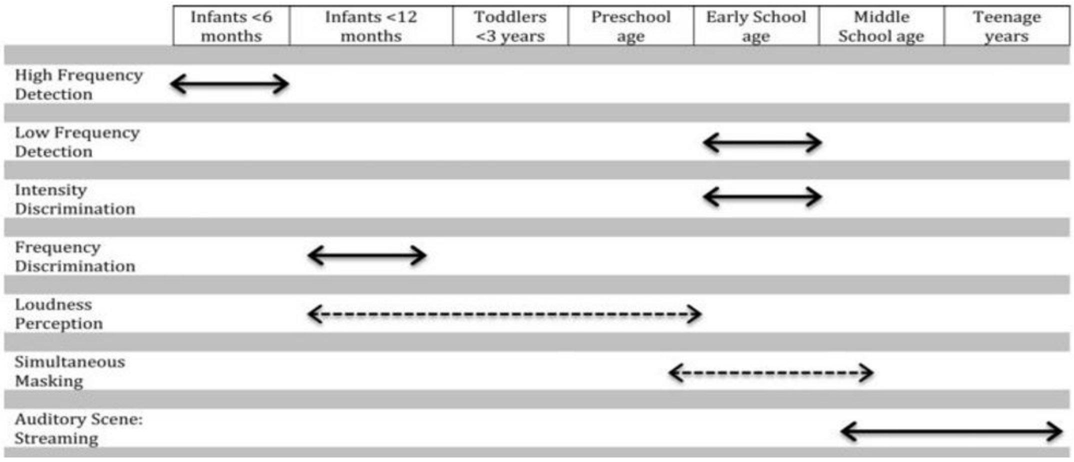

Figure 1.3. Development of the specific auditory functions across early development (adapted from Litovsky, 2015).

Mechanisms involved in processing the basic acoustic features of sounds, i.e., intensity, pitch, timbre and frequency or spatial and temporal resolution (Čeponiené et al., 2008; Irvine & Malmierca, 2005; Litovsky, 2015; Werner, 2012) mature earlier than discrimination of more complex characteristics, such as categorisation or attentional bias (Rihs et al., 2013; Werner, 1996).

Frequency discrimination.

The ability to identify change between two frequencies has been studied across development using motor (gross body movement, head turn, sucking rate, habituation) and electrophysiological cortical and brain stem responses. The frequency limen decreases throughout infancy, with frequencies lowering to 200 and rising to 8000 Hz range beyond the first month, with better sensitivity in the higher frequency levels (Cheour et al., 2004; Kushnerenko, Van den Bergh, & Winkler, 2013; Olsho, 1984; Olsho, Koch, & Halpin, 1987; Wormith, Pankhurst, & Moffitt, 1975). While 3-month-old infants still demonstrate immature discrimination, from the age of 6 months onwards, they exhibit adult-like responses to frequencies above 1000 Hz. In contrast, low-level sensitivity develops throughout childhood to achieve optimal acuity about 10-11 years of age (Choudhury, Parascando, & Benasich, 2015; Fischer & Hartnegg, 2004; Halliday, Taylor, Edmondson-Jones, & Moore, 2008; Halliday, Taylor, Millward, & Moore, 2012; Litovsky, 2015; Maxon & Hochberg, 1982; Moore, Ferguson, Halliday, & Riley, 2008).

Notably, the ability to discriminate acoustic change is dependent upon the degree of frequency separation between the deviating stimuli. (Sussman & Steinschneider, 2009) investigated frequency discrimination in 9-12 years old children and adults. Whilst adult discrimination thresholds were narrower than in children; both age groups were unable to process auditory change when the difference was below 84 Hz (183 Hz for children). Frequency limen between stimuli is, therefore, an important feature to consider in study design.

Temporal resolution.

The temporal window of integration theory proposes that a silent pause between auditory stimuli below a specific temporal threshold may be perceived as a continuation of the previous sound, i.e., a single unit and not two individual stimuli (Anderson & Linden, 2016; Luck, 2014; Näätänen et al., 2007; Näätänen & Winkler, 1999; Nelson, Thomas, & de Haan, 2007; Yabe, Tervaniemi, Reinikainen, & Näätänen & Alho, 1997; Yabe et al., 1998).

The ability to detect a silent gap in the sound is present (Otte et al., 2013), although immature in infancy (Werner, 2012). Specifically, the threshold in noise requires a break of at least 40 milliseconds (from now on referred to as 'ms') to be detected (Werner, Mancl, & Constantino, 1994; Werner, Marean, Halpin, Spetner, & Gillenwater, 1992), although 6-month-old infants can process a gap in duration of a tone burst (Trehub, Schneider, & Henderson, 1995) if it is at least 12 ms long. This threshold decreases to 8 ms towards the end of the first year. However, it may even reduce to 4 ms at 6 months of age, if the gap is longer than the tone bursts it divides and it is the differentiating factor in the design (Trainor et al., 2001). It is generally noted that pause between higher frequencies reaches adult levels faster, but by the age of 6 years it is comparable with adult levels, i.e., it is close to 5 ms (Irwin, Ball, Kay, Stillman, & Rosser, 1985; Trehub, Schneider, & Henderson, 1995; Wightman, Allen, Dolan, Kistler, & Jamieson, 1989).

However, a wider temporal window of integration has been identified in children if the tones are presented in pairs with a longer intervening pause following the pair within the trial (Choudhury et al., 2015; Musacchia et al., 2013). Although a longer temporal window of integration is present for tone pairs than individual tones or noise, its perception also undergoes developmental acoustic narrowing. For example, 5- to 8-year-olds require 300 ms break between the tone pairs, but this decreases to 250 ms in 9- to 11-years-old children (Wang et al., 2005).

In a study by Choudhury and Benasich (2011), tone pairs were divided with 70 or 300 ms pause between each 70 ms tone. The overall trial duration was 915 or 1140 ms, respectively, to aid the perception of the tone pair as a single continuous unit rather than two individual tones. Participants were tested at 6, 9, 12, 16, 24, 36 and 48 months of age. Their electrophysiological responses indicated that they processed both presentation rates as a continuum, not a tone pair, in the first year of life, but presented less defined electrophysiological responses to 70 ms within tone pair pause and more apparent distinction for each of the tones with 300 ms pause in the pair thereafter (see also Benasich, Choudhury, Realpe-Bonilla, & Roesler, 2014; Benasich et al., 2006).

Similar findings were reported, when the tone pair gap was 10, 70 and 300 ms with the intertrial interval reduced to 705 ms in 6- to 11-year-olds and for adults (Choudhury et al., 2015). Children processed 10 ms pause as a continuation of the tone, but 70 and 300 ms elicited individual responses. Adults processed the pause in all conditions.

More discerning results were produced by adults in a study by Wang and colleagues (2005). Tones of 50 ms duration were intersected by frequency and intensity deviants, which were presented consecutively as a double deviant (one tone per trial). These deviant pairs were processed as single units rather than two unique sounds when each trial duration was 150 ms, but as individual sounds when it was 200 ms or longer (see also Yabe et al., 1998).

Overall, substantial evidence has been found for the temporal window of integration in early development. This is an important stimulus characteristic in auditory paradigms associated with early language development (Benasich et al., 2016; Cantiani, Riva, et al., 2016; Cantiani et al., 2019; Choudhury & Benasich, 2011; Fitch & Tallal, 2003; de Haan & Matheson, 2009; Kolesnik et al., 2019; Riva et al., 2018).

Auditory scene analysis.

Research in auditory perception drew interest in the second half of the twentieth century when Cherry (1953) identified the phenomenon of selectivity in processing the auditory scene. His 'cocktail party' effect revealed that adults filter out irrelevant sounds and focus on a single speaker in the multi-speaker environment. Supporting evidence for this effect in early development comes from a study by Barker and Newman (2004), in which 7-month-old infants selectively listened to their mother's voice and appeared to recognise words they had previously heard her saying, even if her voice was superimposed onto speech by another female speaker. They appeared to separate their mother's voice from that of a stranger.

Smith and Trainor (2011) attempted to assess stream segregation with a preferential looking technique in 6-8 months old infants. They were exposed to a stream of 2200 and 2400 Hz tones in one of three conditions: target alone, target with 1460 Hz flankers and target with flankers and captors, which were 1460 Hz tones distributed in random temporal position to the flankers. Participants were required to look only towards the target played among the other sounds from the speaker. The performance was, as expected, the highest to the target alone condition. It decreased in the flanker condition, but in the captor condition, it reached a similar level as the control condition. It appears that infants ignored auditory distractors and selectively responded to the relevant sounds. Similar findings have been reported in 1- to 3-month-old infants who were presented with a high and a low frequency stream of sounds played alternately. They looked towards a stream of higher frequency sounds while ignoring the lower frequency stream (Demany, 1982).

However, such approaches fail to address the concept of simultaneous processing of the streams, rather than ignoring one in favour of the other. A simplistic view of auditory stream segregation is provided by Snyder and Alain (2007) who propose wide differences between the frequency of the simultaneous streams of sounds as the basis for the efficient perceptual organisation. A more comprehensive account is specified with the auditory scene analysis theory (Bregman, 1978, 1990, 2010; Bregman & Rudnicky, 1975; Sussman, Bregman, Wang, & Khan, 2005). It explains the ability to identify and organise auditory sources based on probabilistic patterns and spatial and spectro-temporal cues, including location, frequency, pitch, and temporal proximity. The model involves segmentation – dividing sounds, followed by integration – combining them into separate streams, and segregation – sorting them by the type of stream (see also Gutschalk & Dykstra, 2014).

Along with separation based on simple acoustic features, streaming may occur at the higher levels of auditory processing, engaging attention, inhibition (including at the basic level neural suppression), sensory memory trace and executive functions in streaming continuous speech and organising words based on meaning at the other end of the spectrum. The level of competition and cognitive engagement between the alternative streams determines whether only one or both streams are processed (Andreou, Kashino, & Chait, 2011; Bregman, 1978; Bregman & Rudnicky, 1975; Carlyon, 2004; Cusack, 2005; Deike, Deliano, & Brechmann, 2016; Deike, Heil, Böckmann-Barthel, & Brechmann, 2012; Hartmann & Johnson, 1991; Micheyl et al., 2007; Romanski et al., 1999; Sussman et al., 2005; Sussman, Horváth, Winkler, & Orr, 2007; Wrigley & Brown, 2004).

The externally driven networks are based on the saliency map (Kalinli & Narayanan, 2007; Kaya & Elhilali, 2012, 2014; Kayser, Petkov, Lippert, & Logothetis, 2005; Tsuchida & Cottrell, 2012; Wang, Zhang, Madani, & Sabourin, 2015) and the ability to discriminate the target sound or stream from the background noise through habituation to recurring sounds and dishabituation to an unexpected sound (Duangudom & Anderson, 2007; Kaya & Elhilali, 2014), such as a doorbell, while listening to music. The internally directed attention differs from the latter as it is task dependent. Weight is then given to the goal-relevant sounds (Carlin & Elhilali, 2015; Holt & Lotto, 2007; Kalinli & Narayanan, 2008, 2009; Patil & Elhilali, 2013; Schneider, Parker, & Murphy, 2011; Shinn-Cunningham, 2006;

Shinn-Cunningham, 2009), e.g., speech over birdsong in conversation, but infant cry over speech when expecting the child to wake up.

Computational models based on the theory explain the ability to process competing stimuli, for instance when isolating speech (Balaguer-Ballester, Bouchachia, Jiang, & Denham, 2012; Denham & Winkler, 2006) or other sounds from the noisy background, processing two streams of speech simultaneously (Akram, Presacco, Simon, Shamma, & Babadi, 2016) or switching between auditory streams (De Coensel & Botteldooren, 2008, 2010; Oldoni et al., 2013) in the complex auditory environment.

In simple models based on sensory processing, only two competing streams (based on the type of sound) are considered, such as car traffic versus train noise or bird chirp versus bird chorus and only one stream is processed at any given time. Consequently, the listener switches between streams, which are then sorted based on saliency and spectro-temporal cues online into two separate messages. All this happens at the sensory level before attentional processes are triggered. Only after the messages are transferred through to bottom-up auditory processing, the selection (or inhibition) top-down processing is engaged, based on relevance (Neill, 1979; Snyder & Alain, 2007; Snyder, Alain, & Picton, 2006; Snyder, Holder, Weintraub, Carter, & Alain, 2009).

The models of the complex auditory processing based on attentional bias by contrast suggest that adults tune in to sounds from all sources and continuously sequentially switch between them in order to efficiently generate information from all of them (Golob, Venable, Anderson, Benzell, & Scheuerman, 2017; Wang & Brown, 2006; Wrigley, 2002; Wrigley & Brown, 2004)

Despite the evidence in adult research, the effect of streaming has been given little consideration in developmental research. Considering that auditory attention develops throughout childhood (Gomes, et al., 2000), the number of streams in a paradigm may have a different impact on the MMR in infants and children than in adults. Accordingly, this is relevant for the thesis, as understanding this relationship may provide insights into the clarification of the functional attributes of the MMR in infants and children and why it might differ between these two populations.

1.2 Language development in early childhood

This section begins with an account of early developmental trajectories of receptive and expressive communication, followed by a report on the behavioural assessments of language performance in children. The remaining passages provide a brief description of the language networks in the adult brain and then examine language specialisation from birth to the primary school age.

1.2.1 Language milestones in early childhood.

Despite the wide behavioural variability in the trajectories of receptive and expressive communication in typically developing children, some critical periods have been identified (Gervain & Mehler, 2010; Rescorla et al., 2000; Sampallo Pedroza et al., 2015; Werker et al., 2009; Werker & Hensch, 2015). The broadly defined developmental stages are outlined below. Falling behind in achieving these milestones may be an indicator of language delay and prospective specific language difficulties (Carson, Klee, Perry, Muskina, & Donaghy, 1998; Duff, Nation, Plunkett, & Bishop, 2015; Laasonen et al., 2018).

In the first year of life

Infants are born with neural predisposition to language acquisition (Kisilevsky, 2016; Lecanuet & Schaal, 1996). They generally prefer speech to other sounds (Shultz & Vouloumanos, 2010) and are able to discriminate any sounds and even subtle differences between them in any language (Gomez et al., 2014; Key et al., 2007; Stefanics et al., 2009). Due to exposure in the womb (Gervain, 2018; Voegtline et al., 2013), they already recognise their mother's voice (Jardri et al., 2008, 2012) and quickly become familiar with speakers heard on a daily basis, such as the other parent and siblings. While they are exposed to speech sounds before birth, they begin to practise speech themselves postnatally. This usually begins with gradual differentiation between types of cries and cooing around first to third month (Mampe, Friederici, Christophe, & Wermke, 2009). As babies grow and are exposed to more linguistic sounds they become to sigh, squeal, laugh, grunt, gurgle and learn that they can produce vowels (Mersad & Dehaene-Lambertz, 2016).

Around four to six months of age they begin blowing raspberries and imitating consonants and more sophisticated language sounds. This is followed by bubbling which usually commences around six to nine months of age (Hochmann et al., 2011; Kuhl, 2004). They begin to recognise their own name in this period (Mandel, Jusczyk, & Pisoni, 1995). Also, around this time infants become specialised in recognising native linguistic auditory nuances while their sensitivity to languages they are not familiar with discrimination of vowels and syllables in other languages is attenuating (Iverson, Wagner, Pinet, & Rosen, 2011; Eira Jansson-Verkasalo et al., 2010; Marcus, Vijayan, Bandi Rao, & Vishton, 1999; S. Ortiz-Mantilla, Hamalainen, Musacchia, & Benasich, 2013; Scott & Wise, 2004). From 9 months, they learn to draw attention from the caregiver by using exclamations and communicate their wants by pointing (Parise & Csibra, 2012; Parise, Handl, Palumbo, & Friederici, 2011; Parise, Reid, Stets, & Striano, 2008). They also respond appropriately to ‘no-no’ (Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004). By 12months, they have usually spoken their first word and learn to recognise labels for objects they are frequently exposed to (Mcduffie, Yoder, & Stone, 2006; Yeung, Chen, & Werker, 2014; Yeung & Nazzi, 2014). Figure 1.4 illustrates the development of language acquisition in the first year of life.

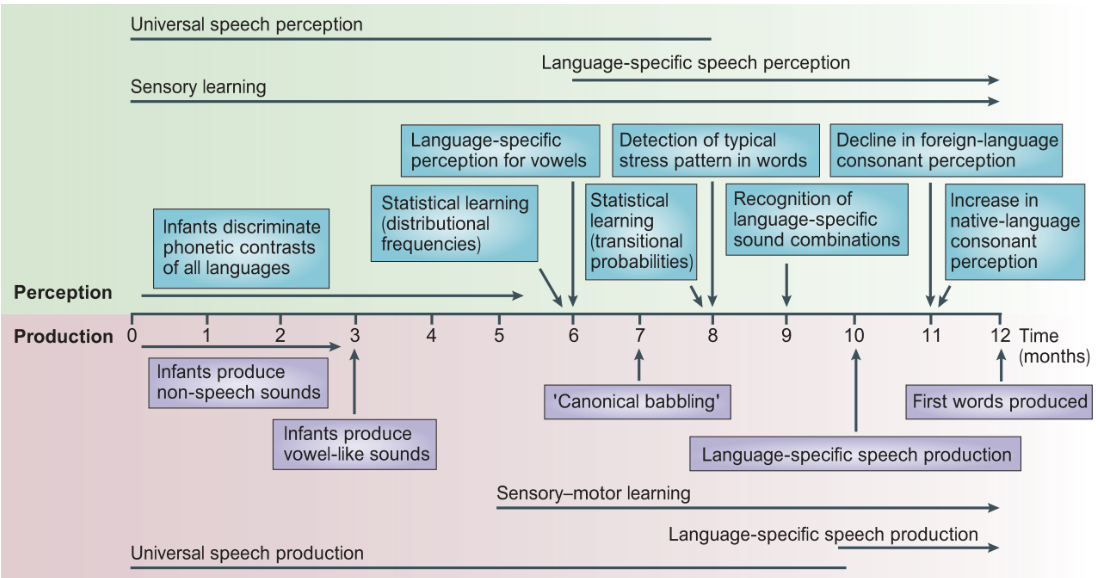

Figure 1.4 The diagram demonstrating a timeline in the development of speech perception and production (copied from Kuhl, 2004).

Following from that, one-year-olds practise producing various phonetic combinations called ‘jabbering’ as the closest family may not recognise most of the produced words (Green & Wilson, 2006; Karousou & López-Ornat, 2013). By 18 to 24 months, they recognise a number of objects, animals and people in the environment and learn how to name and categorise them (Adams et al., 2018; Fernald & Marchman, 2012; Marchman et al., 2018). By second birthday, children on average have a vocabulary of around 50 words (Cattani et al., 2014; McGillion, Pine, Herbert, & Matthews, 2017; Stokes & Klee, 2009). They begin responding to questions with 'yes' or 'no' and begin to put two words together (Collisson et al., 2016; Fernald & Marchman, 2012; Jackson-Maldonado, Marchman, & Fernald, 2013; Kabdebon, Pena, Buiatti, & Dehaene-Lambertz, 2015). Gradually, they realise that objects in front of them can be represented with images (Swingley, Pinto, & Fernald, 1999). They learn to follow one- and later two-part instructions (Sweller, 1988).

Preschool

In the third year, children' vocabulary dramatically increases. They begin to distinguish and later correctly label the sizes of objects. Their sentences become more complex (consist of 3-5 words), with the use of pronouns and plurals. By four years of age, children can follow up to three-part instructions and describe a picture or an event (Dollaghan et al., 1999; Harold & Barlow, 2013; Menn & Ratner, 2000). They understand relations between objects, such as 'under' or 'behind' (Shimpi & Waterfall, 2019; Yang & Pan, 2021) and describe physical states such as 'hungry' or 'sleepy'(Bedford, Walton, & Ahn, 2013; Desmarais, Sylvestre, Meyer, Bairati, & Rouleau, 2008). Toddlers learn to count (Starr & Brannon, 2015; Starr, Libertus, & Brannon, 2013). They use egocentric speech (Calderwood, 1999; Gillen, 2000; Levy, 1984; Shields, 1979), especially in 'pretend' play (Mundy & Crowson, 1997; Sawyer, 1997; Sigman & McGovern, 2005). Conversations become more complex, and children are curious about the world phenomena. They ask interrogative questions beginning with 'who', 'what' or 'why'. They begin to understand the simple reasons behind and consequences following actions (Fiveash, Thompson, Badcock, & McArthur, 2018; Menn & Ratner, 2000). By the time a child turns five, their vocabulary reaches 2500 words (Girolametto, Wiigs, Smyth, Weitzman, & Pearce, 2001; Washbrook, Waldfogel, Bradbury, Corak, & Akbar Ghangro, 2012).

Primary school age

From the age of five years, spontaneous speech is increasingly enriched with adjectives and children speak using mostly grammatically correct sentences(Dollaghan et al., 1999; Harold & Barlow, 2013; Jia & Fuse, 2007; Menn & Ratner, 2000). They begin to follow instructions which are not presented in order, relate to different dimensions of an objects, or use negation (Crestani et al., 2010; Davis & Matthews, 2010; Katsipis, 2016; Ridgeway et al., 1985). As they learn to read and write, they begin to breakdown words into phonemes and generate words related to a specific category (Chall & Jacobs, 1983; Colmar, 2014; Fish & Pinkerman, 2003; Marchman, Martinez-Sussmann, & Dale, 2004; Zubrick, Taylor, & Christensen, 2015). They are able to answer the 'why' questions. They learn about the irregular verbs in past tense (Budd et al., 2013; Thomas et al., 2013). By the age of 11 years children begin to elaborate on abstract phenomena (Katsipis, 2016; Vigliocco, Ponari, & Norbury, 2018) and discuss their and others' emotional states (Doost et al., 1999; Schneider, 1938; Taghavi et al., 2003).

1.2.2 Behavioural assessment of language development.

Behavioural measures are commonly used in assessing early language development (Bedford et al., 2013). To objectively examine behavioural language performance in early development, remove the age effects in data analysis and ensure the different age groups are comparable, standardised tests should be employed (Denman et al., 2017; Dockrell & Marshall, 2015; Pham et al., 2014; Spencer, Clegg, & Stackhouse, 2012). Such treatment ensures that any differences in performance within the sample and in group comparison are a result of the experiment, not due to developmental changes, i.e., where older participants outperform the younger ones. For clarification, in this thesis, this relates specifically to English (Bedford et al., 2013).

However, it is important to acknowledge that not all individuals who participate in English language assessments are monolingual English speakers. Some have been exposed to at least one other language on a regular basis. Restricting language assessment criteria to English when some participants are monolingual while others have broader language experience, naturally has its limitations (Dockrell & Marshall, 2015; Kirby, 1997; Washbrook, Waldfogel, Bradbury, Corak, & Akbar Ghangro, 2012). The major disadvantage is that it is difficult to ascertain the ratio of exposure to English versus other languages in the participants' receptive and expressive vocabulary, especially in younger individuals (Deanda, Arias-Trejo, Poulin-Dubois, Zesiger, & Friend, 2016). The level of familiarity with English and other languages is likely to vary between participants, and this may affect their proficiency in English.

The natural choice would be then to study children who are exposed only to English but restricting recruitment to only monolinguals also has drawbacks. Regional variability between native English dialects and accents may affect performance (Snell & Andrews, 2017). At the national level, North American infants outperform their British peers on receptive and expressive language (Buckler & Johnson, 2019; Floccia et al., 2016), which is why British infants may score below the normative range (Albers & Grieve, 2007; Bayley, 2005; Luttikhuizen dos Santos, de Kieviet, Königs, van Elburg, & Oosterlaan, 2013; Piñon, 2010; Soleimani et al., 2016). However, this pattern reverses when children enter primary school (Barnett, Lamy, & Jung, 2005; Law, Mahr, Schneeberg, & Edwards, 2017), as British children are younger when they enter the education system than their American, African, Australian, Canadian, or South Asian counterparts: at 4-5 versus 5-7 years (The World Bank Data, 2020).

Caution must be therefore exercised here since most English language assessments are based on the typically developing monolingual US cohorts (Brooks, Sherman, & Strauss, 2010; Davis & Matthews, 2010; Korkman, Kirk, & Kemp, 2007a; Walker, 1994; Zimmerman, Steiner, & Pond, 2009), although some attempts to adapt the assessments to cultural settings have been applied (Cattani et al., 2014; Hamilton, Plunkett, & Schafer, 2000; Moore, Goodwin, & Oates, 2008). Research shows differences in the performances between British, English Canadian, and American English native speakers. However, due to the shortfall in alternative methods of setting equivalent standardisation for specific nationalities, North American language assessments are largely used in developmental studies investigating the English language (Bayley, 2005; Korkman et al., 2007a; Zimmerman et al., 2009).

Other factors may be adding to the challenges associated with measuring behavioural language performance. Despite relatively well mapped out language trajectories in typically developing children (Gomez & Gerken, 1999; Kuhl, 2004; Roulstone et al., 2011; Werker & Hensch, 2015), the behavioural language indicators are fewer the younger the child. In addition, they do not translate the developmental communication ability reliably as they may be subject to the child's variable mental and emotional state (Spinelli, Fasolo, Shah, Genovese, & Aureli, 2018) due to factors such as teething, flue or other physical ailments (Benasich, 2002; Fenson et al., 2000), or environmental contributors, such as a change to daily routine or unfamiliar people (which researchers or medical staff assessing their milestones tend to be). Finally, the impact of the socioeconomic status on language development has been widely evidenced with children brought up in poorer families at a higher risk of language delay (Adler & Snibbe, 2003; Bradley & Corwyn, 2002; Clearfield & Jedd, 2013; Hackman, Gallop, Evans, & Farah, 2015; Noble et al., 2015; Noble, Norman, & Farah, 2005).

Consequently, it is still a challenge to accurately gauge behavioural language performance early in development (Dockrell & Marshall, 2015). Therefore, considering that the focus of this project was to assess children's general language proficiency with the aim to apply the results to wider population, the best and more realistic course of action was to collect the data from infants and children of variable proficiency in English, as long as they were exposed to it from birth (Floccia et al., 2013; Paradis, Emmerzael, & Duncan, 2010). The other potential factors would be acknowledged but if their contribution was found to be nominal, they would not be included in the analyses (Zubrick et al., 2015). Ultimately, assessment of brain activity in response to auditory stimuli (Guzzetta, 2014; Leppänen et al., 2004; Parthasarathy, 2006) and the corresponding brain networks (Brauer, Anwander, & Friederici, 2011a; Brauer, Anwander, Perani, & Friederici, 2013a; Duffau, 2016; Leroy et al., 2011; Su, Kuan, Kaga, Sano, & Mima, 2008; Vannest, Karunanayaka, Schmithorst, Szaflarski, & Holland, 2009) may be a more objective measure to evaluate the level of language acquisition in infants and children (Davis & Matthews, 2010; Guzzetta et al., 2011; Nelson & Franzen, 1997).

1.2.3 Functional neuroanatomy of language.

The first attempt to identify the functional anatomy of language in the brain was made by Gall (1835). Influenced by his work, Broca (1865) proposed that damage to the left inferior frontal gyrus (later named Broca's area) was the cause of disorders of speech production (Dronkers, Plaisant, Iba-Zizen, & Cabanis, 2007) in the absence of oromotor impairment. Another significant development came from Wernicke (1874), who researched disorders of speech comprehension. He became known for identifying the left superior temporal gyrus as the region processing receptive language, and the impairment in this area was named Wernicke's aphasia in recognition of his work. Finally, in 1965, Geschwind identified fibres connecting both the inferior frontal and the superior temporal gyri along each hemisphere.

Since then, the neural bases of language have been found both in the inferior frontal and across the temporal lobes (Brauer, Anwander, & Friederici, 2011; Flinker et al., 2015; Schoenemann, 2009) with general dominance in the left, over the right hemisphere, although more recent research suggests that lateralisation of language functions is not as clearly divided as historically believed (for review see Dronkers & Baldo, 2001; Scott & Wise, 2004; Specht, 2014). Figure 1.5 illustrates the language connections across cortical areas. The two main networks - dorsal and ventral, are explained.

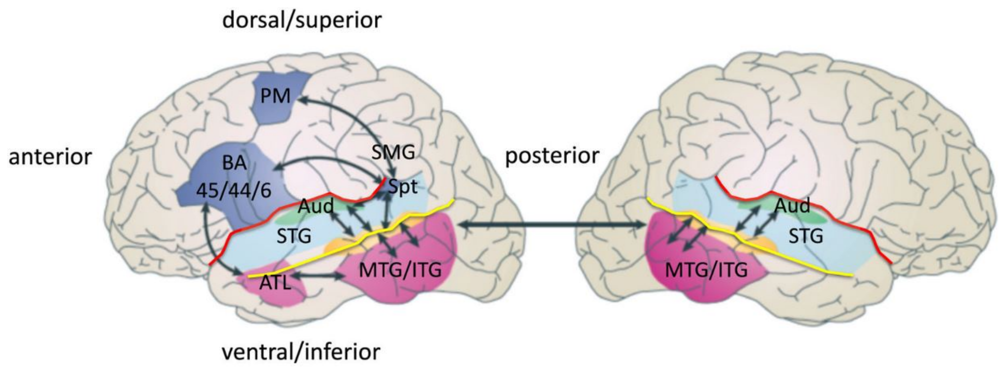

Figure 1.5 Language network in the brain comprises a ventral stream for speech comprehension that is largely bilaterally organised, and which flows into the temporal lobe, and a dorsal stream for sensory-motor integration that is more dominant in the left hemisphere, and which involves structures at the parietal- temporal junction and frontal lobe. Anterior temporal lobe (ATL on the brain model) and auditory cortex (Aud) are activated in early processing stages, then Brodmann areas 45, 44, & 6 (BA 45/44/6), middle temporal gyrus (MTG), inferior temporal gyrus (ITG) and pre-motor cortex (PM). Dorsal stream involves activation of supramarginal gyrus (SMG), left Sylvian parieto-temporal region (Spt), superior temporal gyrus (TG). The red line indicates Sylvian fissure and yellow line superior temporal sulcus (STS). The image reprinted from Hickok (2013).

It is crucial to recognise that both receptive and expressive language engage a broad network of cortical and subcortical regions (see also section 1.1.1 for thalamic projections and processing layers within primary auditory cortex). As such, the areas involved can be identified with neuroimaging methods, while their electrophysiological activity recorded with EEG.

1.2.4 Development of language networks in the brain.

As argued in section 1.2.2, structural and functional changes in the brain may be a more objective and consistent measure of language development (Chen et al., 2016; Dawes & Bishop, 2008; Doesburg et al., 2016; Gozzo et al., 2009; Knowland et al., 2014; Kushnerenko et al., 2013; Litovsky, 2015; Mundy et al., 2003; Ortiz-Mantilla et al., 2016; Poulsen et al., 2009; Ragó et al., 2014; Shafer et al., 2011; Sharma et al., 1997; Su et al., 2008; Taylor, 2012; Weber-Fox & Neville, 1996; Werker & Hensch, 2015) than behavioural assessment. Namely, automatic neural responses to sounds may be more robust against epigenetic and environmental factors in assessing whether the infant is progressing as expected for their age or whether atypical cortical wiring is in progress, indicating that the at-risk trajectories are emerging, and intervention may be required to rewire the cerebral connections before they are consolidated. In order to record these, various non-invasive techniques have been developed, such as functional Magnetic Resonance Imaging (fMRI), diffusion tensor imaging (DTI) and Near-Infrared Spectroscopy (NIRS) to measure hemodynamic fluctuations in the regions involved in the processing or production of speech sounds and magnetoencephalography (MEG) and EEG to record electrophysiological brain activity (Kuhl, 2010; Kuhl & Rivera-Gaxiola, 2008).

Indeed, several maturational changes have been reported. Whilst the language network in the brain is quite established in children of the primary school age, DTI evidence (Hämäläinen, Ortiz-Mantilla, & Benasich, 2011; Perani et al., 2011) indicates that these connections are not fully developed at birth (see Figure 1.6). The ventral pathway is present though immature, the dorsal pathway connecting the precentral gyrus with the premotor cortex is weak and the fibres connecting the superior temporal gyrus with the Broca's areas not yet developed (Leroy et al., 2011).

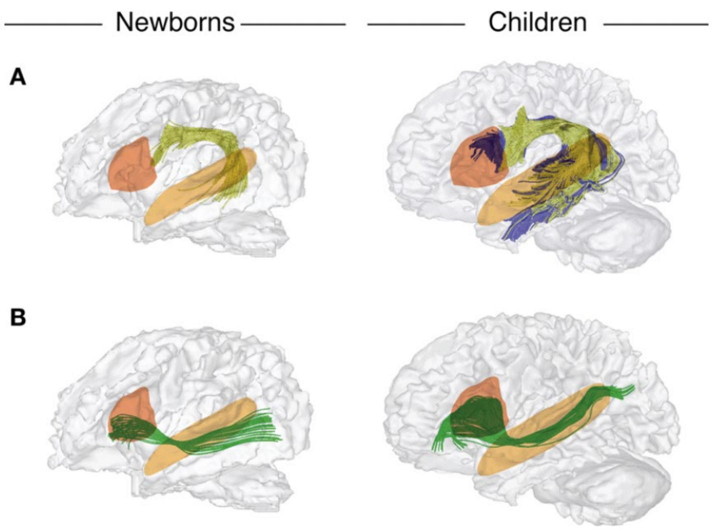

Figure 1.6 Structural connectivity of the language network in the newborn (left) and 7-year-old brain (right). Left hemisphere is demonstrated on top (A) ad right hemisphere at the bottom (B). Fibre tracking for speech-specific regions with the origins in Broca's area and in the precentral gyrus/premotor cortex. Two dorsal pathways are present in children: the blue one connecting the temporal gyrus/cortex (orange) with the inferior frontal gyrus, i.e., Broca's area (red), and the yellow one linking the temporal cortex with the precentral gyrus, i.e., premotor cortex. In newborns, only the latter dorsal pathway can be found. In contrast, the ventral pathway (green) connecting the inferior frontal gyrus to the temporal cortex is present in children and newborns. Reprinted from Brauer (2014).

The visible development of lateralisation of the pathways is also represented in electrophysiological activity, Teinonen et al. (2009) reported some left hemisphere advantage in processing phonetic contrast by sleeping newborns, although the focus of the study was the ability to identify novel phonemes in a sequence by generating large EEG deflections to the unexpected sounds, not where the neural activity originated. However, with the use of fMRI, 3-month-old brains have been shown to engage the left temporal gyrus in response to speech stimuli (Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002). Less conclusive evidence has been collected with NIRS. Grossmann and colleagues found increased blood flow to speech in the right temporal cortex in 4-month-old infants. However, 7-month-olds produced larger activity in the left temporal cortex. The pattern in older infants resembled adult response (Grossmann, Oberecker, Koch, & Friederici, 2010; see also Bach et al., 2010; Burton et al., 2000; Galaburda et al., 1978; Gazzaniga, 2000; Teismann et al., 2004; Wang et al., 2014). Nonetheless, this inconsistency may be related to changes in electrophysiological response around 6-9 months of age, when their polarity indicating discrimination of sounds switches from positive to the more mature negative deflections (Kushnerenko, 2003; Kushnerenko et al., 2013).

The findings on the development of cortical response are corroborated by MRI data on synaptogenesis of auditory cortex by Huttenlocher (2000, 2002). While auditory areas reach the fullest synaptic density around three years of age, the rate of synaptic growth varies between the language areas, but also gradually reaches parity levels by 3 years of age (Figure 1.7). After that period, the number of synapses decreases, signifying increased synaptic pruning and maturation of the neural fibres (Chaudhury, Sharma, Kumar, Nag, & Wadhwa, 2016; Petanjek et al., 2011).

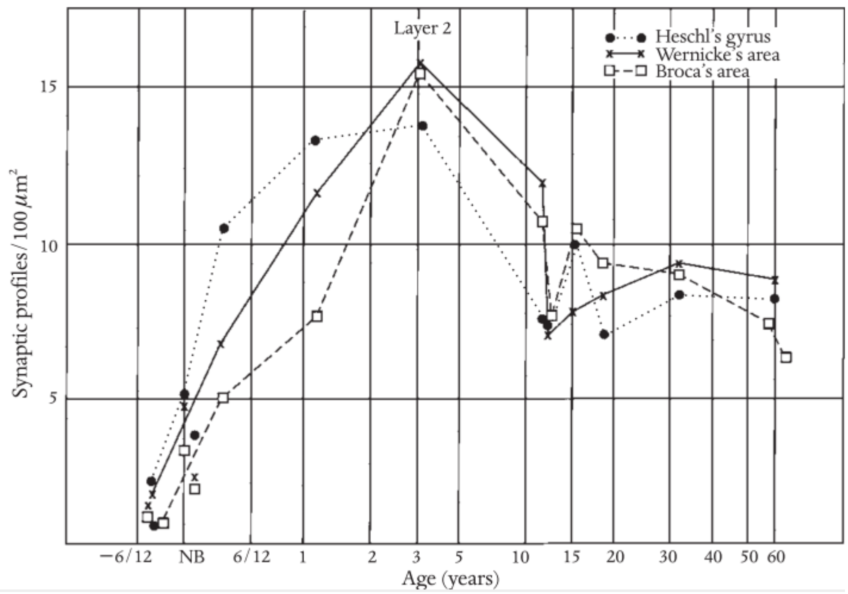

Figure 1.7 Synaptic density as a function of age in three cortical regions important for language processing. The dotted line represents auditory cortex (Heschl's gyrus), solid line -Wernicke's area in the left temporal lobe and dashed line - Broca's motor speech area in the left frontal lobe (reprinted from Huttenlocher, 2002. p. 50).

Indeed, other studies have reported the developmental increase in connectivity between language areas from 4 to 18 years of age (Doesburg et al., 2016; Youssofzadeh, Williamson, & Kadis, 2017). This may be also related to myelination of the axons, the fatty tissue which wraps around and insulates them and as a result increases conductivity of the signal (Alho, Salmi, Koistinen, Salonen, & Rinne, 2015; Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004; de Haan, 2013; Kushnerenko et al., 2002a; Näätänen et al., 2007; Pekkonen et al., 1996; Wunderlich et al., 2006; Yu & Goodrich, 2014)

The synaptic maturation in turn increases specialisation and modulation of the language network, as reported in 5- to 7-year-olds (Szaflarski et al., 2006). The mechanisms underlying this process are the increase in processing speed and efficiency across the dorsal and ventral cortical pathways (Brauer, Anwander, Perani, & Friederici, 2013b) and their lateralisation to speech nonspeech stimuli (Ressel, Wilke, Lidzba, Lutzenberger, & Krägeloh-Mann, 2008). Likewise, in a brief review of their own fMRI studies, Vannest et al. (2009) found gradual functional specialisation to semantic versus prosodic processing of speech between 7-30 years of age. They reported that while both the frontal and temporal areas were activated, with age, the left hemisphere became more responsive to the content of the speech, while processing intonation and other acoustic properties lateralised to the right.

Clearly, developmental maturation and the type of sound may affect cortical response (Rosselli, Ardila, Matute, & Vélez-Uribe, 2014), and so are of importance for the current project. The final point of this section is to recognise that brain reorganisation for language develops through social interaction (Gratier & Devouche, 2017; Kuhl, 2004) with others. Infants respond to auditory stimulation better when adults communicate with them in 'parentese' or infant-directed-speech, which is characterised by heightened pronunciation and clearer breakdown of phonemes in words (Fernald, 1985; Hepper et al., 1993; Kuhl et al., 2014; Mampe et al., 2009) Exposure to native language or languages as well as the quality of speech and intensity of the stimulation shape the development of language network in the brain (Dehaene-Lambertz et al., 2010; Holmes Reich, & Pasternak, 1984; Huttenlocher, 2002; Key et al., 2007). While these factors are outside of the scope of this thesis, their potential differential effects should be recognised and controlled for in the studies where appropriate.

1.3 Neural signatures of auditory processing

1.3.1 Event-related-potentials.

The primary interest of developmental scientists in EEG is the ability to reveal sensory or covert responses to external stimuli and internal mental states in the absence of behavioural indicators. As such, EEG may be an invaluable tool in assessing preverbal infants or other vulnerable populations (Bell & Cuevas, 2012; Casey & de Haan, 2002; de Haan, 2013; Hoehl & Wahl, 2012). Although of relatively low spatial resolution, EEG is a very temporally specific electrophysiological technique. It records ERPs, which are electrical neural responses. They are time-locked to a specific stimulus and fluctuate between positive and negative voltage potentials over the cortical surface.

Polarity of the ERPs represents the projection of a population of pyramidal neurons located in the cortex. They may be positively or negatively charged based on inhibitory or excitatory postsynaptic potentials in response to a stimulus. These, in turn, are determined by action potentials, which spike in an ‘all or nothing’ manner based on the concentration of positive and negative ions inside and outside the cellular membrane of a neuron. The process of activating action and postsynaptic potentials is called electrogenesis (Shah et al., 2004). Figure 1.8 demonstrates a schematic model of electrogenesis of individual ERPs. The larger proportion of positive or negative potentials determines how they are represented on the surface of the brain and recorded with EEG channels, also referred to as electrodes.

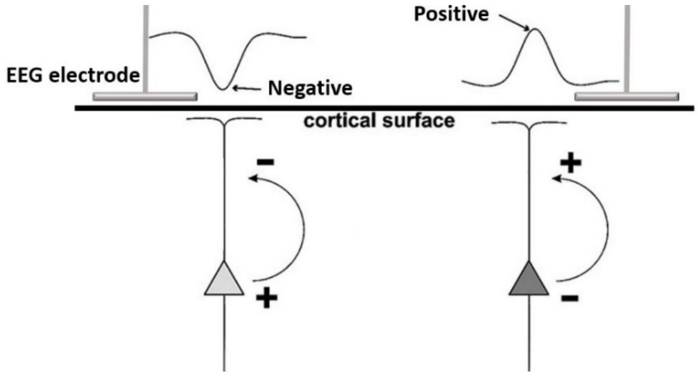

Figure 1.8 Model of electrogenesis of negative and positive ERP peaks (adapted from Allison et al., 2002). Negative peak recorded on the scalp surface is the result of excitatory depolarisation of dendrites of pyramidal neurons. Positive peak is the surface recording of inhibitory hyperpolarisation of the dendrites. The presented current flows are extracellular and generate ERPs by synchronous excitation or inhibition of populations of such cells. They are recorded on the surface of the scalp with EEG via EEG channels.

1.3.2 A brief history of EEG recording.

Research into the history of EEG attributes the first recording of resting current to du Bois-Reymond (du Bois-Reymond, 1848; Finkelstein, 1888), who reported changes to an action potential in response to external stimulus. This was followed by the first human EEG recording obtained by Von Berger (Berger, 1934; Millett, 2001). His suggestion that changes in electrophysiological activity may be associated with mental states aided discovery of individual ERP components (Bridwell et al., 2018; Chapman & Bragdon, 1964; Davis, 1939; Gross, Begleiter, Tobin, & Kissin, 1965; Haider, Spong, & Lindsley, 1964; Handy, 2005; Picton, 1994; Sur & Sinha, 2009; Sutton, Braren, Zubin, & John, 1965; Walter, Cooper, Aldridge, McCallum, & Winter, 1964; Woodman, 2010). The largest obligatory ERPs (Lohvansuu et al., 2013; Mancini et al., 2018) are illustrated in Figure 1.9. The P1 and N1 components are associated with sensory response to a stimulus in the environment, P2 and N2 are linked to object recognition (e.g., deviant versus standard sounds), and P3 as well as present in some waveforms N4 are thought to reflect cognitive processes, such as the meaning of a word (Friederici, 2005; Woodman, 2010).

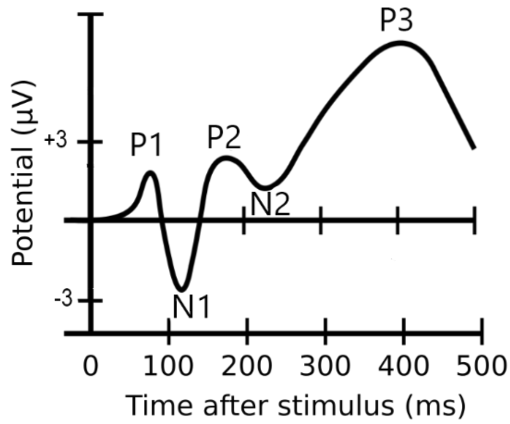

Figure 1.9 Schematic representation of time-amplitude ERP waveform with individual components labelled *(adapted from image by Choms, https://commons.wikimedia.org/w/index.php?curid=5543904)*.

The earlier components do not require the generation of active attention to stimulus events (Garrido, Kilner, Stephan, & Friston, 2009; Lehtokoski et al., 1999; Näätänen et al., 1978; Ritter et al., 1992; Sussman, Steinschneider, Gumenyuk, Grushko, & Lawson, 2008; Tiitinen et al., 1994; Woodman, 2010) and are particularly suitable for studying automatic (preattentive) discrimination and perception processes in young subjects (Čeponiené et al., 2008; Fellman & Huotilainen, 2006; Hövel et al., 2014; Kabel, Mesallam, & Ghandour, 2009; Kushnerenko et al., 2002b; Mahajan & McArthur, 2012; Shafer et al., 2015; Sharma et al., 2006; Vantanen, 2004; Wunderlich et al., 2006).

1.3.3 MMR component.

Mismatch response (MMR) is an electrophysiological component obtained through averaging ERPs to infrequent deviant and frequent standard sounds in a paradigm design called ‘oddball’ and subtracting the ERP amplitude to standard from the ERP to deviant sounds (Movshon & Lennis, 1979; Näätänen et al., 1978, 2007; Näätänen & Alho, 1997). Figure 1.10 illustrates the subtraction process between ERPs to deviants and standards required to compute the MMR. In adults, it is represented by a negative deflection from the baseline, which is why it is called mismatch negativity or MMN (Garrido et al., 2009; Todd, Harms, Schall, & Michie, 2013).

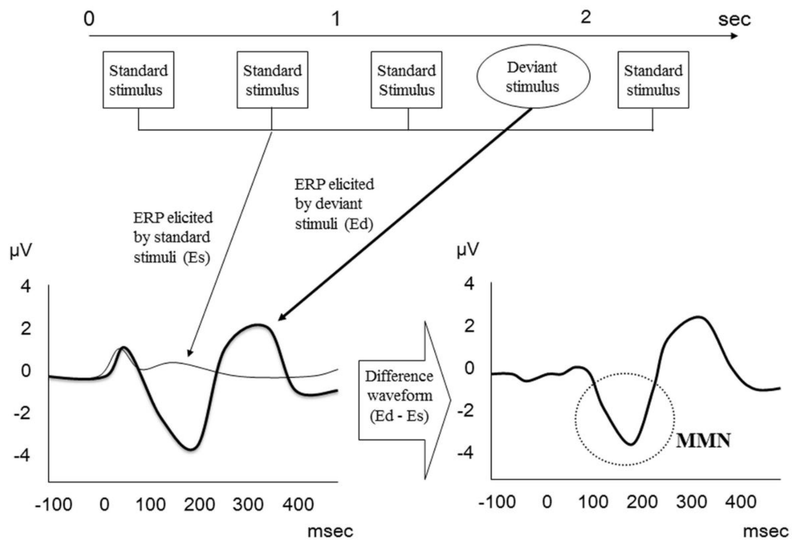

Figure 1.10 Schematic representation of obtaining MMR (here MMN) from ERP waveforms (Gilley et al., 2017)). The ERPs are averaged across all standards and deviants to a single wave for each category. The MMR difference wave is acquired by subtracting the standard from the deviant ERP waveform.

The presentation rate of the deviant is kept between 5-20% in relation to standard stimuli in an EEG paradigm, with lower probability of the deviant producing more significant MMR (Bruggemann, Stockill, Lenroot, & Laurens, 2013; Takaura & Fujii, 2016). The difference between deviant and standard waveform is considered significant if the probability of random occurrence is 5% or less (Guthrie & Buchwald, 1991; Sterne, Smith, & Cox, 2001).

The oddball design used to elicit the MMR difference was introduced by Squires, Squires and Hillyard (1975). In their study, 1000 Hz tones of 50 ms duration were overlaid over wideband noise at 65 decibel sound pressure level (dB SPL). The standards and deviants differed on the intensity: 65 versus 70 dB SPL. Deviants in the oddball paradigm were presented at 10% probability while the control involved the same sounds but at 50% probability. The authors reported the largest ERPs (to deviants) in the oddball than the equiprobable paradigm.

Similar findings have been reported by Čeponiené and colleagues (2002a) when exploring phonetic discrimination in newborns. The advantage of the oddball paradigm in eliciting large ERPs as opposed to the equiprobable design was measured with vowel contrast in syllables /pe/, /pi/, /te/ and /ti/ (Partanen et al., 2013). Although both paradigms produced significant ERP deflections, the larger ERPs were obtained in response to deviants in the oddball paradigm. However, the study was of between-subject design and while the control measures were to ensure the groups were homogeneous, the comparison between the infants participating in the equiprobable and oddball paradigms ought to be taken with caution.

Nonetheless the oddball paradigm has proven to be an efficient and easy to administer method to assess neural discrimination between stimulus features and so a successful technique to generate significant MMR (Näätänen et al., 1978) at all ages (Friederici, Friedrich, & Weber, 2002) both at the covert and overt level of processing (Debener, Kranczioch, Herrmann, & Engel, 2002; Guiraud et al., 2011; Kushnerenko et al., 2002b).

Subsequently, Näätänen and colleagues (1978) identified MMR as the neuromarker of auditory discrimination. In two experiments, their standard stimuli were frequent 1000 Hz tones at 70 dB SPL. The rare (2.6% of all trials) deviant tones had either a higher intensity (80 dB SPL in experiment 1) or frequency (1140 Hz in experiment 2). When ERPs to standard stimuli were subtracted from the deviant ERPs, the results revealed a preattentive automatic ‘processing negativity’, followed by an attention-modulated positive deflection. The first component was later labelled MMN and the second was linked to P3 (Garrido et al., 2009; Näätänen et al., 2007; Näätänen, Pakarinen, Rinne, & Takegata, 2004; Näätänen, Tervaniemi, Sussman, Paavilainen, & Winkler, 2001).

This indicated that the MMR is the result of an automatic, precognitive comparison between memory traces built on the previous auditory pattern and its predictions as to the nature of the next sound. (Sams, Hari, Rif, & Knuutila, 1993; Winkler, 2007). Several theories explain this mechanism:

Change Detection.

The MMR represents sensory detection of acoustic deviance on one or more dimensions of the stimulus in comparison with the previous sequence (Schröger & Winkler, 1995; Sorokin et al., 2010; Winkler et al., 1999).

Adaptation.

The MMR reflects the difference in stimulus-evoked action potentials between adapted and non-adapted sensory neurons (Dykstra & Gutschalk, 2015; May & Tiitinen, 2010).

Model Adjustment.

The auditory cortex holds a model of the acoustic environment, and stimulus-induced updates of this model are indexed by the MMR (Angelini et al., 2009; Näätänen & Winkler, 1999; Winkler & Czigler, 1998; Winkler, Karmos, & Näätänen, 1996).

Novelty Detection.

The MMR reflects the degree to which the current event is surprising or new (novel) in comparison to the previous pattern based on the probability of what the next stimulus should be. This model explains change as well as silence as a form of deviance, which may be more surprising, if unexpected, than contrast between two types of stimuli (Escera & Corral, 2007; Kushnerenko et al., 2013c; Sorokin et al., 2010; Tiitinen, May, Reinikainen, & Näätänen, 1994; Wacongne et al., 2011).

Prediction Error.

The cortex implements Bayesian inference using predictive coding. The MMN reflects the neural activity encoding the prediction errors that drive this process, i.e., differences between actual and predicted inputs. In contrast to novelty detection, the error indicates that the new sound violates the predictive pattern based on probability (Dürschmid et al., 2016; Friston, 2005; Wacongne et al., 2011).

Although the first two theories are founded in sensory processing, the remaining models engage early attention mechanisms, which suggests that the MMR may not be completely preattentive after all (Garrido et al., 2008, 2009; Lieder, Daunizeau, Garrido, Friston, & Stephan, 2013).

Indeed, some researchers propose MMR as the neuromarker of early attentional processes that govern early information processing (Dykstra & Gutschalk, 2015; Escera & Corral, 2007; Garrido et al., 2008; Näätänen, 1990; Näätänen et al., 1978, 2007; Näätänen, Paavilainen, Titinen, Jiang, & Alho, 1993; Näätänen & Teder, 1991; Sussman, Ritter, & Vaughan, 1998). Support for this assumption comes from the finding that the latency of the MMR is related to the timing of behavioural responses to change in the auditory environment (Näätänen et al., 1993; Tiitinen et al., 1994).

Typical latency of the MMR in adults ranges between 100-250 ms after the onset of the deviant stimulus (Escera & Corral, 2007; Garrido et al., 2009; López-Caballero, Zarnowiec, & Escera, 2016; Mahajan, Peter, & Sharma, 2017; Näätänen et al., 2007; Näätänen & Picton, 1987; Pekkonen et al., 1995; Sams, Paavilainen, Alho, & Näätänen, 1985; Trejo, Ryan-Jones, & Kramer, 1995; Winkler, 2007). It is recorded with EEG as frontocentral negative potential (Liebenthal et al., 2003; Picton et al., 2000) with sources thought to include primary auditory cortex and inferior frontal gyri (Dürschmid et al., 2016; Garrido et al., 2008; Giard, Perrin, Pernier, & Bouchet, 1990; Halgren et al., 1995; Imada, Hari, Loveless, McEvoy, & Sams, 1993; Molnár, Skinner, Csepe, Winkler, & Karmos, 1995; Näätänen, Astikainen, Ruusuvirta, & Huotilainen, 2010; Scherg, Vajsar, & Picton, 1989). The amplitude and latency of the MMR are related to how distinctly different the deviant and standard stimuli are from each other. Large deviance elicits MMR at earlier latencies, in some cases even overlapping the N1 component (Campbell, Winkler, & Kujala, 2007a; Näätänen & Picton, 1987).

As signified above, the spatial and temporal distribution of the MMR is stimulus-specific (Anderson, Christianson, & Linden, 2009; Angelini et al., 2009; Ayala & Malmierca, 2013; Todd et al., 2013) and dependent on paradigm features such as type of deviance (Cacciaglia et al., 2015; Hoonhorst et al., 2012; Kathmann et al., 1999; Morlet, Demarquay, Brudon, Fischer, & Caclin, 2014; Szymanski, Yund, & Woods, 1999; Winkler et al., 2003), trial duration (Čeponiené et al., 1998; Escera et al., 2000; Sussman et al., 2008) or number of alternating streams in a paradigm (Müller, Widmann, & Schröger, 2005; Snyder & Alain, 2007; Snyder et al., 2009).

1.3.4 MMR in early development.

Several features distinguish the infant and child MMR from that of an adult. One major disparity is that the MMR has positive rather than negative deflection. Although Cheour et al. (1997) found MMN in newborns, this was due to larger positive ERPs to standard than deviant stimuli (in the ERP to deviants minus ERP to standards subtraction), not negative ERP component to deviants, as found in adults (Näätänen et al., 2010). The transition from the MMR to MMN (He et al., 2009; Ortiz-Mantilla, Hamalainen, Realpe-Bonilla, & Benasich, 2016; Trainor et al., 2003) implies that maturational change in morphology of the brain (Chen et al., 2016; Kushnerenko et al., 2002a; Näätänen et al., 2007; Shafer et al., 2010) and increased synaptic density and myelination of the axons (Alho, Salmi, Koistinen, Salonen, & Rinne, 2015; Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004; de Haan, 2013; Kushnerenko et al., 2002a; Näätänen et al., 2007; Pekkonen et al., 1996; Wunderlich et al., 2006; Yu & Goodrich, 2014) may be the cause. See also section 1.2.1 for changes in synaptic density in auditory cortex across development.

Furthermore, research shows that latency of the MMR amplitude begins later, and it is longer in infants, with the onset around 150 ms and reaching a peak after 200 ms (Cantiani et al., 2016b; Kushnerenko et al., 2002a; Maurer et al., 2003c; Morr et al., 2002; Shafer et al., 2010). There is also some evidence for a double peak of the MMR, with the first immature small negative deflection and second larger amplitude within the P3 component range (Dehaene-Lambertz & Gliga, 2004; Garrido et al., 2009; Gou, Choudhury, & Benasich, 2011; Halliday, Barry, Hardiman, & Bishop, 2014; He et al., 2009; Irwin et al., 2017; Korpilahti & Lang, 1994; Mahajan & McArthur, 2012).

Finally, whilst the MMR in children and adults indicates either automatic detection of change or early attentional bias, in infants, it is a neuromarker of automatic or involuntary attention. Indeed, infants produce MMR even during their sleep (Cheour-Luhtanen et al., 1995a; Cheour, Čeponiené, et al., 2002; Háden, Németh, Török, & Winkler, 2016; Hirasawa, Kurihara, & Konishi, 2002; Martynova et al., 2003; Otte et al., 2013; Wanrooij, Boersma, & Zuijen, 2014) which is probably attributable to immature selective attention and inability to ignore environmental sounds (Forssman, 2012; Smith & Trainor, 2011; Stewart, 2016; van de Weijer-Bergsma, Wijnroks, & Jongmans, 2008).

1.3.5 MMR as a neuromarker of language development.

Assessing language development in infants proves to be challenging. Behavioural measures are limited to examining acoustic contrast and general attention to voice and expressive communication with the head turn, preferential looking (Golinkoff, Ma, Song, & Hirsh-Pasek, 2013), dummy sucking rate (Vivona, 2012), or eye-tracking methods (Tomalski, 2015) as well as standardised psychometric tests (Bayley, 2005; Zimmerman et al., 2009). While relatively easy to administer, accessible and cost-effective, these methods of assessing infant language ability have a few serious drawbacks. These include experimental bias, infant mood and alertness or individual differences in looking behaviour. For instance, infants may either look away or towards, stop sucking the dummy or suck with higher frequency in response to a novel stimulus, depending on preference (Beeghly, 2006). Besides, these tend to be less reliable the younger the infant is (Guzzetta, 2014; Hack, 2005; Volden et al., 2011; Walker, 1994).

Although more sophisticated and reliable measures are available to evaluate language skills in preschool (Dockrell & Marshall, 2015; Volden et al., 2011; Zimmerman et al., 2009) and primary school age (Bishop, Snowling, Thompson, & Greenhalgh, 2017; Korkman et al., 2007a; Law, Charlton, & Asmussen, 2017; Lindsay & Strand, 2016; McKean et al., 2017), the auditory and specifically language networks would have been established by then (see section

1.2.1 for the early development of synaptic density). Neuroimaging may be the more consistent and objective approach to measuring language proficiency in early development (Benasich et al., 2006; Karmiloff-Smith, 2010; Kuhl & Rivera-Gaxiola, 2008; Lloyd-Fox, Blasi, & Elwell, 2010; Paterson, Heim, Thomas Friedman, Choudhury, & Benasich, 2006).

Indeed, sound discrimination in infancy and childhood has been linked to individual differences in language proficiency. Attenuated MMR amplitude to phonemes and tones has been reported in individuals at risk (Benasich, Thomas, Choudhury, & Leppänen, 2002; Lovio et al., 2010; Volkmer & Schulte-Körne, 2018) or with diagnosis of language impairments (Bitz, Gust, Spitzer, & Kiefer, 2007; Chen et al., 2016; Friedrich et al., 2004; Lachmann, Berti, Kujala, Schrfger, & Schröger, 2005). Exposure to other languages than English modulates MMR to linguistic contrast in infants (Garcia-Sierra, Ramírez-Esparza, & Kuhl, 2016; Shafer et al., 2012) and children (Cheour, Shestakova, Alku, Čeponiené, & Näätänen, 2002; Jost et al., 2015).

Moreover, linguistic MMR marks developmental stages in early speech processing, starting with vowel (Cheour-Luhtanen et al., 1995b, 1996; Ramus, Nespor, & Mehler, 1999; Uhler, Hunter, Tierney, & Gilley, 2018; Warner-Czyz, Houston, & Hynan, 2014; Werner, 2013) and lexical tone discrimination Xi, Zhang, Shu, Zhang, & Li, 2010) in newborns and young infants followed by consonant contrast in phonemes (Cheng et al., 2015; Mersad & Dehaene-Lambertz, 2016; Pakarinen et al., 2009), phonological processing and word learning (Dehaene-Lambertz & Baillet, 1998; Kushnerenko, Tomalski, Ballieux, Ribeiro, et al., 2013; Nazzi, Poltrock, & Von Holzen, 2016; Rost & McMurray, 2009; Werker & Tees, 1999) and higher-level language processing later in development (Barry, Hardiman,

& Bishop, 2009; Chandrasekaran, Krishnan, & Gandour, 2007; Ghislaine Dehaene-Lambertz, 1997; Friederici, 2005; Rost & McMurray, 2009; Strotseva-Feinschmidt, Cunitz, Friederici, & Gunter, 2015).

The brain mechanisms underlying this relationship are outlined in sections 1.1.2 and 1.2.4. The increased sensitivity to slight changes in the frequency of spectral sounds in native language is an important contributor (Figure 1.3). However, categorical specialisation for speech may be the main driver in language acquisition. Auditory scene analysis (in section 1.1.2) at a categorical level, i.e., phonetic discrimination involving attentional engagement, is expected to be an important mechanism of language processing, particularly in complex audiovisual environments, where speech competes with other environmental stimuli (Bidelman & Dexter, 2015; Sussman et al., 2015, 2017). Accordingly, in a study by Kushnerenko and colleagues (2013), 6–9-month-old infants, who were less efficient in auditory speech processing (indicated by reduced MMR and looking behaviour to incongruent audiovisual stimuli) at the age of 6–9 months had lower receptive language scores at 14–16 months.

However, it should be noted that the switch from positivity to negativity of the MMR (outlined in section 1.3.4) can be problematic when exploring the relationship between neural discrimination and language ability. This is of particular importance when the sample age range is wide enough to encompass both the earlier positive and later negative polarity of the MMR. Pinpointing the exact age of the transition may be difficult, as the variable pace of maturational development between infants further broadens the transition period (Kushnerenko et al., 2002a, 2013a). A similar effect may be induced with more complex tasks in children (Linnavalli et al., 2018; Maurer et al., 2003b; Putkinen, Tervaniemi, & Huotilainen, 2019; Shafer et al., 2010). One way of overcoming this issue is to use the absolute difference between ERPs to deviants and standards. The non-directional values indicate whether the MMR diverges significantly from the baseline but without describing it as positivity or negativity, i.e., without determining if the discrimination is less or more mature. Such manipulation, along with the standardised scores on language ability, removes the effect of age in the sample.

Using this approach, researchers have also been able to predict language outcomes in preschool based on the linguistic (Guttorm et al., 2005; Jansson-Verkasalo et al., 2010; Molfese, 1989, 2000; Molfese & Molfese, 1985, 1997; Molfese & Searock, 1986; Molfese et al., 2001) and non-linguistic MMR in infancy (Benasich et al., 2006; Benasich & Tallal, 2002; Cantiani et al., 2016b; Carral et al., 2005; Choudhury & Benasich, 2011). Generally, larger MMR amplitude in infancy is also associated with more advanced reading skills in primary school (Molfese, 2000; Molfese & Molfese, 1997; Molfese et al., 2001).

The sample age range selected for the thesis was based on the optimal maturation of the neural MMR in infancy (Kushnerenko et al., 2002b) and childhood (Cheour, Leppänen, & Kraus, 2000) and its effect on the linguistic proficiency in early childhood (Choudhury & Benasich, 2011; de Haan, 2013, pp. 208-213). The additional criteria involved selecting age groups based on previous literature in the processing of complex auditory stimuli (Barker & Newman, 2004; Fellman et al., 2004; Kushnerenko et al., 2002a; Smith & Trainor, 2011).

1.3.6 Paradigm design and its effect on the MMR.

There is a need for a more systematic approach to assessing early neural signatures of auditory discrimination. This is of particular importance to researchers investigating maturational changes influencing the MMR in early development. Paradigm design may be inadvertently increasing an already large variability gap between developmental data. In the worst-case scenario, it may conduce spurious results, and this adverse contribution must be acknowledged. The paradigm features explored in this thesis are deviance, trial duration, stimulus type and the number of alternating streams in a paradigm.

Deviance type.

The neural capacity to identify a change between frequent and rare sounds has been of interest to neuroscientists. The original design which elicits MMR is called ‘oddball’ (Squires et al., 1975). It is characterised by a train of frequent stimuli intersected with infrequent sounds which differ in one or more of acoustic properties from the standard sounds. The assumption is that repetition of the same frequent stimulus creates a memory trace, based on which postsynaptic potentials learn to fire in expectation of the same stimulus in the sequence. If the following stimulus differs from the expected template, the expectation error generates a surge of potentials correcting the expectation. The difference between ERPs to standard and deviant stimuli is observed as the MMR component. Section 1.3.3 provides more details on the oddball design and describes theories related to the generation of the MMR.

Roving design is a variation of the oddball paradigm (Garrido et al., 2008). It differs from it in the way the standard and deviant stimuli are ordered and in their probability in relation to each other. In the simplest example, two trains of sounds are presented in an alternating pattern. The first stimulus in the sequence constitutes a deviant, while the remaining stimuli, though not different acoustically from the first, become standards due to neural habituation induced by the repetition. The second train contains stimuli which vary on one or more dimensions from those within the first train and so the first sound in the second train, as different from the first train, becomes the deviant and the following sounds in the sequence become standards. ERPs to deviants and standards (regardless of which stimulus they represent) are averaged for analysis (Halliday et al., 2008; Lieder et al., 2013; Leung, Greenwood, Michie & Croft, 2015; Takaura & Fujii, 2016).

Research in adults suggests that roving deviance may not be as efficient at inducing habituation to standards as the oddball design due to the neural network forced to reset the stimulus template every time a new train begins. This may result in attenuated MMR despite the large ERP to deviants, as ERP to standards is not sufficiently reduced (Baldeweg, Klugman, Gruzelier, & Hirsch, 2002; Cooper, Atkinson, Clark, & Michie, 2013; Haenschel, Vernon, Dwivedi, Gruzelier, & Baldeweg, 2005; Rosch, Auksztulewicz, Leung, Friston, & Baldeweg, 2017, 2019). Nevertheless, both types of design have been utilised in studying neural discrimination in early development without the concern as to how this may influence the MMR (Muenssinger et al., 2013b). In particular very little is currently known about the effect of deviance on the MMR in infants (although see Muenssinger et al., 2013a).

Trial duration.

Presentation rate of the auditory paradigms has been reported to affect the development of ERP peaks and in turn, the MMR (Andreou et al., 2011; Escera et al., 2000; Sussman et al., 2008; Wunderlich & Cone-Wesson, 2006; Wunderlich et al., 2006; Xu & Ma, 2009). In order to develop the optimal inter-trial-interval (ITI) for the relevant age group, the duration of the trial, i.e., onset to onset between trials, how long the stimulus itself lasts, as well as offset to onset duration, i.e., the pause between the end of the stimulus to the beginning of the next trial should be taken into account (Escera et al., 2000). All of these trial parameters may affect the peak and latency of the MMR. It is therefore difficult to identify the optimal ITI in younger age groups (Čeponiené et al., 1998; Cheour et al., 1998; Gomot et al., 2007; Sharma et al., 2006).

For example, trials within range of 600-800 ms at least are required for the development of the obligatory P1 and N2 components in 8-to 16-years old children and adults (Sussman et al., 2008). These peaks are essential to generate MMR, although their influence changes across the lifespan (Benasich, 2002; Benasich & Tallal, 1996; Choudhury et al., 2015; Näätänen et al., 2007; Paavilainen, 2013; Sussman et al., 2008; Wang, Datta, & Sussman, 2005). Nonetheless, 500 ms trial duration (with 100 ms stimulus duration) is sufficient to produce P3 deflection, which significantly deviates from baseline in 3-8-year-old children (Stevens, Paulsen, Yasen, & Neville, 2015). The obligatory ERP components in infants have been shown to take longer to develop (Kushnerenko et al., 2002; Silvia Ortiz-Mantilla et al., 2012). Studies in infants tend to present ITI of 900 ms or longer (Benasich et al., 2014; Choudhury & Benasich, 2003, 2011; Guttorm et al., 2001, 2003, 2005, 2010; Hämäläinen et al., 2011; Musacchia et al., 2013; Ortiz-Mantilla et al., 2013, 2016) but perhaps a shorter duration may be sufficient.

Stimulus type.

Several lines of evidence suggest that linguistic and non-linguistic stimuli have differential effect on the MMR in adults (Jacobsen, Schröger, &

Sussman, 2004; Kuuluvainen et al., 2014; Volkmer & Schulte-Körne, 2018), with some evidence in children (Maurer, Bucher, Brem, & Brandeis, 2003a; Sharma et al., 2006) and infants (Kostilainen et al., 2018; Liu et al., 2019; Zhao & Kuhl, 2016). To date, there has been little agreement on which of the sounds elicit larger MMR deflections in early development (Jacobsen, Schröger, et al., 2004; Kozou et al., 2005; Xi, Zhang, Shu, Zhang, & Li, 2010; Zatorre, Belin, & Penhune, 2002). Controversy as to the cortical areas engaged in processing speech and nonspeech stimuli has also been subject to considerable discussion (Belin et al., 1998; Celsis et al., 1999; LoCasto, Krebs-Noble, Gullapalli, & Burton, 2004; Luo et al., 2006; Molholm et al., 2014; Vouloumanos, Kiehl, Werker, & Liddle, 2001).

Overall, studies indicate that this phenomenon may be stimulus dependent. Given the sensitivity of auditory discrimination to sensory features of the stimuli, the lack of consensus in the reports may reflect methodological differences in the properties of sounds used to elicit the MMR. Traditionally, MMR has been elicited to either purely acoustic or linguistic contrast with an assumption that discrimination across stimuli is comparable. This has been more common in early development studies where short duration of a paradigm determines the number of repetitions for the given type of stimulus. This results in a trade-off between the presentation rate and the number of stimulus types in a paradigm required to generate significant MMR (Kujala, Kallio, Tervaniemi, & Näätänen, 2001; Ritter et al., 1992).

However, as research in older children and adults shows, discrimination of linguistic and non-linguistic contrasts may differ not only in terms of the engagement of particular regions (Alho, Rinne, Herron, & Woods, 2014; Brechmann, Baumgart, & Scheich, 2002; Burton, LoCasto, Krebs-Noble, & Gullapalli, 2005; Celsis et al., 1999; Moerel, De Martino, & Formisano, 2012;

Szycik, Stadler, Brechmann, & Münte, 2013; Vouloumanos et al., 2001) but also the level and timing of involvement of those cortical areas (Draganova et al., 2005; Luo, Husain, Horwitz, & Poeppel, 2005; Parviainen, Helenius, & Salmelin, 2005). As the electrophysiological activity to acoustic and phonetic contrast has not been systematically compared in younger children, this is an important question to be addressed by the current thesis. Based on findings from previous studies which employed either of the stimulus types, infants are expected to produce a larger and earlier MMR to tone pairs (Háden, Németh, et al., 2015; He et al., 2009; Hirasawa et al., 2002), than phonemes (Eira Jansson-Verkasalo et al., 2010; Kushnerenko, Teinonen, Volein, & Csibra, 2008). Regarding the comparison between infancy and the primary school age children, the research is limited and inconclusive as to the distinction and similarities between these age groups (Čeponiené et al., 2008; Lohvansuu et al., 2013; Partanen, 2013; Uwer et al., 2002) but some differentiation in processing the two types of stimuli was expected.

The stimuli employed in this project were phonemes /ba/ and /da/ (Teinonen, Fellman, Näätänen, Alku, & Huotilainen, 2009) and tone pairs of 100-100 Hz and 100-300 Hz (Choudhury et al., 2015). They were chosen as the primary linguistic (Benasich, 2002; Bishop et al., 2010; Čeponiené et al., 2008; Guttorm et al., 2005, 2010; Uwer et al., 2002) and non-linguistic examples (Benasich et al., 2002; Cantiani, et al., 2016a; 2016b; Choudhury & Benasich, 2011; Heim et al., 2013; Musacchia et al., 2013, 2017; Vliegen et al., 1999) developed and previously used in electrophysiological studies assessing auditory processing in association with language development in infants and younger children.

Although not selected based on their resemblance to each other, comparisons were made, as both their similarities and differences could contribute to the results of this thesis. They stimuli differed on a number of features. Whilst the phonemes comprised spectral frequency range, the tone pairs were narrowband sound bips of frequencies much lower than the lowest frequency in phonemes. In addition, although both sound types lasted approximately 200 ms, this was the duration of a single phoneme whereas the nonverbal counterparts consisted of two tones and a silent pause dividing them, each 70 ms long. Such a design of an acoustic stimulus could be considered too distinct from phonemes in adult studies. However, based on the TWI theory, infants and younger children do not discern the sounds the same way as adults (see section 1.1.2 for details). Instead, they appear to process the pause as a continuation of the first tone. De facto they perceive the tone pair as one continuous sound, even if the second tone in the pair is of different frequency to the first. Essentially, infants and younger children both phonemes and tone pair stimuli are processed as single units of sounds. Consequently, they were considered sufficiently similar to not influence the electrophysiological responses based on their physical properties alone. The detailed information on the features of the EEG stimuli is provided 2.4.1 in General Methods.

Streaming.

Research shows that infants are able to segregate streams of sounds (Smith & Trainor, 2011; Winkler et al., 2003) and ignore irrelevant noise in the background (Barker & Newman, 2004; Demany, 1982), even in the presence of a salient distractor, such as white noise (Kushnerenko et al., 2013c) or other maskers (Schneider, Trehub, Morrongiello, & Thorpe, 1989).

However, whilst processing competing contrasts has been assessed in adults in various multi-feature designs (Almonte, Jirsa, Large, & Tuller, 2005;

Bregman, 2015; Bressler, Masud, Bharadwaj, & Shinn-Cunningham, 2014; Denham & Winkler, 2006; Iverson, 1992; Nager, Teder-Sälejärvi, Kunze, & Münte, 2003; Sorokin et al., 2010; Sussman, 2004; Sussman, Ritter, & Vaughan, 1999; Vliegen & Oxenham, 1999) and explored to some extent in children (Sanders et al., 2006; Sussman et al., 2001; Sussman & Steinschneider, 2009), this has not been examined systematically in infants. In addition, while stream segregation has been explored in early development, speech discrimination against other background sounds has rarely featured in infant studies (Barker & Newman, 2004; Smith & Trainor, 2011). In children this has only been investigated in studies exploring selective attention, i.e., when they are required to attend to a story in one ear and ignore the other (Karns, Isbell, Giuliano, & Neville, 2015; Stevens et al., 2015; Courtney Stevens & Bavelier, 2012), rather than process both streams. It may, therefore, be of interest to find out how infants and children process competing sounds and specifically speech among a salient contrast. This has not been extensively studied by developmental scientists but may be crucial in language development.

1.3.7 Measurement of the MMR in early development.

EEG recording.

It is conducted either on the surface of the scalp or directly on the surface of the brain in intracranial recordings, although the latter only with clinical populations (Karoui et al., 2015; Hu, Stead, & Worrell, 2007; Taylor & Baldeweg, 2002). ERPs are recorded with channels made of non-polarisable silver or silver chloride. They are placed either directly on the scalp or in a 32-, 64-, 128- or 256-channel montage within an elasticised cap or net. They form an interface between the electrical activity on the scalp and the input circuitry of the amplifier. The level of electrical impedance at the scalp should be less than the input impedance of the amplifier by a factor of at least 100. If this is compromised, the signal will include contributions from artefactual signals arising from electromagnetic fields within the recording environment (Picton et al., 2000).

The high-density 128-channel EGI system (EGI, Eugene, OR) is prominent in developmental research due to the ease of application and the reduced need for the precise location of the individual channels on the scalp (Seeck et al., 2017). The additional advantage comes from the ability to interpolate missing data from surrounding channels in case of noise artefacts in one of them (Tucker, 1993), availability of which feature is much reduced in the 32- and 64-channel montages. They adhere to the 10-20 system, in which each channel is at 10 or 20 inches away from its neighbour (Jasper, 1958) and so may be too far for interpolation. Moreover, recording from the less dense montages than 128-channel system may lead to misinterpretation of the collected data. In adults, it can be presumed that individual channels are placed in the same scalp space across all individuals. However, due to variable shape and size of an infant's head, even when controlling for age, such inference may be misleading in developmental research and the broader region of interest is required to cover specific cortical areas (Hoehl & Wahl, 2012). Figure 1.11 demonstrates channel distribution on 128-channel montage on the scalp.

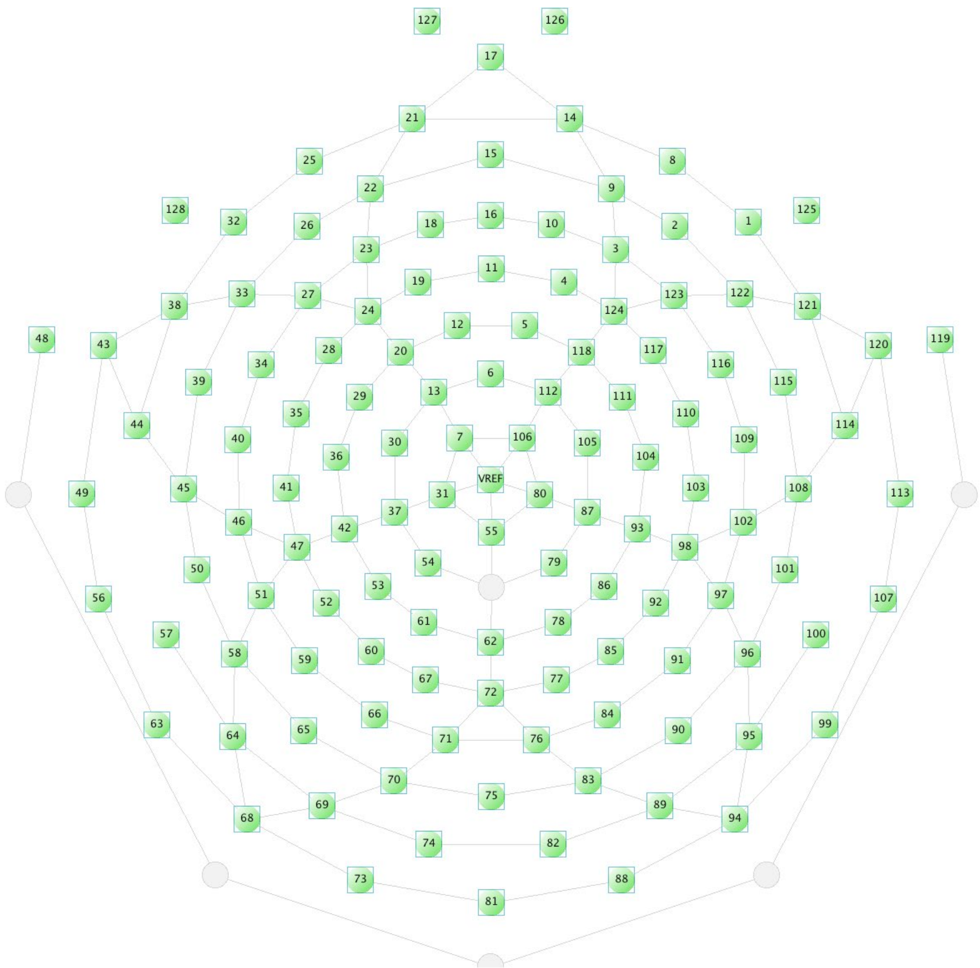

Figure 1.11 The HGSN 128- channel montage with the vertex (adapted from Geodesics, 2003).

Referencing the signal.

Using 128 channels enables for the vertex (Cz on the 10-20 system) to be the reference against the ground as the channels cover a broader area on the scalp, theoretically encircling the head (Luck, 2004, p.165). Offline re-referencing to average reference allows for more balanced (i.e., less inflated) and less lateralised ERPs then when mastoid bones, earlobes or nose are used as reference instead. Also, the wide distribution area of the channels markedly increases the signal to noise ratio. This is crucial in developmental research with subjects who may exhibit large movement artefacts (Lei & Liao, 2017; Otero et al., 2011; Qin et al., 2017; Yang, Fan, Wang, & Li, 2017). The average reference, however, creates a dipole. When the frontal channels demonstrate positive peak in voltage potentials, the posterior channels show a reversed component. Furthermore, voltage potentials appear larger the further away they are from the reference. Ultimately, any effects originating in the central portion of the brain may disappear, and others may be biased towards the scalp periphery (Dien, 1998; Junghöfer, Elbert, Tucker, & Braun, 1999; Mahajan et al., 2017; Tomberg, Noël, Ozaki, & Desmedt, 1990; Yao, Wang, Arendt-Nielsen, & Chen, 2007). This effect is reduced with the use of other references. When interpreting the spatial distribution of ERPs, the dipole effect should, therefore, be taken into consideration.

Amplifying, digitising, and filtering the EEG signal.

The EEG recorded from the scalp includes both the signal of interest and electromagnetic noise from the environment. For example, electrical equipment emits 50 Hz line noise, and the display monitors can be a particular problem in this respect. The use of differential amplifiers removes electromagnetic noise at inputs recorded between the ground and the scalp channels. This is usually referred to as the common-mode rejection (Picton et al., 2000).

Analogue to digital converters (A/D) sample the ongoing EEG signal and convert the voltage fluctuations into numerical representations. The resolution of the A/D converters determines that the amplifiers avoid exceeding the range of the recorded signal. The settings of the A/D converters are referred to as the sampling rate. These parameters control the temporal resolution of the recording. The recording reflects samples of voltage at discrete intervals of time at each channel minus the reference. A sampling at 500 Hz is considered sufficient for developmental data (Lopes da Silva et al., 2009).

The use of on-line filters rejects those frequencies outside the filter settings, predetermined by the experimenter and usually to reflect a signal within a waveband of interest. In effect, the experimenter may set a bandpass that limits the recording to frequencies set within these parameters. When setting the sampling rate and filter setting for the recording, it is important to use the Nyquist-Shannon theorem as a guide (Shannon, 1949). It states that the sampling rate must be twice as high as the highest frequency in the signal. Otherwise, aliasing may distort the signal by attenuating or clipping samples outside of the recording range.

Off-line filtering distorts temporal information across samples. Filters can ‘smear’ effects within the time domain, in effect changing the usefulness of ERPs, as their power is their high temporal resolution. Still, filters are useful, as they remove environmental noise and can help to locate signals within particular frequencies. Besides, developmental ERP researchers are usually only interested in signals lower than 30 Hz, so removing higher frequencies cleans the signal of noise (McFarland, McCane, David, & Wolpaw, 1997).

Artefact detection and bad channel replacement.

EEG data from developmental and clinical populations tend to be noisy and require both automatic and manual cleaning. Large artefacts can be removed with the crude rejection of voltage potentials above a certain cut off point. However, to avoid removing the EEG signal along with the artefacts, manual rejection of individual channels or trials may be required. For example, in cases of eye blinks or movement (He, Wilson, Russell, & Gerschutz, 2007). EGI Net Station software (EGI, Eugene, OR) allows for such individual manual rejection, while other EEG recording, and processing systems specialise in the use of correction algorithms based on linear interpolation. The removed channels are then replaced by averaging data from the surrounding channels in the scalp area. (Delorme & Makeig, 2004; Delorme et al., 2011; Delorme, Sejnowski, & Makeig, 2007; Makeig, Debener, Onton, & Delorme, 2004).

Baseline correction.

Factors such as skin hydration and potentials, static electrical charges or ongoing activity from the previous stimulus may affect the continuous EEG data. Baseline correction is performed in the period before the stimulus onset in order to reduce the drift in the EEG signal due to noise or response to the previous stimulus. The recommended baseline duration should be approximately 20% of the epoch duration, but it should not be made too excessive to avoid any overlap with the ERPs to the previous stimulus. Visual inspection of the baseline may inform if it is late enough after the stimulus onset or if it overlaps with an earlier response. In such event, The ERPs during the baseline period and within 100 ms after stimulus onset will significantly deviate from zero, in which case the components following such deflections may be inflated and not an accurate response to the current stimulus (Luck, 2004; Luck, 2014, pp. 251-258; Luck & Gaspelin, 2017).

Averaging ERP data

ERPs are derived from the ongoing spontaneous EEG and reflect fluctuations in electrical field potentials in response to the presentation of a time-locked event. The signal of interest is usually much smaller than the ‘noise’ or ongoing EEG in which it is embedded and cannot be usually seen on individual trials (Luck, 2014, pp. 258-266). In addition, due to the rapid speed of information processing in the brain and variability in timing and amplitude across individuals, the precise origin and mapping the trajectory of the signal going through the language network in the brain may be difficult to pinpoint at the group level (Matsumoto et al., 2004). As a resolution, longer timing (averaged into time windows) and broader cortical areas in response to auditory stimuli tend to be examined to find similarities in specific age groups. As responses within wider time windows and clusters are generally considered to be invariant across trials that represent the same experimental condition and the background noise is random, it is possible to use averaging techniques time-locked to the stimulus to extract the related response.

Averaging is carried out across each sampled point and includes only artefact free trials. As the number of trials increases, the signal to noise ratio improves (as a factor of the square root of the number of presentations). In effect, averages based on a higher number of trials will represent the signal of interest with less contamination from the background EEG. Averaging is performed separately for each channel in each experimental condition. This process derives the ERPs upon which statistical analyses are then performed.

Signal averaging is not unproblematic. If for example, the ERPs from experimental condition comprise a variable number of trials, ERPs may differ quantitatively as averaging may 'smear' the amplitude or latency in one condition compared to another. This can lead to an assertion of a qualitative difference where none may exist. It is a concern in an oddball paradigm where the number of deviant trials is always significantly smaller in comparison to the standards.

'Latency jitter' and variable trial duration may also cause a problem when components in individual trials are varied in time or amplitude. The resulting ERP may produce long latency components that are reduced in amplitude. These trials may require a higher signal to noise ratio in order to remove the background noise from the signal (Picton, Lins, & Scherg, 1995).

Temporal averaging: segmenting epochs into time windows. In order to organise the data for analysis, it is further collapsed into epochs, which are time-locked to stimulus and the epochs are further segmented into time windows (Luck, 2014, pp. 292-296). Duration of a time window can be based on visual inspection of the averaged epoch (Lyytinen et al., 2004a; Musacchia, Ortiz-Mantilla, Realpe-Bonilla, Roesler, & Benasich, 2015; Winkler, Mueller, Friederici, & Männel, 2018) or depend on the expected temporal distribution of the sought-for ERP component. In the first option, the peak itself determines how wide the selected window is but this results in considerable variability in the duration of the time windows between studies. The alternative, with time windows of 50, 100, 150 ms or longer duration is used in a more standardised approach (de Haan & Thomas, 2002; Rivera-Gaxiola et al., 2005).

In order to systematise the data and make it comparable between experiments within a study, one could opt for shorter time windows, which are distributed across the whole epoch. This approach may be particularly beneficial in developmental research (Wass, Daubney, Golan, Logan, & Kushnerenko, 2018), where temporal distribution of the ERPs may vary between ages and so averaging the data into, for example, 50 ms time windows may reveal individual peaks polarity of ERPs in older children, while recognising that younger children may produce ERP peaks which extend over more than one time window (Cheng et al., 2015; Cheour et al., 1999; Friedrich et al., 2004; Martynova et al., 2003; Virtala, Huotilainen, Partanen, Fellman, & Tervaniemi, 2013).

Spatial averaging: clustering ERP data. Although analysing individual channels is common in adult research, especially with 32- or 64-channel montages, clusters of channels in the region of interest instead of individual channels may be more appropriate for the interpretation of the spatial and temporal distribution of ERP components in developmental research. Selection of the channels may be data or theory driven. The first relates to visual inspection of topographic maps of the MMR and the latter to the assumptions of the potential generators of the response based on the literature on the researched topic.

Previous research findings suggest that auditory ERPs are expected to be found over the temporal or frontal areas of the scalp with sources found in the primary auditory cortex, prefrontal cortex and from thalamic projections (see section 1.1.1 for the auditory network in the brain). Channels on the 10-20 system in these areas include F3, F4, T3 and T4, equivalent of which on 128-channel EGI system are 24, 124, 45 and 108, respectively. Clusters of channels surrounding these channels on 128-system would be most appropriate for analysis of auditory function.

Support for the use of these areas in searching for the MMR comes from a wealth of studies exploring auditory processing. Namely, the MMR in adults (Baldeweg, Klugman, Gruzelier, & Hirsch, 2002; Bidelman & Dexter, 2015; Dürschmid et al., 2016; Karoui et al., 2015; Escera, Yago, & Alho, 2002; Giard et al., 1990; Rihs et al., 2013; Rinne, Alho, Ilmoniemi, Virtanen, & Näätänen, 2000; Squires et al., 1975) and children (Choudhury et al., 2015; Gomot, Giard, Roux, Barthelemy, & Bruneau, 2000; Gomot, Bruneau, Laurent, Barthélémy, & Saliba, 2007; Gumenyuk et al., 2003) has been recorded in the frontal and temporal regions of the scalp.

1.4 Aims of the thesis

Existing research recognises the critical role played by deviance (Baldeweg & Hirsch, 2015; Cowan, Winkler, Teder, & Näätänen, 1993; Muenssinger et al., 2013), length of a trial (Andreou et al., 2011; Čeponiené et al., 1998; Choudhury et al., 2015; Escera et al., 2000; Háden, Honing, Török, & Winkler, 2015; Imada et al., 1993) stimulus type (Kathmann et al., 1999; Kozou et al., 2005; Kuuluvainen et al., 2014; Maurer et al., 2003a; Sharma et al., 2006; Volkmer & Schulte-Körne, 2018), as well as the number of alternating streams in a paradigm (Almonte et al., 2005; Bregman, 1990, 2015; Iverson, 1992; Nager et al., 2003; Snyder & Alain, 2007; Sorokin et al., 2010; Sussman et al., 1999, 2001; Vliegen, Moore, & Oxenham, 1999) on the auditory MMR in older children and adults but these parameters have not been systematically compared in infants and children in the early years of primary school. Notably, the mechanisms behind the auditory scene analysis (which streaming represents in this project) in the early development have not been examined as yet. The next and final step in the investigation, assessing the relationship between auditory discrimination and behavioural language proficiency in these age groups is of critical importance in order to identify both the markers of good as well as poor performance. The overall aim of this thesis is to shed light on the auditory and more specifically language development in children in order to identify the precursors of language difficulties.

The overarching objectives of this thesis were, in sequence, to compare the differential effects of paradigm features on the MMR in infants and children, to develop new paradigms producing large MMR in infants and children and subsequently to compare the relationship between MMR and language ability in infancy and at the primary school age. The individual research aims of the thesis are outlined below.

Research Aim 1.

To determine the optimal paradigm features which evoke large MMR in early development. In correspondence with the wealth of literature in electrophysiological research, the paradigm modulations were expected to influence the spatial and temporal distribution of the MMR to change in the phoneme and tone pair paradigms in infants and children. The selected paradigm features included deviance (oddball versus roving), trial duration (932 ms versus 802 ms) and linguistic (phonemes) and non-linguistic (tone pairs) stimulus.

Research Aim 2.

To reveal the effect of stream modulation on the MMR in infants and children. In line with previous research, the number of streams in a paradigm was expected to influence the temporal and spatial distribution of the MMR in infants and children. The modulation included a streaming paradigm consisting of a phoneme and a tone pair stream and two single stream paradigms, which were treated as control: a phoneme and a tone pair paradigm.

Research Aim 3.

To determine the predictive potential of the auditory MMR in infancy on language ability at 2 years of age. Following literature in this research area, MMR to deviance in the streaming and control phoneme and tone pair paradigms in infancy was expected to predict behavioural language ability at 2 years.

Research Aim 4.

To compare the MMR between infants and children. Following previous literature, group differences between the temporal and spatial distribution of the MMR in infants and children were expected.

Research Aim 5.

To assess the relationship between linguistic and non-linguistic MMR and language ability in early development. In accordance with the literature, MMR to deviance in the streaming and control phoneme and tone pair paradigms would be associated with behavioural language scores in infants and children. Relationships within each of the cohorts and between the MMR across both age groups and language ability was anticipated. The mean MMR to deviance, in the phoneme and tone pair paradigms and phoneme and tone pair streams in the streaming paradigm in infants and children, were expected to correlate with the language composite in infants and children.

1.5 General summary

As a consequence of the scientific deduction and based on the literature review, an unexplored niche in the study of early language development was identified. Despite being under-researched, the effect of paradigm features such as the form of deviance, length of a trial, stimulus type and the number of streams in a paradigm on the MMR in infants and children should be acknowledged. The type of design may, in turn, influence the relationship between auditory MMR and early language development. Its potential importance for developmental neuropsychological and neurolinguistic research lies in studying the electrophysiological index of the MMR in early development and in association with language proficiency. Due to high prevalence of language difficulties in children from the lower socioeconomic backgrounds, the anticipated socioeconomic impact of the thesis relates to its contribution in explaining the developmental auditory and specifically language correlates both at the neurophysiological and behavioural levels.

Chapter 2. General Methods.

2.1 Ethics

This project was accepted by the University of East London Research Committee (UREC). Studies 1, 2, 3, 5 and 6 were approved on 18th August 2015 (UREC 1415 109), with an amendment on 15th April 2016 (AMD 1516 10). The final version of the project with additional Studies 4 and 7 was approved on 31st May 2016 (UREC 1516 105), with approval of the amendment of the title on 17th September 2019 (ETH1819-0215). Additionally, the project was accepted by the Research Governance Framework at Tower Hamlets Council on 21st August 2015 (CERGF185). The author of the project passed the academic and ethical integrity quiz on 28th April 2015 and received the enhanced clearance from the Disclosure and Barring Service (DBS) on 6th May 2015 (Certificate Number: 001485300201). The ethics applications and approvals, as well as the Academic Integrity certificate, are available in Appendix P.

All parents signed informed written consent, which followed the University of East London Research Ethics Committee and the Declaration of Helsinki (Rickman, 1964; WMA & World Medical Association, 2013) guidelines.

2.2 Participants

Families living in East London known for its broad socioeconomic diversity (Aldridge, Theo, Tinson, & MacInnes, 2015; Trust for London, 2011b) were invited to participate in the project. The 2010-2011 and 2015-2017 birth cohorts were assessed at the Babylab, the University of East London either once or on two occasions (extract from the infants' cohort) throughout 2015-2018.

2.2.1 Recruitment.

Recruitment was carried out through local children's centres, nurseries, playgroups, midwifery services, via the UEL Babylab Facebook page and word of mouth. Advertisements were additionally distributed in local libraries and places of social gathering, such as cafes, restaurants, and local community centres. Families which expressed their willingness to participate in the research were added to the UEL Babylab database and subsequently invited for an experimental session once the child reached the appropriate age.

2.2.2 Inclusion Criteria.

The recruitment and subsequent selection process ensured inclusivity wherever possible but was controlled for certain criteria. These included vision problems (e.g., strabismus, refractive error, or field deficits), prolong hearing difficulty (including tinnitus, glue ear, swimmer's ear or reported hearing loss) or any risk factors or diagnosis of atypical neurological development (e.g., genetic disorders, developmental delay, autism, or ADHD), as per parental report.

2.2.3 Study division.

The schematic model below (Figure 2.1) represents two birth cohorts (infants and children) and the seven studies they participated in. There are two samples taken of infants. One of which participated in Study 1 whilst the other in Study 2. Participants from Study 2 were also involved in Study 3. Moreover, a subset of infants from Studies 1 and 2 was examined at 2 years of age. Those categorised as children participated in Studies 5 and 6. The final comparisons were conducted between results in infants and children in Studies 2 and 5 and again between Studies 3 and 6 in in the final Study 7.

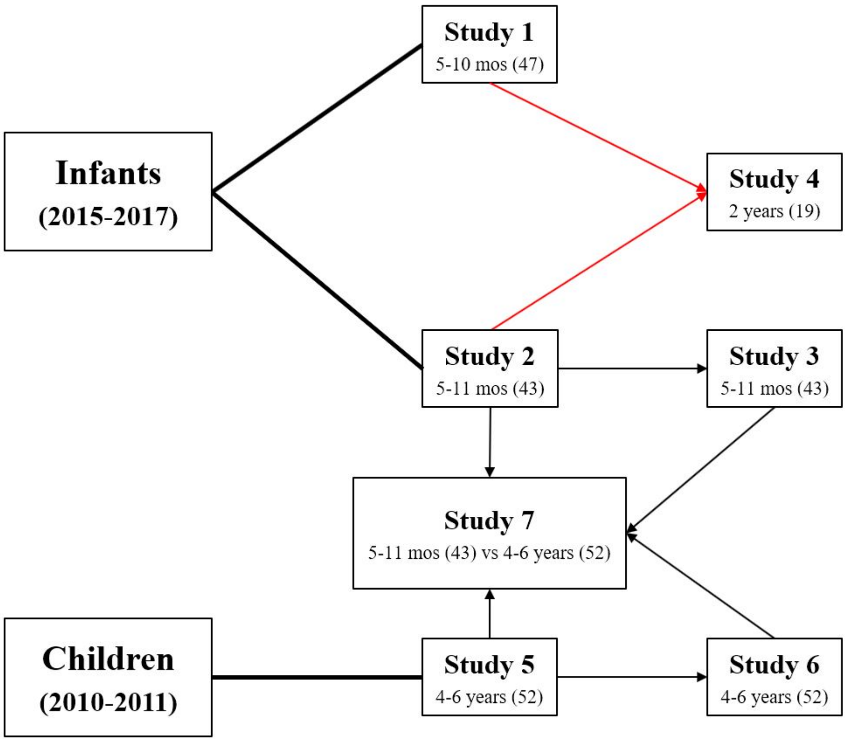

Figure 2.1 Schematic representation of participants in all seven studies. Arrows demonstrate in which studies infants and children were included. The red arrows show which studies a subset of infants included in Study 4 was recruited from. The birth years for each cohort are included in the two main blocks. The age range and the number of participants recruited in each study are included in the individual study blocks.

2.3 Project design.

The project involved random sampling based on age: 5-11-month-old infants (Studies 1, 2 and 3) and 4-6-year-old children (Studies 5 and 6), longitudinal (Study 4) and cross-sectional research (Study 7) of both the within-participants (Studies 1-6) and between-participants (Study 7) design. The analyses employed in the studies were experimental (Studies 1, 2, 5 and 7) and correlational (Studies 3, 4 and 7). The manipulations in all the studies are outlined in Figure 2.2.

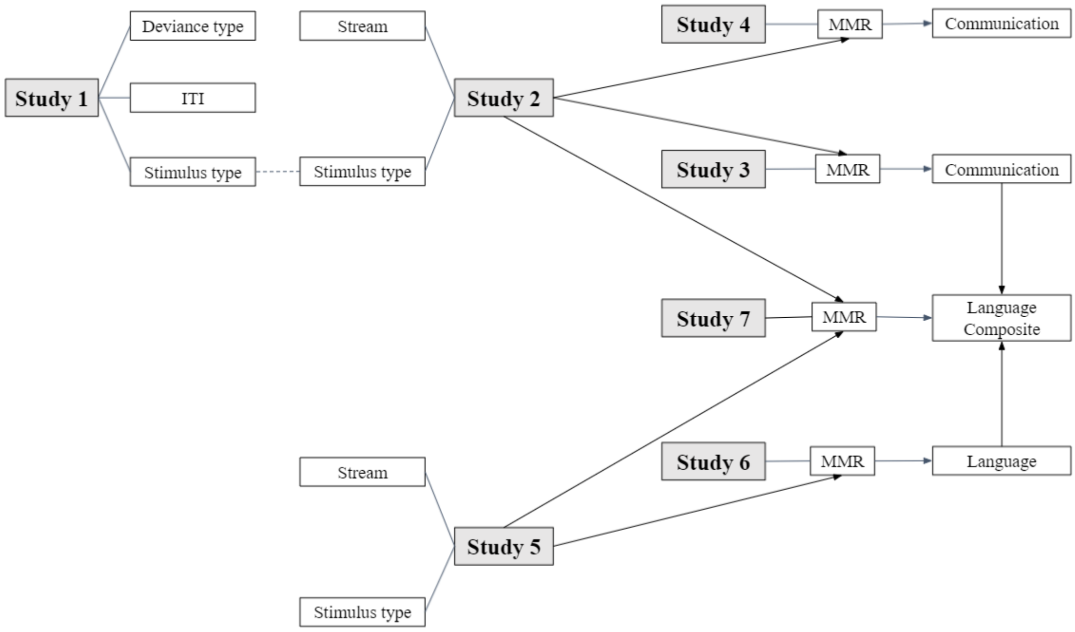

Figure 2.2 Model of all seven studies with individual modulations in each and the relationships between them. The dotted line shows in which study the manipulation was originally developed, and the studies the arrows originate from, demonstrate the origins of the collected data used in specific modulations.

2.4 Stimuli and apparatus

The tasks used in the study were the passive auditory EEG paradigms and behavioural assessments of receptive and expressive language.

2.4.1 EEG paradigms.

Phoneme paradigm.

The synthetic phonemes were developed by Teinonen et al. (2008) and comprised audiotaped repetitions of a female speaker saying the syllables /ba/ and /da/. One token was selected for each syllable based on the best quality of the articulation and the clarity of the soundtrack, at each end of /ba/-/da/ continuum, i.e., the most unambiguous /ba1/ and /da8/. The pitch and intensity of the soundtracks were selected to be approximately equal. Both syllables consisted of a voiced plosive (stop) consonant (bilabial: /b/ or alveolar /d/) followed by a voiced vowel /a/. Their waveforms are known to comprise a short noise burst followed by a longer voiced segment (Kent & Read, 2002, p.153). The syllables differed on the frequency of the second formant transition (higher in /da/ than /ba/ though both starting below 500 Hz and of 50 ms duration). The third formant included vowel /a/ of spectral frequency between 790-1190 Hz. Figure 2.3 illustrates the amplitude and a frequency heatmap for each of the phonemes.

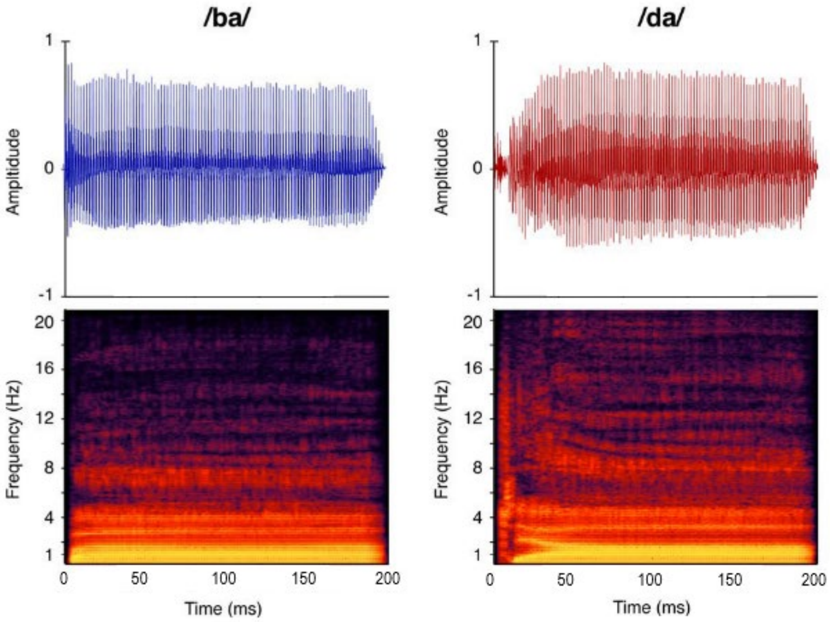

Figure 2.3 Time-amplitude waveforms (top images) and time-frequency spectrograms (bottom) of /ba/ and /da/ phonemes (adapted from Gilley et al., 2017).

Each phoneme duration was 200 ms with onset-to-onset inter-trial-interval (ITI) of 932 ms. The offset-to-onset (pause after one phoneme ends and before the next begins) was 732 ms. A model of the trial with /da/ and /ba/ phonemes is available in Figure 2.4.

Figure 2.4 Schematic representation of stimuli in the phoneme paradigm. Frequency distribution (Hz) of the /da/ and /ba/phonemes is visible on the y-axis. Their temporal distribution (200 ms), as well as the offset-to-onset (732 ms) and onset-to-onset (932 ms) duration between the phonemes, are demonstrated on the x-axis (ms).

Tone pair paradigm.

The second type of stimuli were complex tone pairs with frequencies of 100-100 Hz or 100-300 Hz with 15 harmonics (6 dB roll-off per octave). The amplitude and a frequency heatmap for each of the tones are presented in Figure 2.5.

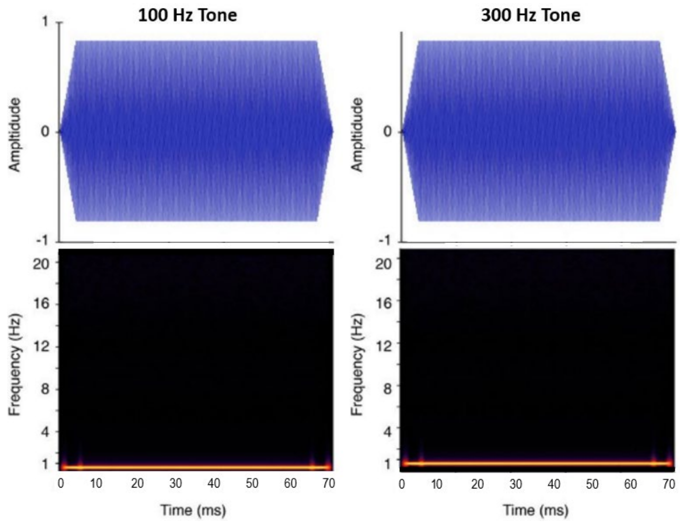

Figure 2.5 Time-amplitude waveforms (top images) and time-frequency spectrograms (bottom) of 100 and 300 Hz tones (adapted from Gilley et al., 2017).

The duration of each tone in the pair was 70 ms, (5 ms rise and 5 ms fall time) with 70 ms inter-stimulus-interval (ISI), constituting 210 ms across the tone pair. The inter-trial-interval (onset-to-onset) was 802 ms (592 ms offset-to-onset) in the short ITI in Study 1 or 932 ms (722 ms offset-to-onset) in the long ITI in Studies

1-7. The standard tone pair was a /low-low/ pair (100–100 Hz), and the deviant stimulus was a /low–high/ pair (100–300 Hz). Figure 2.6 demonstrates the frequency and temporal distribution of the tone pairs.

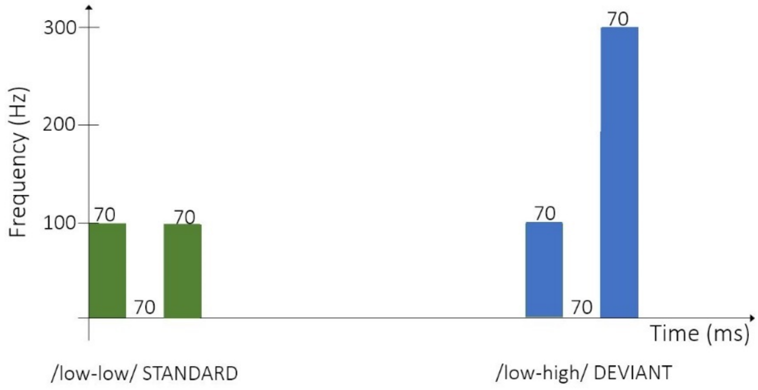

Figure 2.6 Schematic representation of stimuli in the tone pair paradigm. Frequency distribution of the /low-low/ standard (100-100 Hz) and /low-high/ deviant tone pairs (100-300 Hz) is represented on the y-axis. Temporal distribution of each tone (70 ms), inter-stimulus-interval (70 ms) and the duration of the whole tone pair (210 ms) is visible on the x-axis (ms).

Streaming paradigm.

The EEG paradigms used in Studies 2-7 were of the streaming design. The phoneme oddball and the long ITI tone pair paradigms were included in the streaming paradigm in alternating order: tone pair - phoneme – tone pair - phoneme, and so on. The deviant sounds were present in each stream with the same order as in the phoneme and tone pair paradigms. The inter-trial-interval between each stimulus was 483 ms. The offset-to-onset duration following each phoneme to a tone pair was 283 ms and after a tone pair leading to a phoneme was 273 ms. The-onset-to-onset duration between stimuli of the same type (tone pairs or phonemes) was 966 ms. As a result, the offset-to-onset duration between two tone pairs was 756 ms and between two phonemes was 766 ms. This included a pause but also the duration of the other stimulus type. See Figure 2.7 for the temporal and frequency distribution of the stimuli in the study.

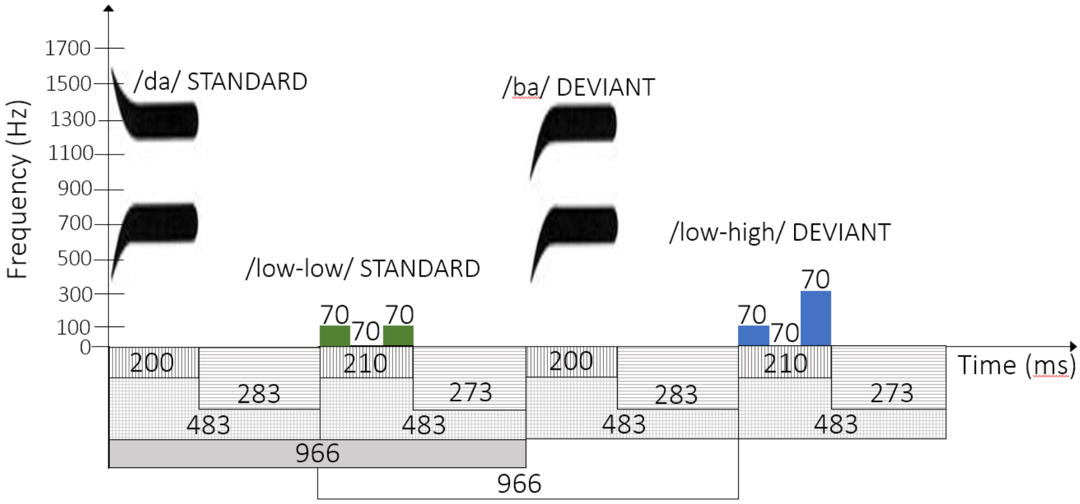

Figure 2.7 Schematic representation of stimuli in the streaming paradigm. Frequency distribution (Hz) of the /da/ standard and /ba/ deviant phonemes and the /low-low/ standard (100-100 Hz) and /low-high/ deviant tone pairs (100-300 Hz) is demonstrated on the y-axis. Their temporal distribution (200 ms for a phoneme and 210 ms for a tone pair) as well as the offset-to-onset (283 ms) and onset-to-onset (483 ms) duration between each stimulus and between stimuli of the same type (966 ms) is detailed on the x-axis (ms).

2.4.2 Language assessments.

Bayley-III.

Pearson Bayley Scales of Infant and Toddler Development, Third Edition (Bayley-III; Bayley, 2005) assessment is used to assess the development of children from birth to 42 months (0-3.5 years). It comprises five subtests: cognitive skills, receptive and expressive communication for language development and fine and gross motor domain. Age-appropriate tasks are used to assess a child's performance in each domain. They begin with the easiest and progressively increase in difficulty. Passing a task equates to one point, and the assessment is continued until the child does not pass five consecutive tasks. The scores are added and standardised to the child's age using Bayley-III standardisation tables to determine whether the child's performance is at the level expected for their age.

The assessment is divided into two subtests: receptive and expressive communication, the scores of which are standardised to the child's age to the scale with 1-19 points. Both language components are combined into the Sum of Scaled Scores, which then are transposed into the Language Composite Scores.

Receptive communication. It is composed of 49 tasks with ability ranging from attending to a person for a few seconds and responding to attention to understanding descriptive labels and identifying categories of the objects.

Expressive communication. The subtest consists of 48 items beginning with the ability to produce throaty sounds at birth to using past and future tense when describing pictures in a book in 3-year-olds.

Sum of Scaled Scores. It is a total sum of the standardised receptive and expressive communication scores with a range of 2-38 points.

Language Composite Scores. The Sum of Scaled Scores is distributed on a composite spectrum ranging 47-153 points with 100 as the median point in the scores. The composite scores indicate whether the child's performance is as expected for their age.

NEPSY-II.

Children's language ability was assessed with NEuroPSYchological Assessment, Second Version (NEPSY-II; Korkman, Kirk, & Kemp, 2007a, 2007b, 2007c). It is designed for children ages 3-16 years and includes six functional domains: attention and executive functions, sensorimotor functions, learning and memory, social perception and language and communication. Scores on most tests are standardised to age on a scale between 1-19, where 1-3 indicate scores well below expected, 2-8 below expected, 6-7 slightly below expected, 8-12 at the expected level and 13-19 above the expected level. The language and communication domain explores linguistic functions: receptive language, vocabulary, phonological processing, verbal fluency, and rhythmic and oral motor sequences. The raw scores were mapped out on the 1-19 points scale provided for the other NEPSY-II subtests. Table 2.1 demonstrates the distribution of the available scores and NEPSY-II language components used in the current project are outlined below.

Table 2.1

Distribution of NEPSY-II Standardised Scores and Percentile Rank in Language Subtests

NEPSY-II SCALED SCORE	NEPSY-II PERCENTILE RANK	CLASSIFICATION LABEL
13-19	>75	Above Expected
8-12	26-75	At Expected
6-7	11-25	Slightly Below Expected
4-5	3-10	Below Expected
1-3	≤2	Well Below Expected

Note. Percentile rank on the oromotor sequences subtest of NEPSY-II (copied from Korkman, Kirk, & Kemp, 2007b) was manually distributed across the 1-19 point scaled scale while for the other language subtests the scaled score table was provided. Both classifications were standardised to participants' age which was corrected for gestation.

Comprehension of instructions. It consists of 33 items. Participants are asked to point to objects on a picture by following increasingly complex instructions. The instructions range from 'show me a little bunny' to ''point to a shape that is to the right of a circle but not next to it'. The final scores are standardised to a child's age using the relevant table with the scaled scale between 1-19.

Oromotor sequences. The task requires the child to repeat 14 verbal sequences five times each. They begin with simple phonological sounds 'tick-tock' and end with tongue twisters: 'the thistle sifter sifted thistles'. Each correct repetition is given a score of one, with 70 points in total. Based on the language ability expected for the child's age, the scores are given percentile rank from <2 to >75. Percentile rank between 26-75 indicates that the scores are at the expected level for the age and scores below or above indicate performance either below or above the expected range. Scaled scores for this subtest are not provided in NEPSY-II (Korkman, Kirk, & Kemp, 2007b) but they were computed in the current project for comparative and analysis purposes, i.e., to ensure the language data from infants and children can be combined.

Phonological processing. Tests the ability to segment, process and finally modify phonemes in words in order to produce new words. The instructions increase in difficulty and vary from requesting the participant to repeat word /do-g/ through: 'say /meat/ and then say it but don't say /m/' and conclude with: 'say /instrument/, then repeat it but change /strum/ to /v/'. The maximum possible number of scores is 45. These are standardised to age using a 1-19 scale.

Repetition of nonsense words. The test comprises 13 phonological sequences between three and five syllables in length each. Correct repetition of each phoneme constitutes a score, 46 in total. The sequences range from /crum-see/ to /skri-flu-na-fliss-trop/. Scaled scores on scale 1-19 are computed by standardising the scores to the participant's age.

Speeded naming. It involves naming the features of shapes in a list on the picture, under time pressure. The first part involves naming a colour and shape of each object in the sequence (e.g., 'yellow circle'), whilst the more advanced task also includes the size of the object (e.g., 'little yellow square'). Children above the age of 6 are also required to read a composite list of letters and numbers (8, J, G, 2, 7, etc.). Accuracy, number of self-corrected errors and time to complete each part are added individually, each standardised to age. Once individual scales scores are summed up, the combined scaled score (range 1-19) is calculated.

Word generation. The test requires the participant to produce names of animals and types of food and drink. Both tasks are timed to 1 minute each. Children older than 6 are also required to generate words beginning with letters /s/ and /f/. The words are added up, and the score standardised to age using the normalisation scale with range 1-19 points.

Sum of Scaled Scores. Although not part of the analysis protocol for NEPSY-II assessment, for the purpose of this project a total sum of the standardised scores on the language domain in NEPSY-II was calculated by adding up the 1-19 points in the comprehension of instructions, oromotor sequences pomological processing, speeded naming, repetition of nonsense words and the word generation subtest each with a total range of 6-114 points.

Language Composite Scores. The computed sum of scaled scores was distributed on a composite spectrum ranging 47-153 points with 100 as the median point in the scores. The composite scores show an overall behavioural language performance and indicate whether the child's performance is as expected for their age. Table 2.2 demonstrates the distribution of the language composite scores on the manually calculated sum of scaled scores.

Table 2.2

Distribution of NEPSY-II Sum of Scaled Scores and Language Composite

NEPSY-II Sum of Scaled Scores	NEPSY-II Language Composite
106-114	145-153
92-105	131-144
75-91	115-130
61-74	101-114
45-60	85-100
32-44	72=84
16-31	57-71
6-15	47-56

Note. The language composite scale was developed to create an overall language score in children. Percentile rank on the oromotor sequences subtest of NEPSY-II was manually distributed across the 1-19 point scaled scale while for the other language subtests the scaled score table was provided (in Korkman, Kirk, & Kemp, 2007b). Both classifications were standardised to participants' age which had been corrected for gestation.

2.5 Procedure

The visit commenced with the experimenter explaining the procedure to both the parent and to the child if 2 years or older, in a manner commensurate to their age. Once the parent provided informed written consent, the testing session would commence. In addition to that, verbal assent was acquired before each task from the child if they were at least 2 years. The families were reassured that they could ask questions at any time, unless otherwise stated (for instance not during the EEG task, but they could ask questions in the breaks between the EEG recordings). Throughout the visit, the families were fully aware that they could stop or withdraw at any time during testing or after the session.

The testing comprised EEG paradigms followed by a behavioural assessment of language in infants and children. The session concluded with collecting demographic information from the parents. At their second birthday, a subset of infants was invited for the second testing session, which involved only language assessment.

The rest, play, feeding, changing or nap breaks were taken as required. The session was completed with the experimenter providing the verbal and written debrief and answering final questions from the parents. The children were rewarded with the ‘Young Scientist’ certificate, a small age-appropriate toy and £10 Love2Shop voucher.

2.5.1 EEG recording.

During the session, the paradigms in Studies 1, 2 and 5 were counterbalanced between participants. Sounds were presented at 75 dB SPL from the left and right side of the sound-proof booth, approximately 100 cm apart and at an angle of 45 degrees on each side in front of the infant, who was sitting on the parent's lap in the centre of a dimly lit booth which was both acoustically and electrically shielded. Children sat on their own in a chair. The participants watched a silent cartoon on the screen, or the experimenter blowing bubbles, while simultaneously being passively exposed to the sounds played out of the speakers. The paradigm duration was between 6 and 9 minutes, plus net application and re-soaking the channels between the paradigms added up to approximately 40 minutes per EEG session.

EEG data acquisition.

EEG data were collected with high density 128- HydroCel Geodesic Sensor Net (HGSN) produced by EGI (EGI, Eugene, OR). The head circumference of the child's head was measured to determine the size of the net. The data was recorded with EGI Net Station version 4.3.1 software in Studies 1 and 5 and with EGI Net Station Acquisition version 5.2.0.2 in Study 2. The electrical potential was referenced to the vertex (Tucker, 1993), digitised at 500 Hz sampling rate with a bandpass filter set between 0.1–100 Hz. Before recording began, the impedance of each electrode was manually checked to ensure that they were all below 100 kiloohms.

2.5.2 Behavioural tests.

Behavioural tests, which comprised Bayley-III (Bayley, 2005) language subtests in infants and two-year-olds and NEPSY-II (Korkman et al., 2007a, 2007b, 2007c) language subtests in children were performed after the EEG paradigms (see section 2.4.2 for details on the assessments). Order of the subtests (but not the tasks within) was counterbalanced.

Infants were seated at a table on their parent's lap, while children sat on their own but in the presence of their parent or guardian. The experimenter was seated across the table and presented test items to the participant. Objects and images used to elicit an appropriate reaction (e.g., engaging by vocalising, naming, or pointing to the correct item) from the participant were standardised Bayley-III or NEPSY-II assessment tools.

Participant's responses were scored during their performance and videotaped by another experiment for off-line verification. The assessment was completed within approximately 20 minutes in infants and 2-year-olds and up to 60 minutes children. Based on the participant's age, which was corrected for gestation, raw scores were standardised after the experimental session, using the relevant standardisation tables.

2.6 ERP data processing and analysis

2.6.1 Processing EEG data.

The EEG data in Studies 1 and 5 were processed using Waveform Tools in EGI Net Station 4.3.1 (Geodesics, 2003) and EEG data in Study 2 in Net Station 5.2.0.2 software. Justification for the steps taken in the ERP data processing and the challenges associated with each are outlined in section 1.3.7.

The signal was off-line low pass filtered between 0.5 and 25 Hz and segmented into epochs starting 50 ms before and ending 650 ms after the stimulus onset in the tone pair and phoneme paradigms and 400 ms in the streaming paradigm. Segments observed to have more than 40 bad channels and channels containing more than 20% bad segments per category, i.e., artefacts above ±140 μV, were excluded automatically. Channels with motion artefacts, eye movements or eye blinks below this threshold but above 50 μV were rejected manually per segment. Bad channels were interpolated by averaging the surrounding channels and recomputing the new values. Artefact-free segments were re-referenced to the average reference. Baseline correction was performed by subtracting mean amplitudes in the 50 ms window immediately before the stimulus onset to minimise the effects of any ongoing processing from the preceding stimulus.

2.6.2 ERP analysis strategy.

Analyses were focused on regional clusters. ERPs to deviant and standard stimuli in the phoneme and tone pair paradigms were averaged into one response per category (deviant and standard) for each participant in each of the paradigms. They were further averaged into the left frontal – channels 19, 20, 23, 24, 27 and 28; right frontal – 3, 4, 117, 118, 123 and 124; left temporal – 39, 45, 46 and 50, and right temporal clusters – 101, 102, 108 and 115 on the EGI Hydrocel 128-system. These clusters corresponded to F3, F4, T3 and T4 channels, respectively on the 10-20 system. Figure 2.8 illustrates distribution of the clusters on the 128-channel system.

The cluster averaging was followed by dividing the epochs into time windows of 50 ms duration. They included: -50 to 0 for baseline, 0 to 50, 50 to 100, 100 to 150, 150 to 200, 200 to 250, 250 to 300, 300 to 350 and 350 to 400 ms bins in the streaming paradigm and further 400 to 450, 450 to 500, 500 to 550, 550 to 600 and 600 to 650 ms bins in the phoneme and tone pair paradigms.

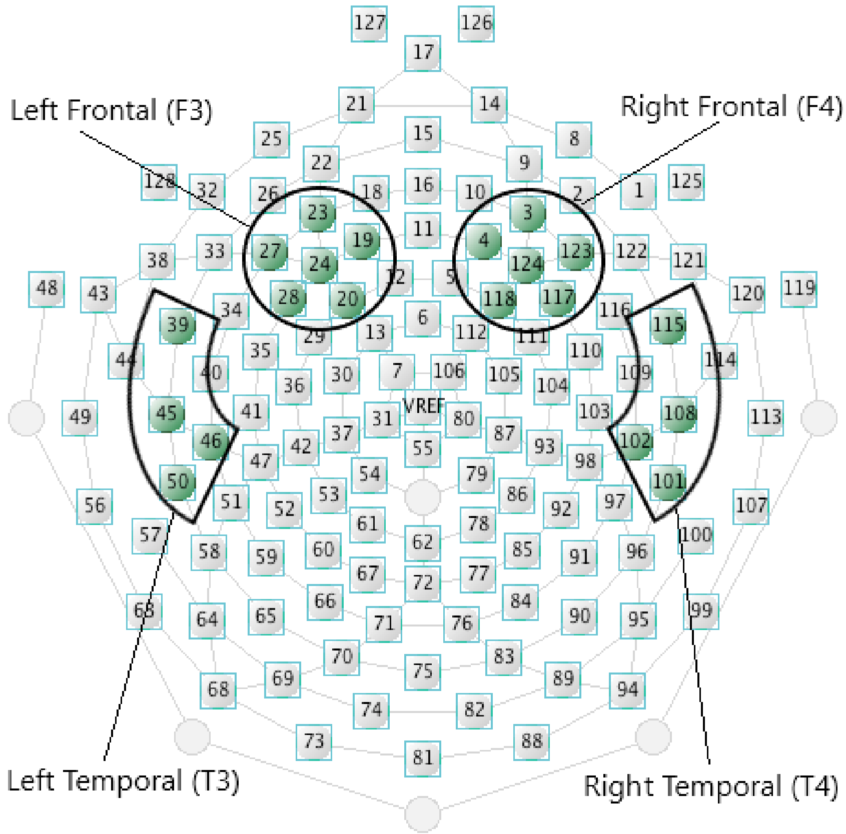

Figure 2.8 The HGSN 128- montage with channels used to analyse the MMR between deviant and standard sounds in each paradigm highlighted. Channels were averaged into clusters, which were located around the F3, F4, T3 and T4 channels on the 10-20 system: F3: left frontal (channels 19, 20, 23, 24, 27 and 28), F4: right frontal (3, 4, 117, 118, 123 and 124), T3: left temporal (39, 45, 46 and 50) and T4: right temporal cluster (101, 102, 108 and 115), as highlighted on the schematic image (adapted from Geodesics, 2003).

Figure 2.9 demonstrates the temporal distribution of the time windows. The EEG data were thus grand-averaged to the single mean ERP waveform per deviant and standard within each channel. Data in the selected channels were further averaged into the left and right frontal and temporal clusters and divided into 50 ms time windows individually per participant a priori to data analysis. The data were exported from EGI Net Station as a text file and imported into SPSS 25 for statistical analysis (George & Mallery, 2016) and into EEGLab 12.0.2 for cluster visualisations (Lopez-Calderon & Luck, 2014).

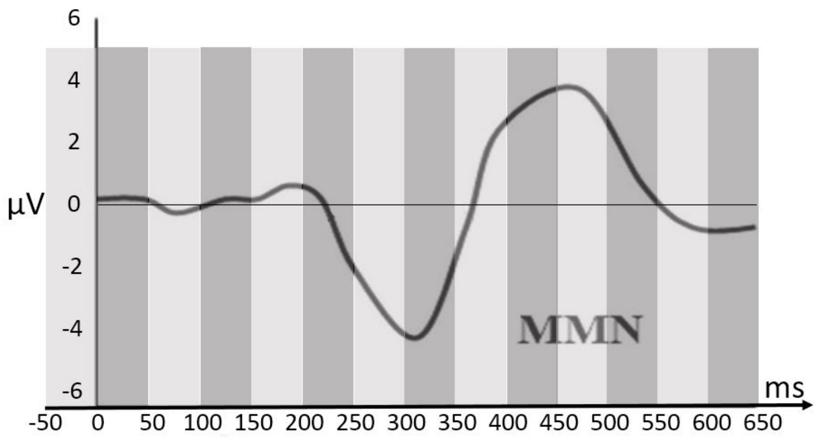

Figure 2.9 Schematic representation of segmenting an epoch into time windows: -50 to 0, 0 to 50, 50 to 100, 100 to 150, 150 to 200, 200 to 250, 250 to 300, 300 to 350, 350 to 400, 400 to 450, 450 to 500, 500 to 550, 550 to 600 and 600 to 650 ms. Each grey bar (lighter and darker shades) represents one 50 ms time window.

Estimating significance of the MMR with a paired t-test.

To reveal the time course of the MMR, a two-tailed paired t-test was conducted between the standard and deviant ERPs independently within each of the four clusters (left and right frontal and temporal) on each 50 ms time window in the epoch between 100-650 ms in the phoneme and tone pair paradigms and between 100-400 ms in the phoneme and tone pair streams in the streaming paradigm (see Figure 2.10 for structure of the t-test). For the internal validity of the data, namely, to reduce the potential inflation of the results due to multiple comparisons (Luck, 2014, pp. 251-258; Maris & Oostenveld, 2007), the MMR was only considered significant at $p < 0.01$ (Guthrie & Buchwald, 1991; Sterne et al., 2001). The MMR, which was the mean absolute difference value between ERPs to deviants and standards in each time window, was then used in modulations in Studies 1, 2, 5 and 7 and correlations in Studies 3, 4, 6 and 7.

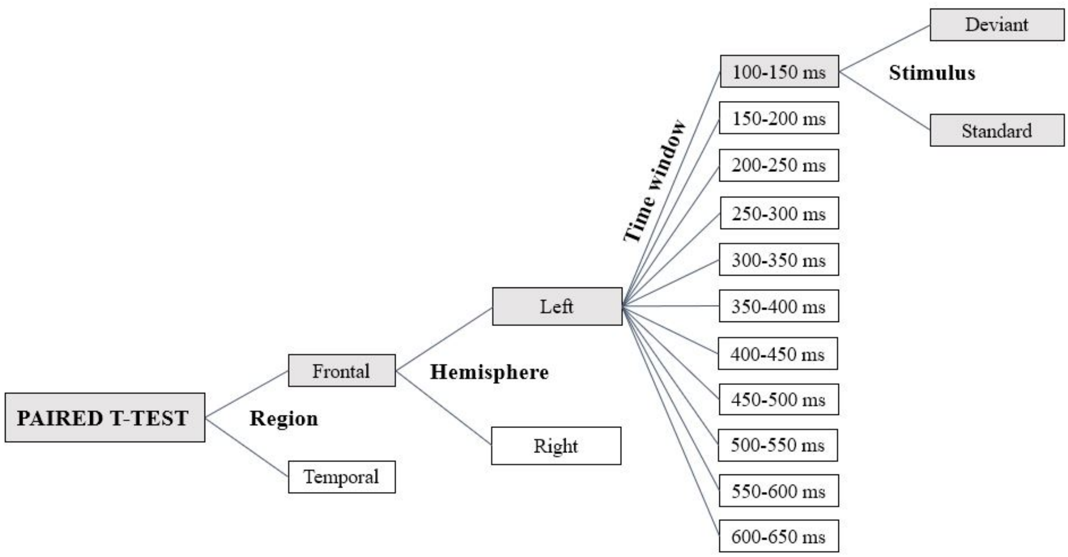

Figure 2.10 Schematic representation of paired t-tests conducted between ERPs to deviants and standards individually on each time window within each of the hemispheres in the frontal and temporal clusters. An example of a single t-test is highlighted in light grey in the model.

Estimating MMR difference in modulations with ANOVA.

Analyses of variance (ANOVAs) were conducted on the differences between MMR value for each of the time windows in examined manipulations. Figure 2.11 demonstrates the ANOVA structure with all the possible factors and levels included. However, only time windows with significant MMR (at $p<0.01$), based on the initial paired t-test results, were included in the analyses in all seven studies.

All analyses initially included age (corrected for gestation) as a covariate and language experience (monolingual versus bilingual) as a between-subject factor, but these were excluded from the final analyses if they did not significantly contribute to the difference in manipulations. Repeated-measures factors were: modulation (which differed between studies), region (frontal versus temporal), hemisphere (left versus right) and time window (which related to the MMR onset and amplitude in each of the included modulations). Study 7 additionally included the age group as a between-subject factor (infants versus children), which is not included in the general model in Figure 2.11.

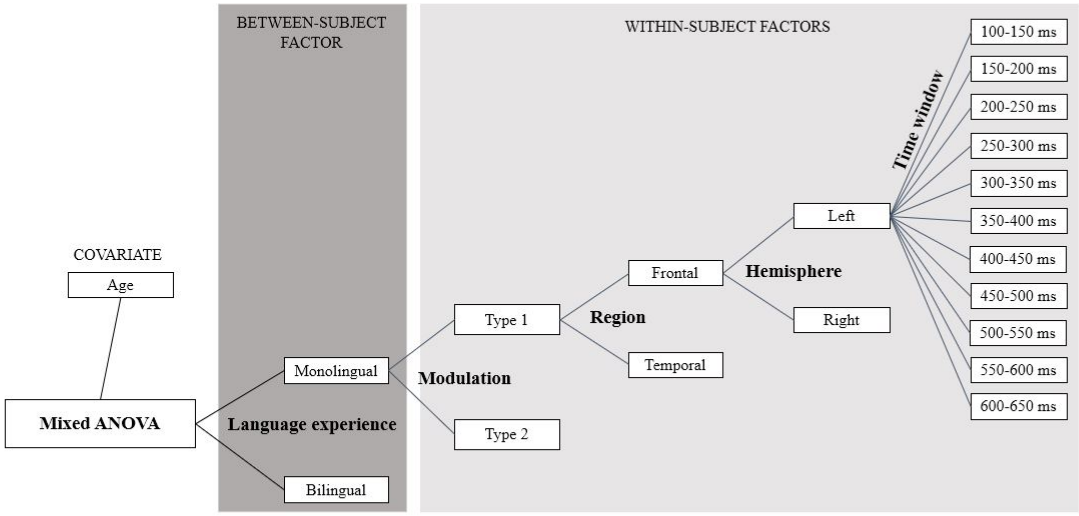

Figure 2.11 A model of ANOVA structure available in Studies 1, 2, 5 and 7. Labels in bold font represent factors and labels in white boxes - levels of each factor. Only levels related to the onset and largest mean MMR amplitude for each modulation were included in the analyses.

While interpreting the results, Leven's test of homogeneity of variances for the between-subject data and Mauchly's W for sphericity of the within-subject data were inspected where appropriate. Greenhouse-Geisser correction was applied to all within-subject results with more than two degrees of freedom and Bonferroni correction to multiple within-subject comparisons (Handy, 2005).

Establishing associations between MMR and language with Pearson correlation.

The relationship between auditory MMR to change in phoneme and tone pair paradigms and each of the streams in the streaming paradigms and language ability was assessed in the correlational studies of the thesis. Pearson correlations (at $p<0.05$, two-tailed) were carried out between clusters and time windows with significant MMR amplitude (based on t-test results) to phoneme and tone pair paradigms and phoneme and tone pair stream in the streaming paradigm and standardised scores on behavioural language performance, as operationalized with Bayley-III: receptive and expressive communication which were combined into the language composite variable in infants in Studies 3 and 4, NEPSY-II: comprehension of instructions, oromotor sequences, phonological processing, repetition of nonsense words, speeded naming and word generation, which were summed up and transposed into the language composite variable in children in Study 6. The final language composite variable in Study 7 was computed by merging the data from infants in Study 3 and children in Study 6.

Estimating association between MMR and language with partial correlation coefficient.

Where language experience (bilingual vs monolingual) contributed to the relationship between MMR to deviance in the streaming and control phoneme and tone pair paradigms and the language composite scores, a partial correlation coefficient (two-tailed) was carried out instead. The aim was to identify the unique link between MMR and language in the correlational studies of the thesis. Figure 2.12 demonstrates the partial correlation model.

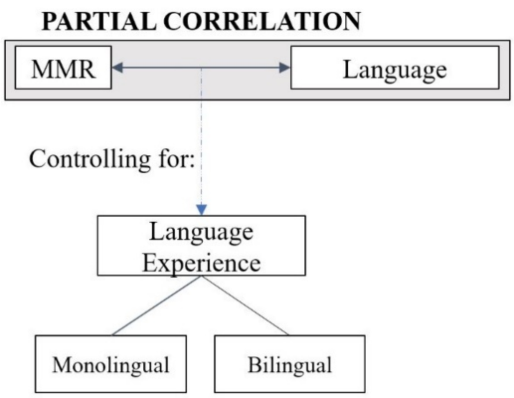

Figure 2.12 A general model of the partial correlation coefficient between the MMR and language ability in infants and children conducted in Studies 6 and 7. The dotted line represents the controlled variable: language experience at levels: monolingual and bilingual.

Chapter 3. Study 1 – The effect of paradigm feature on the MMR in infants.

3.1 Introduction

Inconsistencies between findings in studies investigating MMR indices in early development are common (Bailey & Snowling, 2002b; Kovacs & Mehler, 2009; Shafer et al., 2015; Sussman, Chen, Sussman-Fort, & Dinces, 2014; Volkmer & Schulte-Körne, 2018). They tend to be attributed to maturational changes in ERPs (Cheour et al., 1998; Kushnerenko et al., 2002a) and more explicitly the result of synaptic pruning and increased myelination of the neural axons (Chaudhury et al., 2016; Petanjek et al., 2011). However, this could be partially explained by the variable paradigm features between studies (Garrido et al., 2009). Prior research has shown that in adults, the amplitude and spatial and temporal distribution of the MMR is dependent on specific paradigm parameters (Näätänen et al., 2007; Näätänen, Astikainen, Ruusuvirta, & Huotilainen, 2010; Näätänen, Pakarinen, Rinne, & Takegata, 2004; Tervaniemi et al., 2005; Winkler, 2007). For example, inter-trial-interval (ITI), deviance (oddball or roving) and stimulus type (phonemes or tone pairs) may be contributing to differences in the onset and the mean amplitude of the MMR.

Although the design features and their influence on the MMR have been examined in adults (Jarkiewicz & Wichniak, 2015; Pekkonen et al., 1995), and comparisons between linguistic and non-linguistic stimuli made in children and adults (Lee at al., 2012; Maurer et al., 2003a), there is little research on such comparisons in infants (although see assessments of ERPs to linguistic and non-linguistic tones in infants exposed to tonal languages by Liu, Peter, & Weidemann, 2019; Xi, Zhang, Shu, Zhang, and Li, 2010).

3.1.1 Deviance type and its effect on the MMR.

The origins of the oddball deviance and its associations with the MMR are outlined in section 1.3.3 , and the comparisons of the oddball and roving deviance effect on the MMR in adults are introduced in section 1.3.6 in Chapter 1. The effect of deviance type on the MMR was assessed for the first time in a study exploring ERPs to the oddball versus roving design in tones (Cowan et al., 1993). In the oddball paradigm, the standard tone frequency was 600 Hz with the intermittent deviant of 700 Hz. The roving paradigm included shifts between trains of tones, e.g., a sequence of 420 Hz tones was followed by another sequence of, e.g., 600 Hz tones. As expected, the oddball deviance evoked more negative MMR than the roving design, and a larger number of standards in a sequence were required to reach the significance of MMR: two in the oddball versus four in the roving paradigm. Arguably, the oddball contrast was easier to discriminate in that there was a constant physical difference between the acoustic properties of deviant and standard tones, namely the same frequency distance (Campbell et al., 2007). The roving paradigm was more complex in that phonemes varied between trains and were never repeated.

Other researchers focused on the effect of the number of stimuli in each train on the development of the MMR (Garrido et al., 2009; Haenschel et al., 2005) and found the benefits of using the roving design to discern between neural activity in schizophrenic patients and controls (Baldeweg & Hirsch, 2015; Jarkiewicz & Wichniak, 2015). Furthermore, Haenschel and colleagues (2005) emphasised the importance of active rather than passive listening to elicit MMR to roving deviance as quickly as after the second standard in the sequence.

Similar findings were reported by Garrido and colleagues (Altmann et al., 2011; Angelini et al., 2009; Garrido et al., 2008, 2009; Haenschel et al., 2005), who used the roving design to develop a computational model of the MMR network. Based on the ERPs to the roving paradigm, the neural pathways within bilateral primary auditory area A1, the superior temporal gyri and the right inferior frontal gyrus contributed to discriminating the deviance (see section 1.1.1 for details on the auditory network). The assumption was that the oddball paradigm would render comparable results, although this was not tested statistically. However, treating the same stimuli both as standards and deviants removed the acoustic contrast between them, which ensured that the generated MMR was due to neural expectation bias rather than a difference in the stimulus characteristics (section 1.3.3 outlines theories on the MMR).

The difference in processing oddball and roving deviance may be further explained with the adaptation theory of the MMR. It proposes that with an increased number of repetitions of an auditory stimulus, such as a phoneme or a tone, a sensory memory trace builds up in the action potentials (Cowan, 1984; Dykstra & Gutschalk, 2015; May & Tiitinen, 2010). While initially the stimulus generates heightened electrophysiological response, this is reduced with the increased expectation of the same stimulus over time. Neurons habituate and desensitize to the repeated sounds. This is represented by the attenuated ERPs to standards.

When a novel stimulus appears infrequently and randomly among the repetitions of the standard stimuli, this violates the sensory memory expectation that the following sound should be the same as the past series. Neurons dishabituate and increase activity to the new sound if it is sufficiently infrequent and distinctive from the previous train. Supporting evidence is derived from a study by Eulitz and Hannemann (2010), in which fluctuations between German words 'falke' or 'falte', increased gamma-band power in the left temporal cortex for the first word in the new train but disappeared with the continuation of the train.

After each deviant, the action potentials reset and habituate again, with each repetition in the sequence eliciting lower ERPs to standards and increasing habituation (Atherton, Dupret, & Mellor, 2015; Cooper et al., 2013; Garagnani & Pulvermüller, 2011; Haenschel et al., 2005; Kim, Kwon, Kim, & Han, 2013; Näätänen, 1990; Näätänen et al., 1993a; Näätänen, Schröger, Karakas, Tervaniemi, & Paavilainen, 1993; Sugase-Miyamoto, Liu, Wiener, Optican, & Richmond, 2008).

Depending on the type of deviance, the memory trace may be local or global (Cooper et al., 2013; Herholz, Lappe, & Pantev, 2009). The first involves habituation within a single train of sounds, which begins with a sequence of standards followed by a deviant. The standards elicit gradual decrease in individual ERPs, while the deviant stimulus should recover the response (Baldeweg, 2007; Basirat, Dehaene, & Dehaene-Lambertz, 2014; D'Astolfo & Rief, 2017; Friston, 2005; Garrido, 2008; Garrido, Teng, Taylor, Rowe, & Mattingley, 2016; Todd & Robinson, 2010; Wacongne et al., 2011). The global memory trace, in contrast, may explain the neural adaptation to sequences of deviant and standard stimuli across the paradigm. With the increased number of repetitions, neural adaptation may lead to the gradual decrease in response to standards to the point of reaching the baseline when averaged across the trials, if the deviant and standard stimuli remain the same between the sequences (Herholz et al., 2009; Picton, 1992; Segalowitz & Barnes, 1993).

The roving design (Cooper et al., 2013; Garrido et al., 2008; Haenschel et al., 2005; Halliday et al., 2008; Rosch et al., 2017, 2019; Takaura & Fujii, 2016) and multifeatured paradigms (Partanen et al., 2013; Partanen, Vainio, Kujala, & Huotilainen, 2011; Putkinen et al., 2012) is in contrast expected to generate weaker habituation due to more complex design and the neural network forced to reset predictions after each contrast. Indeed, this was the case in a study by Muenssinger et al. (2013). Attenuated habituation was found to the roving change across trains of tones but not to the oddball change within each train in adults, while this complex design decreased habituation to both types of deviance in 9-year-old children. There is more evidence for this distinction in adults (Jarkiewicz & Wichniak, 2015; Leung et al., 2015), but such systematic comparisons have not been made in infants.

3.1.2 The effect of trial duration on the MMR.

A summary of studies exploring the effect of a length of a trial is available in section 1.3.6 Presentation rate of the auditory paradigms has been reported to affect the development of ERP peaks and in turn, the MMR in adults (Andreou et al., 2011; Escera et al., 2000; Sussman et al., 2008; Wunderlich & Cone-Wesson, 2006; Wunderlich et al., 2006; Xu & Ma, 2009).

Javitt and colleagues (Javitt, Grochowski, Shelley, & Ritter, 1998) assessed the influence of trial duration on the MMR amplitude in adult schizophrenic patients and controls. The optimal ITI in adults was found to be around 150 ms, while schizophrenic patients required a longer duration of 450 ms. Similarly, the MMR decreased when the ITI extended from 600 to 3400 ms (Imada, Hari, Loveless, McEvoy, & Sams, 1993b), suggesting that shorter ITI is more beneficial. In another study lengthening the ITI from 500 to 1500 ms attenuated the MMR both in younger and ageing adults (Pekkonen et al., 1996). By contrast, Sams and team (1993) found an increase in the MMR from 750 through 1500 to 3000 ms ITI and decrease afterwards, when assessed with magnetoencephalography. In support of these findings, the original study on MMR by Näätänen et al. (1978) used constant ITI of 800 ms in adults.

Research in 7- to 9-year-old children found 350 ms duration (250 ms offset to onset) to be the most successful ITI length for efficient MMR produced around the frontocentral area of the brain (Čeponiené et al., 1998; Gomot et al., 2007) although longer ITI (700 and 1400 ms, i.e., 600 and 1300 ms offset to onset, respectively) were also efficient. Typically developing 8-13 years old children generated significant negativity of the MMR to speech and chord sounds with the ITI of 540 ms and tones of 620 ms ITI (Sharma et al., 2006).

Within the phoneme discrimination between /da/ and /ta/ sounds, slightly longer 930 ms ITI has been used while exploring MMR in 6- to 12- months-old infants (Ortiz-Mantilla, Hamalainen, Musacchia, & Benasich, 2013; Ortiz-Mantilla et al., 2016; Ortiz-Mantilla, Hämäläinen, & Benasich, 2012). Other researchers used longer ITI ranging between 3910 and 7285 ms to trigger phonetic discrimination (between syllables /ba/, /da/ and /ga/) in equiprobable design in newborns (Guttorm et al., 2010, 2005, 2001, 2003).

Chen et al. (2016) used shorter 430 ms ITI while exploring tonal discrimination of Mandarin vowels /i2/ and /i3/ longitudinally in the typically developing and children with language delay. They were tested at 3, 5 and 6 years of age. Children with no reported language impairment produced increased negative MMR to sounds at all ages, while the clinical sample exhibited immature positive MMR at 3 years and attenuated MMR negativity at 5 years, but by 6 years no group differences in ERPs were found, suggesting that the short ITI had differential effects on the groups when at a younger age, but in older children, MMR for this trial duration reached its ceiling performance.

Likewise, the optimal activity of the newborns' magnetic MMR to tones was assessed with MEG in a study by Draganova and colleagues (2005). The ITI varied between 200 to 100 and 1050 ms (including 50 ms tone duration in each). The largest MMR was found for the contrast between the longest trial 1050 ms, followed by a sequence of trials with 200 ms ITI (Háden, et al., 2015a).

The processing of tone pairs of variable trial duration has been investigated in older infants. In order to ensure a large MMR in 4- to 7-months-old infants, the trial duration was set at 915 and 1140 ms, with offset to onset duration of 700-705 ms (Benasich et al., 2014; Choudhury & Benasich, 2003, 2011; Hämäläinen et al., 2011; Musacchia et al., 2013). Both appeared to be efficient in generating significant MMR. However, the longer tone pairs elicited increased lateralisation of the MMR signal as recorded bilaterally in the frontal channels.

Shorter ITI of 450 ms with 400 ms-long ascending or descending tone patterns (with 50 ms offset to onset pause within the tone pair and between the trials, which adds up to 900 ms onset to onset) appears to fall below the discrimination threshold for 2-month-old infants, but not for infants aged 4 months (He et al., 2009), indicating rapid maturational changes in this early developmental period.

This concept has, however, been challenged by studies demonstrating infants' ability to process a silent gap between paired up tones if it is the differing factor between the conditions. Trainor et al. (2003) used 17 ms sound bursts of 2000 Hz frequency, which in the deviant condition consisted of 16 ms pause (creating two 0.5 ms pip markers). Four naïve age groups of infants generated significant MMR to the paradigm. The authors claimed that ERPs by 2-, 3- and half of the 4-month-olds did not signify discrimination due to positive rather than negative MMR difference wave. The MMN was generated only by the older 6-month-old infants. Recent research into maturation of the MMR, however, supports the idea that a positive difference wave represents early MMR and that the MMN is a more mature response which presents itself towards the end of the first year (Cheng et al., 2015; Dehaene-Lambertz & Baillet, 1998; Kushnerenko, 2003; Maurer et al., 2003b), but they both signify neural discrimination. See also more details on the early development of the MMR in section 1.3.4.

Overall, the tone pair paradigm has been established as a successful generator of the MMR in infants. However, the paradigm developed by Choudhury and colleagues (Arora et al., 2017; Benasich et al., 2002, 2006, 2014, 2016; Cantiani et al., 2016a; 2016b; Carral et al., 2005; Choudhury & Benasich, 2011; Choudhury et al., 2007, 2015; Jannesari et al., 2019; Musacchia et al., 2013, 2017; Paterson et al., 2006; Tallal & Gaab, 2006) has been mainly carried out with younger infants, up to 7 months of age (although see Choudhury et al., 2011).

However, the older the infant the quicker they become restless, and so shorter paradigm may be needed in order to acquire artefact free trials before this happens (de Haan, 2013; de Haan & Thomas, 2002; Hoehl & Wahl, 2012). It would be useful to determine if the even shorter length of a trial is as efficient in eliciting significant MMR with infants in the second half of the first year. Although shorter trial duration has been shown to be effective in 6- to 11-year-olds and adult controls to 700-705 ITI in tone pairs, suggesting that reduction of trial duration might also be efficient in younger participants (Choudhury et al., 2015; Heim, Keil, Choudhury, Thomas Friedman, & Benasich, 2013), trial duration shorter than 915 minutes seconds has not been tested in infants.

Furthermore, it transpires that the ITI used in developmental research exploring auditory discrimination is hugely variable with inconsistent findings, and there is a need for a more standardised approach.

3.1.3 Stimulus type and its influence on the MMR.

Examples of stimuli thought to trigger neural discrimination include sinusoidal (Hövel et al., 2014) and harmonic tone pairs (Benasich et al., 2002) as well as speech sounds including vowels (Shafer et al., 2012; Tsuji & Cristia, 2014; Wanrooij et al., 2014), various consonant-vowel combinations (Dehaene-Lambertz & Baillet, 1998; Jansson-Verkasalo et al., 2010; Key et al., 2007), linguistic tones (Gandour & Harshman, 1978; Hua & Dodd, 2000; Krishnan & Gandour, 2009; Liu, Peter, & Weidemann, 2019; Meng et al., 2005; Yeung et al., 2014; Zhang et al., 2012) and various modifications of sinusoidal wave or noise to create speech-like stimuli with one or more key features distinguishing them from the actual speech (Bent et al., 2006; Lehnhoff et al., 2004; Molfese, 2000; Vandermosten et al., 2011; Vouloumanos et al., 2001).

Hitherto sparsely researched in infants, the systematic comparison of the MMR to linguistic versus non-linguistic sounds has been successfully performed in children and adults (Volkmer & Schulte-Körne, 2018). In a study by Kozou and team (2005), vowel discrimination between syllables /ka/ and /ko/ was contrasted to harmonic tones matched on frequency, spectral distribution (by adding corresponding wideband noise), intensity and duration (175 ms) in adults. The linguistic and non-linguistic stimuli were blocked into two separate conditions. The high acoustic similarity was masked by adding various types of noise: babble, industrial, traffic and wideband, in addition to the noise-free condition. In general, phonemes elicited weaker MMR than tones. The result indicated that even when differences between linguistic and non-linguistic stimuli are controlled for, participants find discriminating non-linguistic sounds easier. Following the same pattern, typically developing 8-13 years old children generated significant MMR to speech, tones, and chord sounds, but in children with reading difficulty, tones, and chord sounds but not phonemes elicited significant MMR (Sharma et al., 2006).

Similar performance was found in adults by Xi et al. (2010). In their study, Chinese phoneme /pa/ was modulated on the tonality of the vowel. The high rising and falling /pa/ consonant-vowel combinations were treated as deviants, and the middle sounding /pa/ was the standard sound. They were matched with complex tones of the same frequency but lacking the spectral distribution of the speech sounds. Increased negativity of the MMR in the tone in comparison to the phoneme condition was recorded in the central, but similar responses in the frontal EEG channels. The findings suggest that frequency distribution is a vital factor in processing auditory contrasts and that narrowband tones have an advantage over broadband linguistic stimuli. Similar findings were found in infants by Liu and colleagues (Liu, Peter, & Weidemann, 2019). Evidence supporting this also comes from a study by Gilley et al. (2017), in which a larger MMR was elicited by the contrast between tones and white noise than vowel or consonant discrimination in 1-3-month-old infants.

The above findings conflict with those by Maurer and colleagues (2003b). In their study, phonemes /ba/, /ta/ and /da/ and tones of frequencies 1000, 1030 and 1060 Hz (standard and two deviants in each category, respectively) were presented in two blocks to 6-year-old children and adults. Recordings from the central channels demonstrated equally negative MMR to both phonemes and tones in adults. MMR data from the children, by contrast, had a positive and overall larger amplitude. The MMR to consonant-vowel combinations was significantly larger than to the tonal change, reflecting perhaps heightened phonological processing in children of this age (Shafer et al., 2010; Tallal, 1980). There is also evidence showing an increase in the MMR during literacy training in adults (Schaadt et al., 2014). Likewise, Zhao and Kuhl (2016) studied the effect of music training in 9-month-old infants on the detection of deviance in pattern and trial duration separately in tone and phoneme paradigms in MEG. They reported larger magnetic MMR to phonemes than tones, but music intervention increased the amplitudes to both types of sounds.

These data were supported by a combined EEG-MEG study in adults (Kuuluvainen et al., 2014). The stimuli were Finnish syllables /pi/, /pe/, /ki/ and /ke/ and their non-linguistic counterparts. Frequencies of the vowels in the phonemes were modulated to 410, 2045, 2260 and 3320 Hz for /i/ and 320, 2240, 2690 and 3275 Hz for the /e/ vowels. The fundamental frequency, spectral envelope, and intensity of the nonspeech stimuli matched the syllables, but their frequencies were constant at 2240 for the /i/ and 2045 Hz for the /e/ vowel equivalents. The EEG results revealed overall greater MMR negativity to phonemes than to non-linguistic sounds. This included identifying the within vowel category contrast when compared with MMR to the matched vowel-like change and to a lesser extent intensity, frequency, and discrimination between the linguistic and non-linguistic sounds.

The volume of electromagnetic potentials further confirmed discrimination of speech and nonspeech sounds in MEG. Overall, responses to speech deviance rendered increased magnetic MMR negativity than their nonspeech equivalents. It could be inferred that when matched with non-linguistic sounds on acoustic properties, phonemes may be at an advantage due to speech specific mechanisms engaged in their processing, which are not employed during simple acoustic discrimination (Dehaene-Lambertz & Gliga, 2004; LoCasto et al., 2004; Teismann et al., 2004; Yang et al., 2017). This distinction may not be present at birth (see Kostilainen et al., 2018).

Intracranial recordings support the idea of distinct cortical regions involved in processing linguistic and non-linguistic stimuli (Molholm et al., 2014). Data from three adult patients with epilepsy showed differences in the left temporal cortex in neural activity to phonemes, matched non-phonemes (created by inverting the first formant and increasing the slope of the third formant in phonemes) and tones. Deviance between syllables /ba/ and /da/ evoked negative MMR deflections at the anterior end of the medial temporal gyrus and posterior end of the superior temporal gyrus, while the non-linguistic negative MMR to tones originated from the primary auditory area A1. The findings highlighted the differential activation that speech and nonspeech sounds have in the brain (see also Vouloumanos et al., 2001).

Despite the evidence for distinctive mechanisms involved in processing speech and nonspeech stimuli in children and adults, their influence on the MMR in infants has not been systematically assessed.

3.1.4 Rationale for the study.

The influence of paradigm features, including the type of deviance, trial duration and linguistic versus non-linguistic stimulus on the MMR in infants was examined in Study 1 to assess their contribution towards variability in the ERP data.

The EEG paradigms employed in the study were two sets of phoneme paradigms using stimuli developed by Teinonen, Aslin, Alku and Csibra (2008) and two tone pair paradigms adapted from Choudhury and colleagues (2007). Both types were selected based on their effectiveness in eliciting large MMR amplitudes in infants (Carral et al., 2005; Choudhury et al., 2015; Choudhury & Benasich, 2011; Fellman & Huotilainen, 2006; Friederici et al., 2002; Hämäläinen et al., 2011; Maurer et al., 2003b; Musacchia et al., 2013; Näätänen et al., 2010; Vantanen, 2004) and due to their associations with language development (Benasich & Tallal, 2002; Dehaene-Lambertz & Gliga, 2004; Kraus et al., 1996). The oddball design in phoneme and tone pair paradigms was a modified version of the original pattern by Squires and colleagues (1975), while the roving variation was adapted from a study by Garrido et al. (2008).

3.1.5 Experimental predictions.

The current study aimed to evaluate the design features in an EEG paradigm based upon their efficiency in eliciting MMR in infants. The selected paradigm characteristics included deviance, trial duration and stimulus type. The oddball and roving deviance were expected to influence the spatial and temporal distribution of the MMR (H.1.1). Furthermore, the MMR was hypothesised to be affected by trial duration (H.1.2). In terms of stimuli, phonemes and tone pairs were expected to have a differential effect on the MMR (H.1.3).

3.2 Methods

The general methodology is presented in Chapter 2. Any deviations or additional methods for in Study 1 are outlined below.

3.2.1 Participants.

Demographics.

Although 47 infants participated in the study (see section 2.2 in General Methods), data from 37 (20 males) was included in the analysis. Ten participants generated noise artefacts in the EEG responses in at least one of the four paradigms, and as a result, their data was removed from the analysis. Nineteen infants were born to monolingual families, and the remaining 18 were bilingual. They were of Caucasian (18 infants), Asian (6 infants), Afro-Caribbean (5 infants) or mixed (8 infants) ethnicity. Their mean age (when corrected for gestation) was M=8.07 months, SD=1.30 (M=245, SD=39 days), age range: 5-10 months (170 to 319 days).

Thirty mothers agreed to provide their educational qualifications. Two of them passed their GCSEs, three acquired A-Levels, whilst a majority held a higher degree: 13 at the undergraduate level and 12 had a Masters degree. The average gross income of 31 families who disclosed it was £49,456 (SD=25,049) and varied from £8,400 to £100,000, which represented economically diverse households.

3.2.2 Design.

The study was of within-participant design. Four paradigms were presented to all infants in the counterbalanced order. They were sorted first between (phoneme versus tone pair paradigms) and then within the stimulus type (oddball versus roving phoneme paradigm and long versus short ITI tone pair paradigm).

Three types of modulations were performed. The deviance type manipulation was conducted on the phoneme paradigms. The trial duration manipulation was performed on the data collected from the tone pair paradigms. The final stimulus type comparison was conducted on the selected phoneme and tone pair paradigms, based on their efficiency in producing large MMR. Figure 3.1 demonstrates the three manipulations used in the study: deviance, ITI and stimulus type.

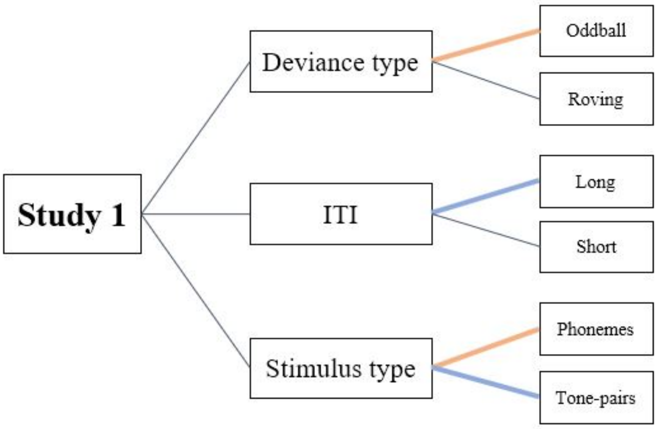

Figure 3.1 Schematic representation of modulations in Study 1. Blue lines demonstrate the oddball phoneme paradigm and the orange lines - tone pair paradigm with the long ITI.

Deviance modulation.

It relates to the change between deviants and standards in a typical paradigm inducing the MMR. In the oddball design, deviants are acoustically different from the standards stimuli, and both deviants and standards are always the same sounds. Roving design, by contrast, involves an alternating sequence of trains of two types of sounds, which differ between but not within the trains. The first stimulus in each train is different from the previous train of sounds, and so becomes a deviant, while the remaining stimuli are the same as the first and become standards due to their repetition. Alternating between trains of two types of sounds creates deviants and standards which do not differ acoustically.

Temporal modulation.

The long ITI design has been successful in eliciting MMR in infants. For comparison, short ITI was examined to determine if it could be used instead, to the same effect or whether this would incur cost on the volume of the MMR. The difference between the long and short ITI was 130 ms.

Stimulus modulation.

The influence of phonetic (phonemes /ba/ and /da/) and tonal (tone pairs of 100-100 Hz and 100-300 Hz frequency) contrasts on the MMR was investigated in infants.

3.2.3 Stimuli and apparatus.

The EEG tasks employed in the study were two sets of phonemes and tone pair paradigms. General information on the paradigms is outlined in section 2.4.1 and details on each of the four paradigms are provided below. Each paradigm consisted of 350 trials, 70 of which were deviant (20% of all trials) and 280 standard stimuli (80% of trials). They were played at 75 dB SPL.

Phoneme oddball paradigm.

The stimuli were presented in a pseudorandomized order so that at least three and no more than six standard /da/ phonemes were presented before and after each /ba/ deviant ensuring that deviants never directly followed each other. Figure 3.2 illustrates an extract of the sequence of trials in the paradigm.

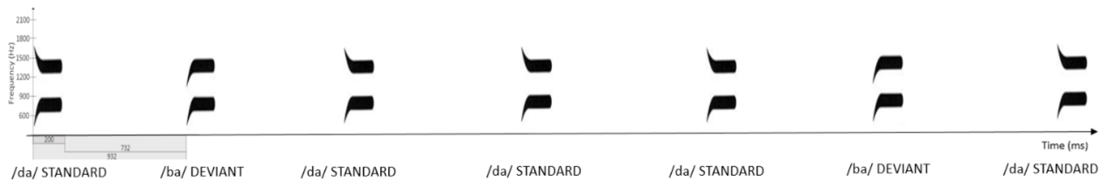

Figure 3.2 Schematic representation of a trial sequence in the oddball phoneme paradigm. The /ba/ deviant and the /da/ standard phonemes are labelled. The spectral and temporal distribution of a single trial is demonstrated in Figure 2.4 in General Methods.

Phoneme roving paradigm.

The phoneme roving paradigm differed from the oddball paradigm in the order the phonemes were presented. The deviance was a result of alternating between trains of phonemes (/ba/ or /da/). Figure 3.3 illustrates order of the sequence. The first phoneme in the train became deviant, while the remainder became standards, until the next train of phonemes. A sequence of /ba/ phonemes was always followed by a sequence of the /da/ phonemes. The number of phonemes in the sequence was pseudorandomised and consisted of four to seven sounds but overall, the trains were equally distributed.

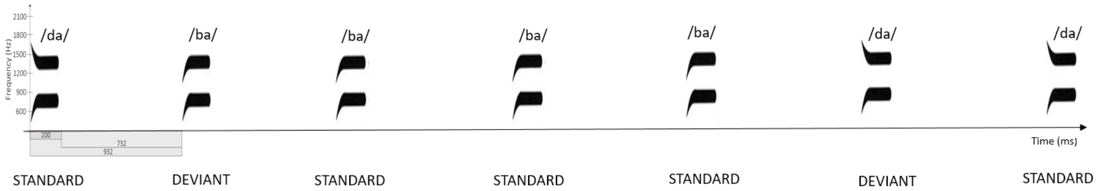

Figure 3.3 Schematic representation of an extract of the trial sequence in the phonemes roving paradigm. The deviant and standard phonemes are labelled. The precise frequency and temporal distribution of a single trial are demonstrated in Figure 2.4 in General Methods.

The long ITI tone pair paradigm.

The stimuli were tone pairs presented in a pseudorandomized order so that at least three and no more than six standard tone pairs were presented before and after each deviant tone pair. In the long ITI, a single trial lasted 932 ms (722 ms offset-to-onset). Figure 3.4 demonstrates the temporal distribution of trials in the paradigm.

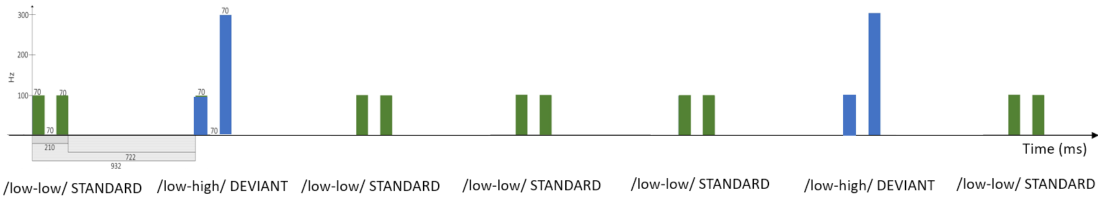

Figure 3.4 Schematic representation of a trial sequence in the long ITI (932 ms) tone pair paradigm. The /low-high/ deviant (blue bars) and /low-low/ standard (green bars) tone pairs are labelled accordingly.

The short ITI tone pair paradigm.

The tone pair paradigm with short ITI consisted of 802 ms trial (592 ms offset-to-onset). The remaining features did not differ between both tone pair paradigms. Figure 3.5 illustrates the distribution of the tone pairs in the timeline.

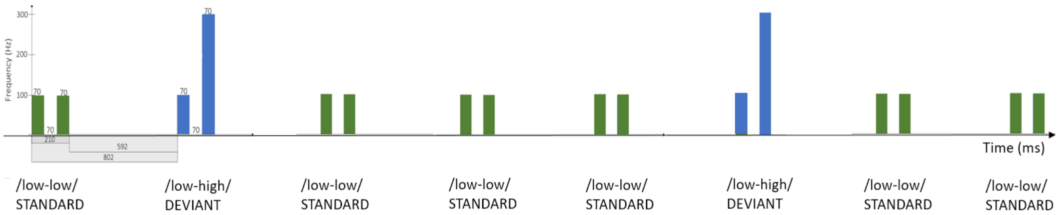

Figure 3.5 Schematic representation of a trial sequence in the short ITI (802 ms) tone pair paradigm. The /low-high/ deviant (blue bars) and /low-low/ standard (green bars) tone pairs are labelled accordingly.

3.2.4 Procedure.

Procedural details relating to all seven studies are detailed within section 2.5.1. The Study 1 experimental procedure involved long and short ITI tone pair and oddball versus roving phoneme paradigms. They were counterbalanced in the order of type of sound and then the type of manipulation within the group of sounds. Each paradigm lasted between 5 and 6 minutes. Figure 3.6 demonstrates the paradigm timeline. EEG responses were collected with HGSN 128-channel saline sensor net and recorded with EGI Net Station version 4.3.1. Section 2.5.1 provides detailed information on the EEG procedure.

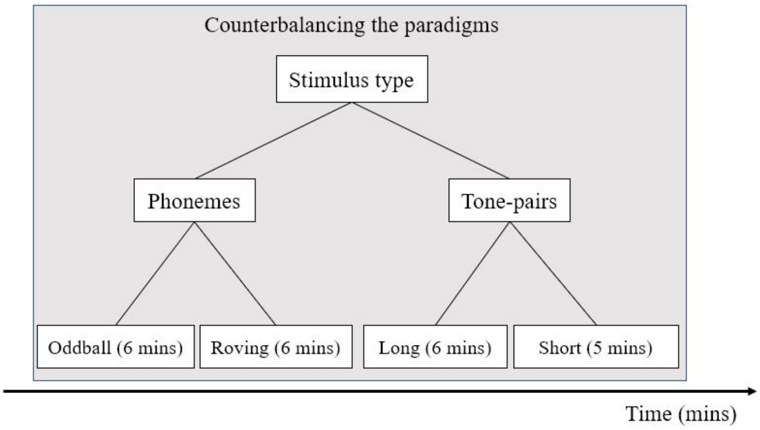

Figure 3.6 Schematic representation of the procedure in Study 1. Counterbalancing by stimulus type and then by modulation in each of the paradigms is presented on a grey background. The resulting order would include any of the allowed combinations between the four paradigms. An example is presented in the timeline with the duration of each paradigm in brackets.

3.2.5 ERP data processing and analysis.

Processing EEG data.

The general information on EEG data processing is included in section 2.6.1. It was carried out using Waveform Tools in Net Station 4.3.1. Following artefact rejection, the average percentage of trials accepted for further analysis was 85% (M=59.419; range: 48-70 trials) for /ba/ and /low-high deviant/ and 85% (M=237.142; range: 191-277 trials) /da/ and /low-low/ standard sounds.

ERP analysis strategy.

General information on the analysis strategy is provided in section 2.6.2, with details on the modulations being outlined below. Figure 3.7 demonstrates the structure of analysis in Study 1. Analysis A represents identifying the significant MMR to each of the paradigms with paired t-tests and Analysis B is the comparison between time windows with the onset and amplitude of the MMR to paradigms within each modulation: deviance (oddball versus roving), ITI (long and short) and stimulus type (phonemes versus tone pairs).

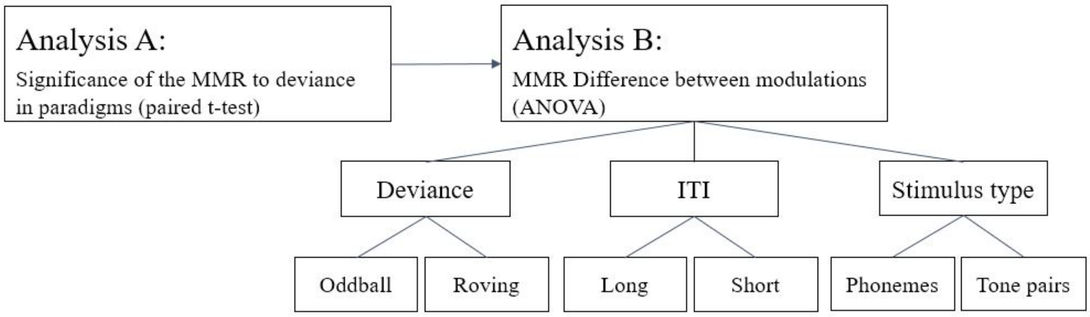

Figure 3.7 Schematic representation of the analysis in Study 1. The detailed structure of a paired t-test in Analysis A is available in Figure 2.10 in General Methods.

3.3 Results

The differential effects of the deviance, ITI and stimulus modulation on the MMR in infants were assessed in the current study. Analyses focused first on establishing the time windows and clusters with the significant MMR onset and amplitude to each of the paradigms. Paired t-test results for MMR in response to deviance in the phoneme oddball, phoneme roving, tone pair long ITI and tone pair short ITI paradigms can be found in Appendix A.

These were followed up with ANOVAs to determine the significance of the absolute MMR difference between manipulations: oddball versus roving deviance, long and short ITI and in the stimulus type modulation: phonemes versus tone pairs. ANOVAs initially included language experience (monolingual versus bilingual) as a between-subject factor and age (corrected for gestation) as a covariate, but these were excluded from the final analyses as they did not significantly affect the manipulations (all $F<3.401$, $p>0.073$). Details on the analysis are provided in section 2.6.2.

3.3.1 Significance of the MMR.

Table 3.1 summarises details on the timing of onset and mean MMR amplitude (as operationalised with 50 ms time windows) in all modulations. Oddball deviance evoked earlier onset and mean MMR amplitude than roving deviance in phonemes. However, tone pairs elicited the MMR earlier than phonemes (as counted from the onset of the deviant tone in the pair). There was no difference in the latencies between the long and short ITI.

Table 3.1

Time Windows with Onset and Mean MMR Amplitude to Deviance in Phoneme and Tone Pair Paradigms

	MMR time windows (50 ms)	
MMR to deviance in:	Onset	Mean MMR amplitude
Phoneme oddball paradigm	300-350 LF	350-400 LF
Phoneme roving paradigm	400-450 LF & RF	400-450 RF
Tone pair long ITI (932 ms) paradigm	400-450 (260-310) LT & RT	450-500 (310-360) RT
Tone pair short ITI (802 ms) paradigm	400-450 (260-310) LT & RT	450-500 (310-360) RT

Note. Where appropriate, numbers in brackets represent time windows after the deviant tone in the tone pair. Abbreviations indicate: LF - left frontal, RT – right frontal, LT – left temporal and RT – right temporal clusters. Paired t-tests the summary is based on are available in Appendix A.

Table 3.2 summarises the MMR mean amplitude results to deviance in the assessed paradigms. Largest MMR positivity was identified in the right temporal cluster to deviance in the short ITI tone pair paradigm. MMR to the oddball phoneme paradigm was identified as the largest frontal MMR negativity. MMR to roving deviance in phonemes also presented frontally, but as a weak positivity.

Table 3.2

MMR at the Onset and the Mean Amplitude to Deviance in Phoneme and Tone Pair Paradigms

	MMR amplitude in μV (averaged into 50 ms time windows)	
MMR to deviance in:	Onset	Mean MMR amplitude
Phoneme oddball paradigm	-1.247 LF	-1.302 LF
Phoneme roving paradigm	1.031 RF	1.031 RF
Tone pair long ITI (932 ms) paradigm	3.931 RT	4.261 RT
Tone pair short ITI (802 ms) paradigm	3.547 RT	4.473 RT

Note. The MMR amplitudes to all contrasts were significant at $p<0.01$. MMR values used in the analyses were absolute, i.e., there were no negative values. Abbreviations indicate: LF - left frontal, RT – right frontal, LT – left temporal and RT – right temporal clusters. Paired t-tests the summary is based on are available in Appendix A.

3.3.2 Deviance modulation.

MMR to both types of deviance was calculated with paired-t-tests (Table A.1 and Table A.2 in Appendix A) followed by ANOVA to identify which deviance elicited the largest absolute mean MMR difference.

MMR to oddball and roving deviance.

Figure 3.8 and Figure 3.9 demonstrate the difference in mean ERP amplitude to deviant minus standard stimuli in both phoneme paradigms. MMR to oddball deviance emerged 300-350 ms after the onset of the stimulus as a negative deflection over the left and positive in the right frontal scalp area. It remained significant until 400-450 ms. MMR to roving deviance presented as positivity across the frontal area within 400-450 ms only.

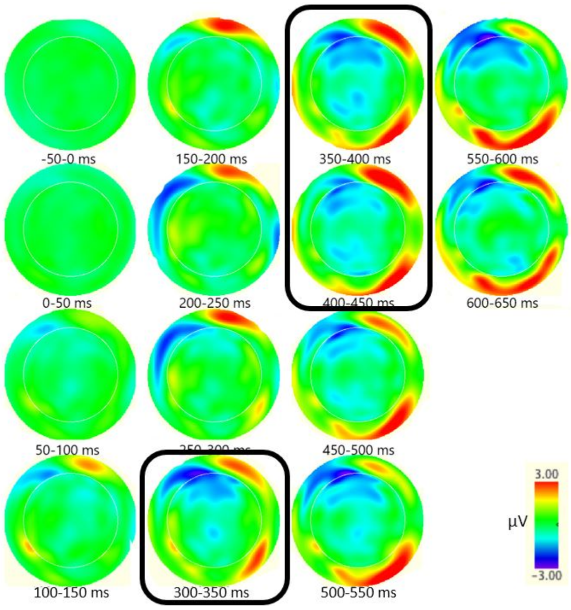

Figure 3.8 Topographic representation of the development of mean MMR amplitude to deviance in the oddball phoneme paradigm. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The encircled time windows indicate significant MMR ($p<0.01$) in the left frontal cluster (channels 19, 20, 23, 24, 27 and 28). See Table A.1 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

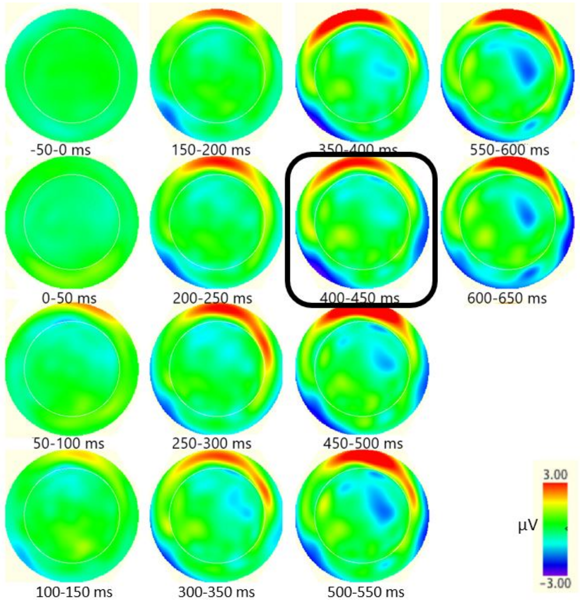

Figure 3.9 Topographic representation of the development of mean MMR amplitude to deviance in the phoneme roving paradigm. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The encircled time window indicates significant MMR (p<0.01) bilaterally in the left (channels 19, 20, 23, 24, 27 and 28) and right frontal clusters (3, 4, 117, 118, 123 and 124). See Table A.2 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

ERPs to oddball and roving deviance were averaged into the left and right frontal and temporal clusters. The grand average ERPs to deviant and standard phonemes in each cluster are presented in Figure 3.10 for the oddball and Figure 3.11 for the roving deviance. Overall, the pattern of activity to both types of deviance was similar. However, the difference between ERPs to deviant and standard was recorded in the left frontal cluster in the oddball modulation while bilaterally across frontal clusters but to a much lesser degree, in the roving paradigm.

Paired t-tests (Table A.1 and Table A.2 in Appendix A) on each 50 ms time window between 100-650 ms within each cluster confirmed the MMR (p<0.01) within 300-450 ms in the left frontal cluster to oddball deviance with the most significant negative deflection within the 350-400 ms. MMR to roving difference presented as MMR negativity within the 400-450 ms time window bilaterally in the left and right frontal clusters. The time windows with significant MMR ($p<0.01$) based on the paired t-tests are highlighted in pink. See also Figure B.1 and B.2 in Appendix B for distribution of the ERPs and the MMR difference waveform in 128-channel scalp topomaps.

GRAND AVERAGE ERPS TO ODDBALL DEVIANCE

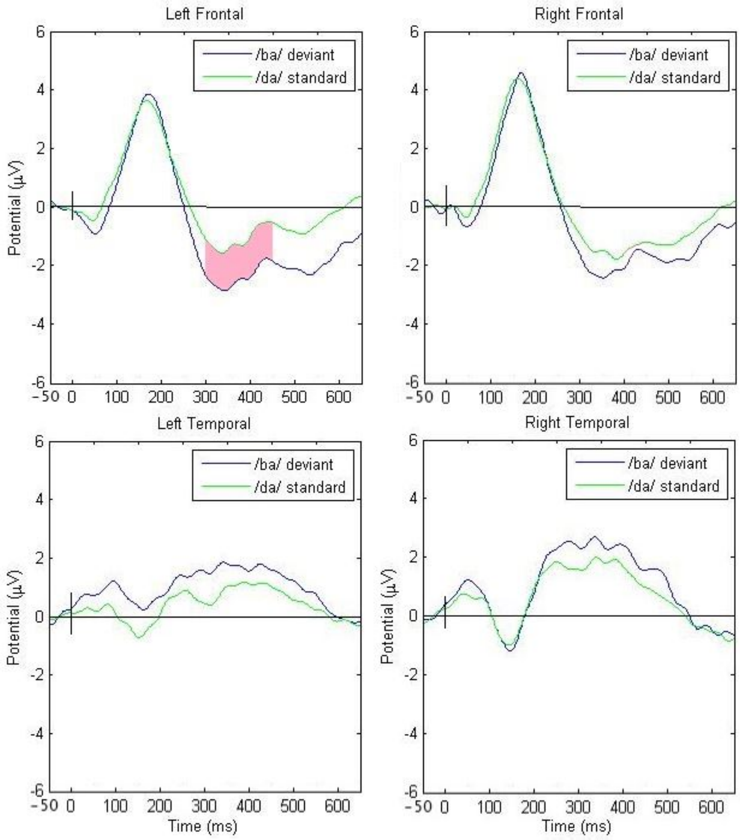

Figure 3.10 Grand average ERP amplitudes to /ba/ deviant (blue line) and /da/ standard phonemes (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) generated to the oddball deviance. Significant mean difference (based on paired t-tests) is highlighted in pink ($p<0.01$). See Table A.1 for t-test results and Figure B.1 for distribution of ERPs across the scalp in EGI 128-channel system.

GRAND AVERAGE ERPS TO ROVING DEVIANCE

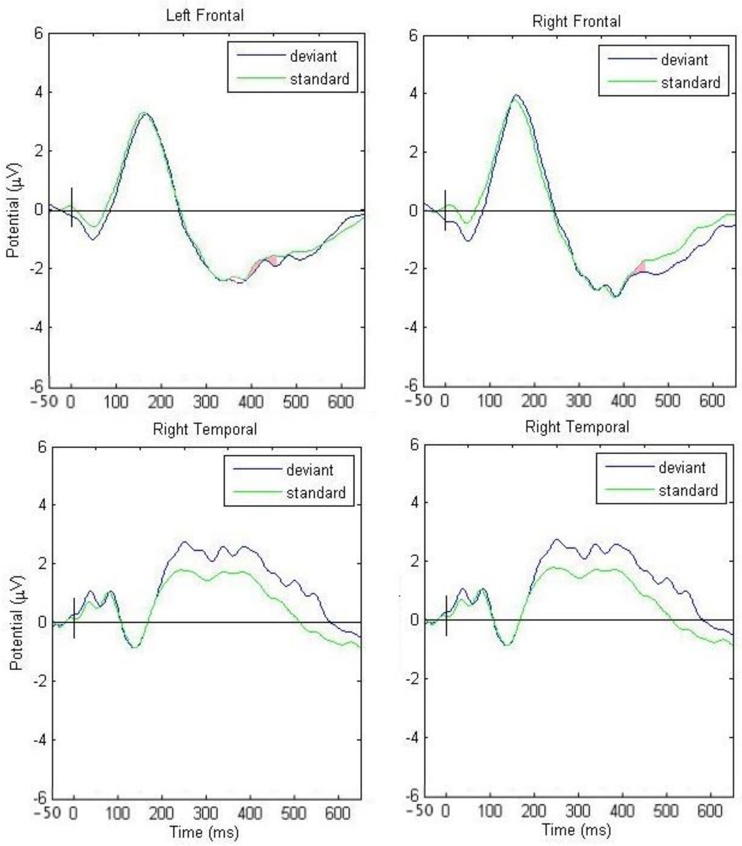

Figure 3.11 Grand average ERP amplitudes to deviant (blue line) and standard phonemes (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) generated to the roving deviance. Significant mean difference (based on paired t-tests) is highlighted in pink ($p<0.01$). See Table A.2 for t-test results and Figure B.2 for distribution of ERPs across the scalp in EGI 128-channel system.

The MMR difference between oddball and roving deviance.

The images of grand average MMR waveforms in the left and right frontal and temporal clusters are provided in Figure 3.12. MMR amplitudes to oddball and roving deviance were close to the baseline in all the clusters except for a single negative deflection to the oddball change in the left frontal cluster. A topographic scalp representation of the difference waveforms in individual channels the grand average images are based on can be found in Figure B.5 in Appendix B.

GRAND AVERAGE MMR TO ODDBALL AND ROVING DEVIANCE

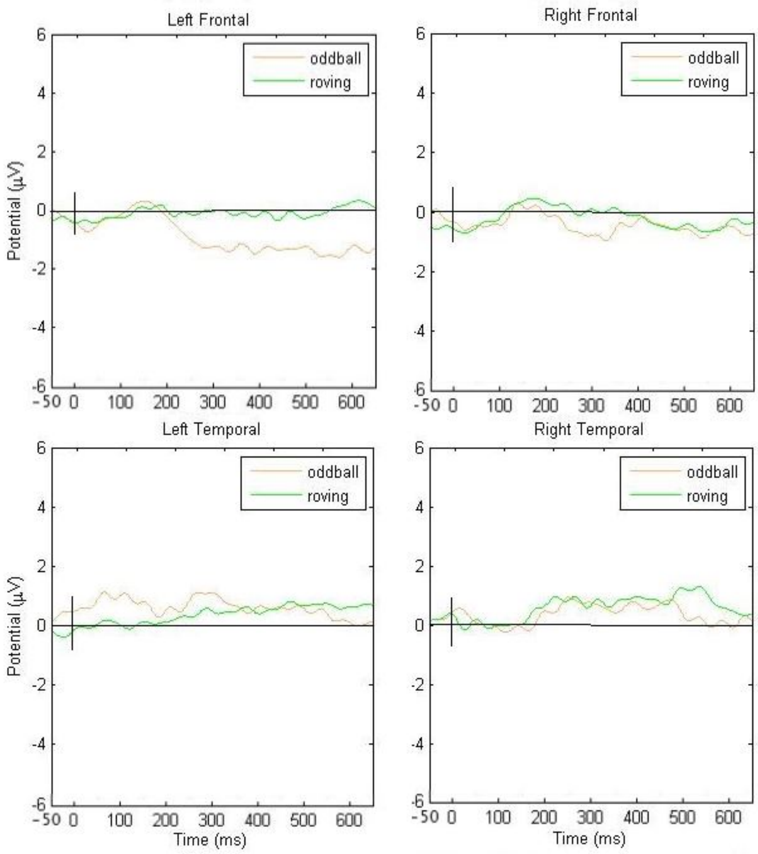

Figure 3.12 Grand average MMR waveforms generated to oddball (orange line) and roving deviance (lime green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in the phoneme paradigms. See Table A.1 and Table A.*2* for mean MMR amplitude values and Figure B.5 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

Based on the onset and mean amplitude of the MMR identified with the paired t-tests to oddball or roving deviance (see Table 3.2 for summary of the results), a repeated-measures three-way ANOVA on the absolute MMR difference in the frontal clusters was carried out. The factors included: deviance (oddball versus roving) x hemisphere (left and right) x time window (300-350 ms, 350-400 ms and 400-450 ms) revealed interaction between deviance and time window, $F_{(1.760,63.364)}$=6.442, p=.004, η^2=0.152.

Post hoc ANOVAs on each time window indicated the more negative MMR to oddball (M=2.444, SD=1.439) than roving deviance (M=1.463, SD=1.156) within the 400-450 ms time window, $F_{(1,36)}$=10.597, p=002, η^2=0.227. No difference was found in the 300-350 and 350-400 ms bins (all F<1.634, p>0.208). Overall, the oddball deviance was shown in the earlier time window and was more negative, widespread, and of longer duration than the MMR to roving deviance.

3.3.3 ITI modulation.

Based on the results in section 3.3.2 above, the oddball deviance was suggested as more reliable than roving. Therefore, this type of deviance was used in all the remaining analyses.

MMR to long and short ITI.

The sample-averaged mean difference between ERPs to deviants and standards in both tone pair paradigms is presented in Figure 3.13 and Figure 3.14.

MMR TO DEVIANCE WITH LONG ITI

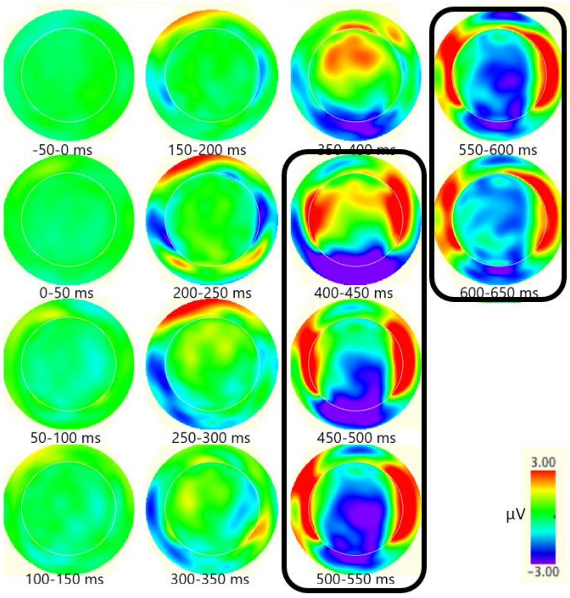

Figure 3.13 Topographic representation of the development of mean MMR amplitude to deviance in the tone pair paradigm with long ITI. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The encircled time windows indicate significant MMR (p<0.01) bilaterally in the left (channels 39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115). See Table A.3 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

Based on the images, the intensity, and the spread of activity of the MMR did not differ between the long and short ITI. Temporal positivity of the MMR emerged in 400-450 ms time window to both trial durations, with the largest absolute mean MMR within 450-550 ms.

MMR TO DEVIANCE WITH SHORT ITI

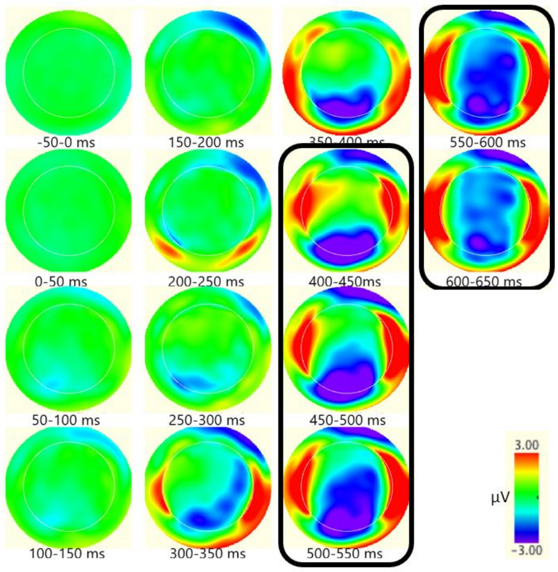

Figure 3.14 Topographic representation of the development of mean MMR amplitude to deviance in the tone pair paradigm with short ITI. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The encircled time windows indicate significant MMR (p<0.01) bilaterally in the left (channels 39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115). See Table A.4 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

Figures 3.15 and 3.16 demonstrate grand-averaged ERPs to deviant and standard tone pairs in the long and short ITI modulations. ERPs to deviant and standard tone pairs were overall similar in both paradigms (see the scalp distribution of individual channels in Figure B.3 and B.4 in Appendix B). MMR was larger across temporal than frontal clusters.

GRAND AVERAGE ERPS TO LONG ITI

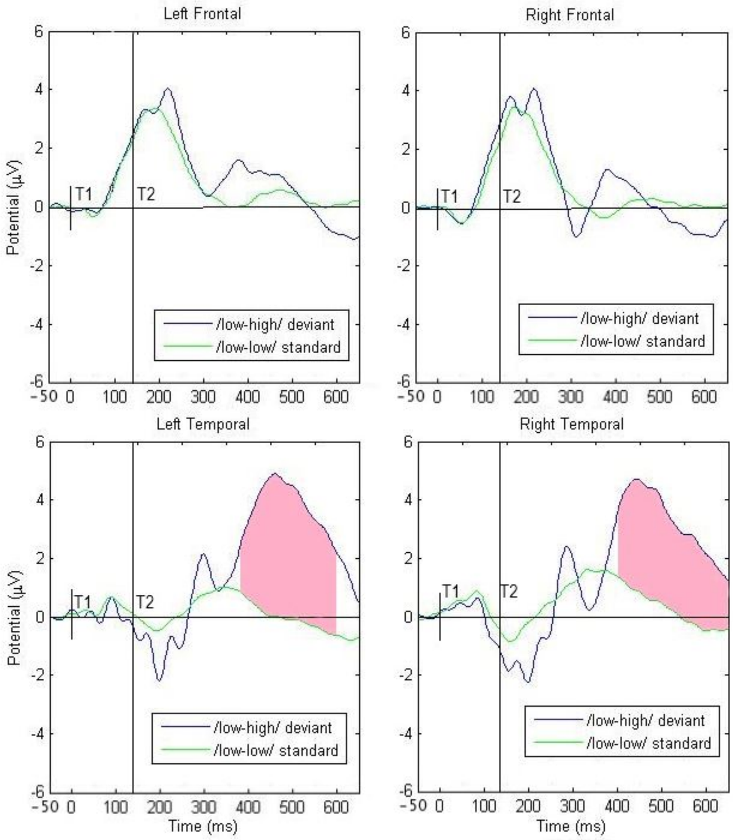

Figure 3.15 Grand average ERP amplitudes to /low-high/ deviant (blue line) and /low-low/ standard tone pairs (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) generated to deviance in the tone pair paradigm with long ITI. T1 and T2 indicate the onset of each tone in the pair. Significant mean difference (based on paired t-tests) is highlighted in pink (p<0.01). See Table A.3 for t-test results and Figure B.3 for distribution of ERPs across the scalp in EGI 128-channel system.

Time windows with significant MMR (p<0.01) were calculated with paired t-tests on each 50 ms time window between 250-650 ms post-stimulus-onset (110-510 after onset of the second tone in the pair) individually in the left and right hemispheres in the front and temporal clusters (see Table 3.1 and 3.2 for summary of the results). Significant positive mean MMR amplitude was found bilaterally in the temporal clusters within 400-650 ms after the onset of the tone pair (260-510 ms after the onset of the second tone in the pair) with largest mean MMR amplitude within 450-500 ms (310-360 ms) to deviance in both ITI modulations.

GRAND AVERAGE ERPS TO SHORT ITI

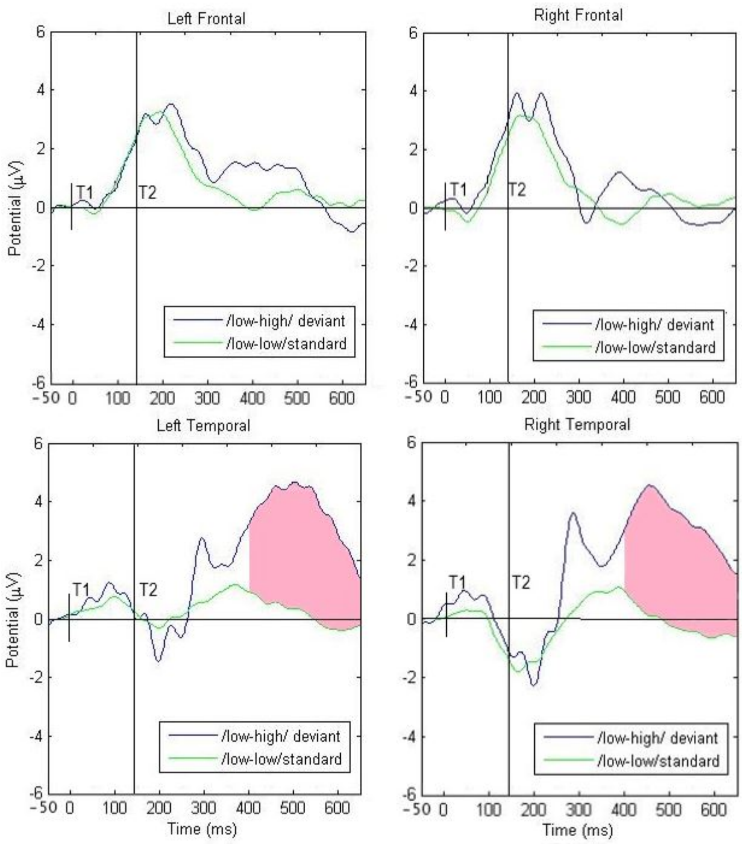

Figure 3.16 Grand average ERP amplitudes to /low-high/ deviant (blue line) and /low-low/ standard tone pairs (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) generated to deviance in the tone pair paradigm with short ITI. T1 and T2 indicate the onset of each tone in the pair. Significant mean difference (based on paired t-tests) is highlighted in pink ($p<0.01$). See Table A.4 for t-test results and Figure B.4 for distribution of ERPs across the scalp in EGI 128-channel system.

The MMR difference between long and short ITI.

Grand average MMR to deviance in the long and short ITI paradigms is represented in Figure 3.17 (see Figure B.6 in Appendix B for the MMR waveforms represented in individual channels on the scalp). The waves in both ITI modulations displayed clear and alike positive MMR deflections in all the clusters.

Based on the time windows with the onset and the largest mean MMR amplitude to deviance in both ITI modulations, a repeated-measures three-way ANOVA was conducted on the absolute MMR values. The factors were: ITI (long versus short) x hemisphere (left versus right) x time window (400-450 and 450-500 ms). However, the analysis did not convey a significant difference between the spatial or temporal distribution of the MMR (all $F<3.205$, $p>0.081$).

MMR WAVEFORMS TO LONG AND SHORT ITI

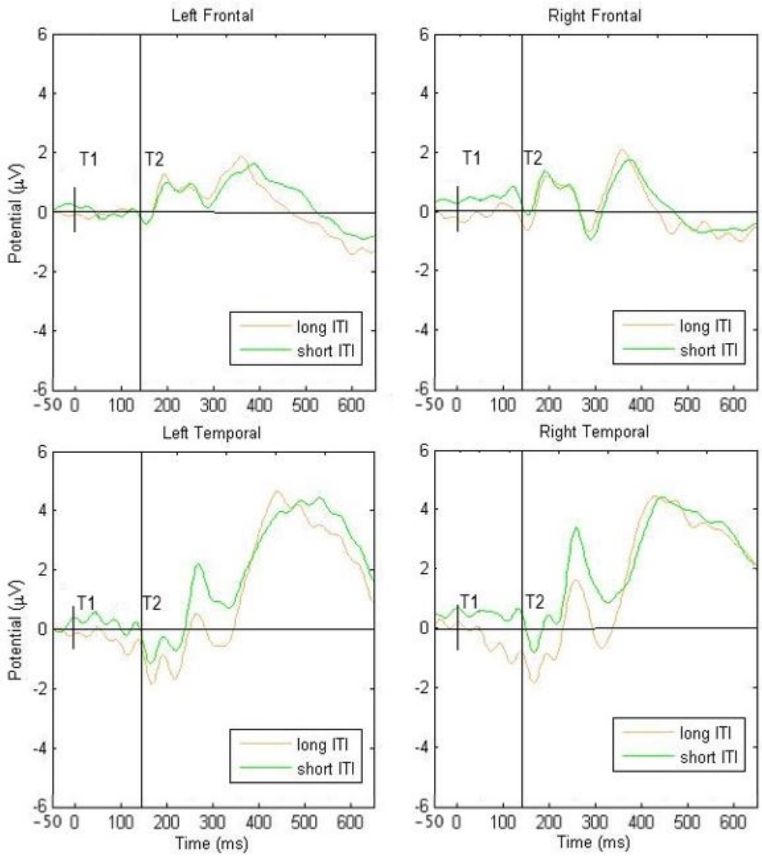

Figure 3.17 Grand average MMR waveforms generated to deviance in long (orange line) and short ITI (lime green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in the tone pair paradigms. See Table A.3 and Table A.4 for mean MMR amplitude values and Figure B.6 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

3.3.4 Stimulus modulation.

Based on the results that the larger mean MMR was detected to oddball than roving deviance in the phoneme paradigms, the phoneme oddball paradigm was selected for the final analysis assessing the stimulus type manipulation (see section 3.3.2). However, there was no significant difference between MMR to long or short ITI in the tone pair paradigms, and either could be potentially employed. The long

ITI tone pair paradigm was chosen due to its established effectiveness in previous research (see section 1.3.5).

Figure 3.18 shows the overall larger positive deflections of the MMR to tone pair rather than phonetic contrast. The MMR difference waveforms originated in the ERPs to deviants and standards in response to oddball deviance in the phoneme paradigm (see Figure 3.10) and the tone pair paradigm with long ITI (Figure 3.15). Distribution of the MMR waveforms across the scalp can be seen in Figure B.7 in Appendix B.

MMR WAVEFORMS TO PHONEMES AND TONE PAIRS

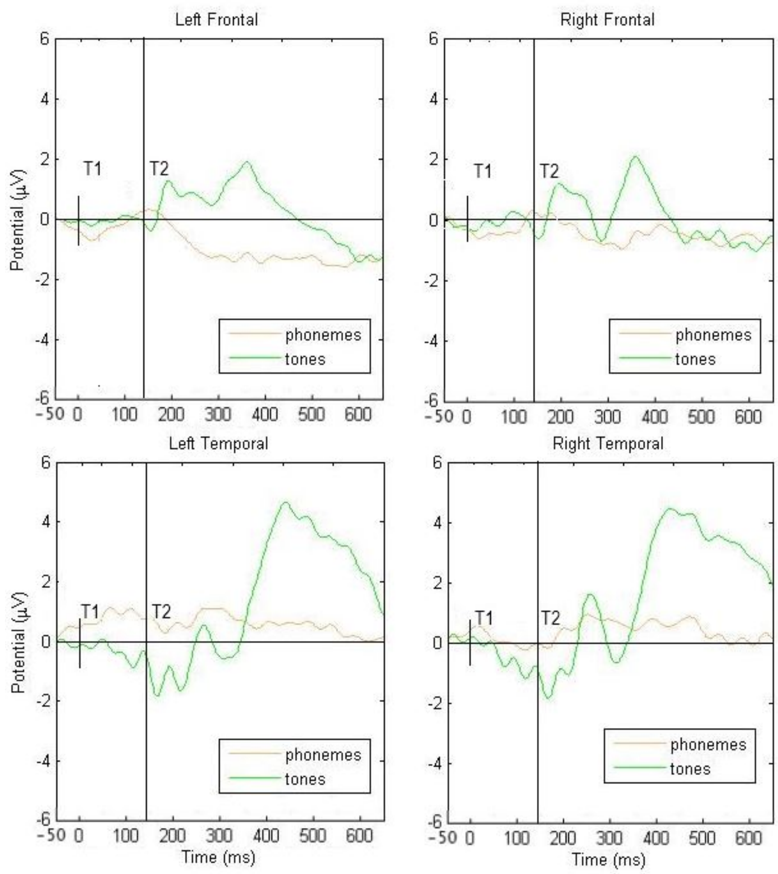

Figure 3.18. Grand average MMR waveforms generated to deviance in phoneme (orange line) and tone pair paradigms (lime green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115). See Table A.1 and Table A.3 for mean MMR amplitude values and Figure B.7 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

The difference between MMR to phonemes and tone pairs was assessed with a repeated-measures ANOVA on the time window with the onset and absolute mean MMR amplitude to deviance in phonemes and the second one on the MMR to tone pairs. The first two-way ANOVA was carried out on the left frontal clusters with factors: stimulus type (phonemes versus tone pairs) x time window (300-350 and 350-400 ms, which related to 160-210 and 210-260 ms after the second tone in the pair). Interaction between the factors ($F_{(1,36)}=7.234$, $p=0.011$, $\eta^2=0.167$) revealed larger MMR to change in the tone pair (M=4.536, SE=0.414) than the phoneme paradigm (M=2.191, SE=0.257) within 350-400 ms. A post hoc t-test confirmed the effect, $t_{(36)}=4.731$, $p<0.001$.

Furthermore, the difference between MMR to deviance in tone pairs was compared to responses to the phoneme paradigm bilaterally in the temporal clusters with 3-way ANOVA with factors: stimulus (phonemes versus tone pairs) x hemisphere (left and right) x time window (400-450 and 450-500 ms). It revealed the main effect of stimulus, $F_{(1,36)}=25.057$, $p<0.001$, $\eta^2=0.410$. Overall, a larger MMR was generated to change in the tone pair (M=4.943, SE=0.468) than phoneme paradigm (M=2.281, SE=0.199). Analyses overall confirmed more significant MMR to deviance in tone pairs than phonemes.

3.3.5 Summary of the results.

Within the phoneme paradigms, oddball generated larger MMR in infants. The effect was significant within 400-450 ms in the left frontal region. The phoneme oddball deviance was selected for the remaining analyses. Within the tone pair paradigms, the long and the short ITI (reduction by 130 ms) produced large but indiscernible MMR bilaterally in the temporal clusters. Therefore, either could be selected for the final comparison. Based on the more extensive research foundations, the long ITI was selected for the final comparison.

As the last analysis, the stimulus modulation was examined. Neural discrimination of the narrowband tonal frequency developed earlier and was consistently more intensive and extensive than of the spectral phonetic change. Tone pairs were confirmed to be more reliable in eliciting the MMR than phonemes, although phonemes produced more lateralised response than tone pairs. Consequently, both would be important to employ in the subsequent studies in the thesis.

3.4 Discussion

The aim of Study 1 was to examine the differential effects of paradigm features such as deviance, trial duration and stimulus type (Choudhury & Benasich, 2011; Choudhury et al., 2007; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Teinonen et al., 2008) on the MMR in infants. Firstly, deviance manipulation revealed the oddball more effective than the roving change in evoking significant MMR (see section 3.3.2), so hypothesis one (H.1.1) was supported. Secondly, while overall large MMR was produced to deviance in tone pairs, it did not render the significant difference between long and short ITI (section 3.3.3), and so hypothesis two (H.1.2) was not supported.

Finally, based on the results from deviance and the ITI modulations, one paradigm from each was selected as the more effective design for the final contrast. As demonstrated above, oddball deviance was considered more advantageous than roving. The difficulty in selecting the more efficient trial duration was that MMR to both manipulations was almost identical. However, due to its established replicability (Arora et al., 2017; Benasich et al., 2002, 2006, 2014, 2016; Cantiani, Riva, et al., 2016; Cantiani, et al., 2016a; Choudhury et al., 2015; Choudhury & Benasich, 2011; Jannesari et al., 2019; Musacchia et al., 2017; Tallal & Gaab, 2006), the long ITI was deemed the more appropriate option. The comparison between the selected stimuli showed differential effects on the MMR (section 3.3.4). Tone pairs (the long ITI paradigm) were confirmed to be the more effective generator of the MMR, as phonemes (the oddball deviance paradigm) produced overall attenuated although significant discrimination. Hypothesis three (H.1.3) was, therefore supported.

3.4.1 Deviance modulation.

The first outcome of the current study was that manipulation of deviance produced discerning results, Namely, the paradigm features of interest did influence MMR in infants. The oddball change was more effective in generating MMR than roving design in the left frontal cluster, suggesting the engagement of adaptation mechanisms in processing the change (Garrido et al., 2009; Rauschecker, 1998a; Schaadt et al., 2014). The overall advantage of the oddball over the roving deviance was similar to the results found by Cowan et al. (1993) and Baldeweg and Hirsch (2015), although their stimuli were tones, not phonemes.

A possible explanation for this finding comes from the global and local processing theory (Denham & Winkler, 2006; Horváth, Czigler, Sussman, & Winkler, 2001; Love, Rouder, & Wisniewski, 1999; Näätänen et al., 2007). The oddball paradigm presumably generated the global memory trace. With repetitions, neurons gradually anticipated that all /da/ are standards and all /ba/ syllables are deviants (Näätänen, Schröger, Karakas, Tervaniemi, & Paavilainen, 1993). This would have led to sensory habituation, i.e., reduced ERPs to standards and increased to deviants, due to violation of the neural expectation.

Responses to the roving design, in contrast, may reflect the local memory trace, due to syllables within a single sequence considered standards and the new phoneme in the following train (/ba/ or /da/ depending on the sequence) a deviant. Such design causes the neural memory trace to reset after each sequence, leading to attenuated expectation bias and reduced habituation to standard sounds. This contrasts with the oddball paradigm, where the MMR is reinforced with each deviant, as it is always the same phoneme, i.e., there is a physical difference between deviant and standard stimuli, and it is constant throughout the paradigm. Indeed, the roving paradigm generated clear development of ERP components to deviants and standards. The attenuated MMR could therefore be the result of reduced habituation to the standard phonemes, not the decreased response to deviants (Angelini et al., 2009; Budd et al., 2013; Carbajal & Malmierca, 2018; Garrido et al., 2008; Nordt, Hoehl, & Weigelt, 2016; Turk-Browne, Scholl, & Chun, 2008).

However, this interpretation should be considered cautiously, since some global memory trace build-up was also possible in the roving paradigm, confounding the effect of deviance, as only two phonemes were interweaving throughout the paradigm and the number of trains was equiprobable (Cowan et al., 1993). Utilising more diverse sequences in both paradigms could lead to more considerable differentiation of the MMR between the manipulations (Angelini et al., 2009) than only in the left frontal cluster, but it would render the paradigms less comparable.

Another source of uncertainty is that the deviance manipulation was explored only within the linguistic stimuli and perhaps employing the non-linguistic sounds would have led to a more distinctive impact on the MMR. Nevertheless, these results corroborate the findings of the previous work on tonal deviance modulation (Baldeweg & Hirsch, 2015; Baldeweg et al., 2002; Cooper et al., 2013; Cowan et al., 1993; Garrido et al., 2008, 2009; Haenschel et al., 2005; Jarkiewicz & Wichniak, 2015; Muenssinger et al., 2013; Rosch et al., 2019).

Although the result was significant, there may be other possible causes for the larger MMR to the oddball than the roving change. Owing to reliance on the local rather than global memory trace, producing grand average MMR may not be the best use of the roving paradigm. Whilst not in the scope of the current study, this type of design might be better utilised to measure the effect of the number of sounds in a sequence on the amplitude and latency of the subsequent MMR (Baldeweg et al., 2003; Baldeweg & Hirsch, 2015; Cooper et al., 2013; Háden et al., 2015b; Haenschel et al., 2005; Jarkiewicz & Wichniak, 2015; Leung et al., 2015) or to assess changes in frequency oscillations during the habituation process (Eulitz & Hannemann, 2010; Kaser et al., 2013) to track development of the MMR across time. This information could also be used to map out the areas and the timeline of activation of the auditory network (Garrido et al., 2008, 2009). Nevertheless, the implication of the finding, based on the deviance modulation, was that the oddball phoneme paradigm was selected for the stimulus comparison in the final analysis.

3.4.2 ITI modulation.

Manipulating the ITI did not show a significant distinction in the MMR or in producing the obligatory ERPs the MMR was based on (Lohvansuu et al., 2013). According to the finding, shorter presentation rate may be as efficient in evoking significant MMR in the tone pair design (Čeponiené et al., 1998; Draganova et al., 2018; Javitt et al., 1998; Sussman et al., 2008; Trainor et al., 2003) as the longer duration of trials (Benasich et al., 2002, 2006, 2014; Cantiani et al., 2016a; Choudhury et al., 2015; Choudhury & Benasich, 2011; Tallal & Gaab, 2006). In support of that, the even shorter 700 ms ITI using the same tone pair design was successful in 6- to 11-year-old children and adults (Choudhury et al., 2015).

It is encouraging to compare the finding on the effect of short ITI in the current study with earlier research into early auditory processing. A number of studies successfully utilised the ITI of 800 ms using a single sound per trial in infants (Čeponiené et al., 2002a; Cheour, Kushnerenko, Čeponiené, Fellman, & Näätänen, 2002; Draganova et al., 2005; Fellman et al., 2004; Guiraud et al., 2011; Kushnerenko et al., 2002b, 2007; Winkler et al., 2003). This is reflected in the current results due to the tone pairs being presumably perceived as single units, not individual sounds (Hoonhorst et al., 2012; Näätänen, 1990; Näätänen et al., 2007; Näätänen & Winkler, 1999; Wang et al., 2005; Yabe et al., 1998, 1997).

As such, reduction of the ITI to 802 ms was perhaps too conservative. Significant MMR has been produced by infants to tones with the ITI as short as 450 to 650 ms (Draganova et al., 2005; He et al., 2009; Jansson-Verkasalo et al., 2010) and as short as 430 ms in phonemes in children (Chaudhury et al., 2016; Chen et al., 2016). Although even shorter 100-250 ms trial durations have been exercised in other studies, those generated significant MMR due to other factors, such as the change in ITI as the dominant feature of the paradigm (Háden et al., 2015a), i.e., mixed ITI design, or stimuli presented as two parallel streams (Winkler et al., 2003 and see section 4.1.1 for more details on stream paradigms).

Nonetheless, the short trial investigated in the current study may be used instead of the long one at little cost to cortical processing and it raises the possibility of shortening the ITI in tone pair paradigm even further in future research. These findings are of importance to developmental research, as too short duration of a single trial may impact the neural processing of sounds (Escera et al., 2000) and the overall length of an EEG paradigm may influence the child's ability to stay calm (Chen et al., 2016), which in turn may affect the number of artefact-free trials.

Still, some uncertainty over the choice of paradigms remains. Contribution of the long ITI paradigm to early language ability has been reliably validated in a number of studies (Benasich et al., 2002, 2006, 2014, 2016; Cantiani et al., 2016a; Choudhury et al., 2015; Choudhury & Benasich, 2011; Tallal & Gaab, 2006), whereas relationship between the short ITI and language ability remains to be assessed. The decision to select the long ITI paradigm for the final analysis was therefore justified, considering that the thesis aims were to identify auditory EEG designs, which elicit MMR and are associated with language development.

3.4.3 Stimulus modulation.

The final result of Study 1 demonstrated the overall advantage of tone pairs over phonemes in producing the MMR. In consistence with the current finding, tone pairs elicited larger MMR than phonemes in adults in studies by Kozou et al. (2004) and Xi and colleagues (2010). This highlighted the advantage of the narrow and distinct tone envelope contrast over the spectral and overlapping frequency of linguistic stimuli in auditory perception. In contrast, Maurer et al. (2003b) found no difference between MMR to phonemes and tones in adults, while MMR amplitude in the typically developing primary school-age children was larger to phonemes than to tones (Sharma et al., 2006). This may, however, reflect increased neural sensitivity to syllables due to learning to read at this age (Shafer et al., 2010) with emphasis on phonics (Tallal, 1980). The reduced MMR to phonemes in children with reading difficulty supports this claim (Leppänen et al., 1999; Maurer, Bucher, Brem, & Brandeis, 2003a; Sharma et al., 2006).

Under certain conditions, however, even adults produce larger MMR to speech than nonspeech sounds (Jacobsen, Schroger, & Alter, 2004; Jacobsen, Schröger, et al., 2004; Kuuluvainen et al., 2014). Vowel and consonant discrimination in phonemes have the advantage when linguistic and non-linguistic sounds are matched on the frequency and spectral envelope. Early processing mechanisms may be playing role here, as neonates and young infants have the ability to discriminate vowels (Benavides-Varela, Hochmann, Macagno, Nespor, & Mehler, 2012; Cheng et al., 2015; Cheour-Luhtanen et al., 1995; Cheour et al., 1997, 1998; Kuhl, 1983; Martynova et al., 2003; Shafer, Yu, & Garrido-Nag, 2012; Tsuji & Cristia, 2014; Wanrooij, Boersma, & van Zuijen, 2014; Werner, 2013) and consonants (Guttorm et al., 2010, 2005; Key et al., 2007; Mersad & Dehaene-Lambertz, 2016).

However, when the sounds are not matched, as it happens in a natural auditory scene, the narrowband contrast in tones (Čeponiené et al., 2002a; Háden, Németh, Török, & Winkler, 2016; Kushnerenko et al., 2007) has the advantage over the spectral phonetic contrast, as demonstrated in a study by Zatorre and colleagues (2002). Moreover, frequency has been reported to produce larger MMR than other stimulus parameters when modulated within the speech sounds. See also Gilley et al. (2017) for frequency oscillations to speech and nonspeech stimuli in infants and other reports (Celsis et al., 1999; Molholm et al., 2014) on the stimulus-specific regions within the temporal cortex in adults.

One unanticipated finding was that although overall MMR to tone pairs was more extensive than to phonemes both in the frontal and temporal clusters, spatial and temporal distribution of the linguistic and non-linguistic MMR was also quite distinctive. Negative MMR amplitude was recorded in the left frontal cluster to consonant change, whereas tonal frequency discrimination had positive deflection and was significantly larger bilaterally over the temporal clusters.

There is some evidence for differences in lateralisation of responses to speech and nonspeech stimuli, particularly in rapidly changing auditory designs, not unlike the current paradigms (Belin et al., 1998; Luo et al., 2006; Molholm et al., 2014; Scott, 2000; Shultz, Vouloumanos, Bennett, & Pelphrey, 2014; Vouloumanos et al., 2001). Other studies report bilateral activation for both types of sounds, but within distinctive, stimulus-specific areas (Alho et al., 2014; Altvater-Mackensen & Grossmann, 2018; Deike, Scheich, & Brechmann, 2010; Gervain, Macagno, Cogoi, Peña, & Mehler, 2008; Hall et al., 2005; Hall, Hart, & Johnsrude, 2003). Caution should thus be exercised in interpreting the result, given how diverse and complex mechanisms of acoustic change can be (Scott & Wise, 2004; Werner, 2012).

Admittedly, additional factors may have contributed to the MMR difference between the phoneme and tone pair paradigms. The first consideration was that whilst each phoneme was played individually within a trial, the tones were presented in pairs. However, the overall duration of both stimuli was similar, i.e., phonemes continued for 200 ms while the tone pair duration was 210 ms. The second distinction was that deviance in phonemes was represented by 50 ms formant transition between /ba/ and /da/ by approximately 200 Hz. Still, this was reflected in tone pairs by an increase in frequency by 200 Hz in the second tone in the deviant pair. It could be argued, therefore, that the stimuli were relatively comparable, although this was not the objective of the study.

3.4.4 Conclusion.

The key objectives of Study 1 were to assess the specific features of auditory paradigms and to identify designs which generate large MMR in infants. The investigation of deviance modulation has shown that oddball was more efficient in producing MMR than roving design. The second major finding was that 933 and 802 ms trial duration were just as effective in evoking significant MMR and so both could be used in infant research without impacting the neural processing. The decision was, however, made to use the long ITI paradigm for the final analysis to ensure consistency with past research. A systematic comparison between the oddball phoneme and the long ITI tone pair paradigm indicated that a tonal change was more reliable in producing MMR across the scalp, whilst the consonant change in phonemes triggered more variable across scalp although attenuated response.

Consequently, the plausible speculation would be that the optimal auditory paradigm should consist of oddball deviance with the trial presentation rate between 802-932 ms. The stimulus type would, however, depend on the evoked response it is expected to produce. Tone pairs would be preferable when the large MMR deflections or the large distribution of activation across the scalp is the priority. In contrast, when assessing the spatial and temporal variability of the auditory and specifically linguistic MMR, phonemes would be more advantageous. In sum, Study 1 highlights the importance of careful feature selection and parameter calibration of the paradigms to ensure the optimal settings for the development of the MMR in infants. This may be of interest to developmental neuroscientists and neurolinguists designing EEG paradigms investigating the MMR and other neural correlates of the auditory and specifically language development.

Chapter 4. Study 2 – The effect of stream modulation on the MMR in infants.

4.1 Introduction

Much of the developmental research up to now has focused on the infants' abilities to process acoustic contrast against a silent background (Benasich et al., 2002, 2014; Cantiani et al., 2016b; Čeponiené et al., 2002a; Cheng et al., 2013; Cheour et al., 1998b, 2002; Choudhury & Benasich, 2011; Conboy, Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2014; Draganova et al., 2005; Fellman & Huotilainen, 2006; Friederici et al., 2002; Guiraud et al., 2011; Háden et al., 2016; Heim et al., 2013; Kostilainen et al., 2018; Kushnerenko et al., 2002a, 2002b, 2007, 2013a, 2013b, 2013c; Leipälä, Partanen, Kushnerenko, Huotilainen, & Fellman, 2011; Marshall, Reeb, & Fox, 2009; Musacchia et al., 2013; Ortiz-Mantilla et al., 2012, 2016; Partanen et al., 2013; Strotseva-Feinschmidt et al., 2015; Van Den Heuvel et al., 2015; Virtala et al., 2013; Wanrooij et al., 2014; Wass et al., 2018; Zhao & Kuhl, 2016), which is not the case in natural auditory scene.

Conversely, infants are exposed to speech and other relevant sounds among various auditory noise, such as toys with attractive sounds, TV, music, or conversations in the background. Few studies have attempted to solve this conundrum, by presenting infants with the target and distractor stimuli, in which they have been reported to ignore irrelevant sounds and process targets if they are sufficiently distinctive from one another (Barker & Newman, 2004; Hollich, Newman, & Jusczyk, 2005; Kushnerenko et al., 2007; Newman, Morini, & Chatterjee, 2013; Smith & Trainor, 2011; Teinonen et al., 2009).

4.1.1 Streaming and its effect on the MMR in infants.

The ability to discriminate streams of sounds depends on the degree of frequency separation between the stimuli (Bregman, 1978; Bregman & Campbell, 1971). Researchers assessed the capacity to process change in a streaming paradigm in 9-12 years old children and adults (Sussman & Steinschneider, 2009). While adult discrimination threshold was lower than in children, both age groups were unable to process auditory change if the difference was below 84 Hz, (children did not perceive both streams separately if the difference in frequency of tones was 183 Hz). By contrast, they appeared to perceive two streams behaviourally and through electrophysiological activity (in the attended condition) if the difference was higher than 294 Hz. Considering that tones are narrowband sounds, they may be easier to discriminate than spectral phonemes.

Although processing of competing streams has been studied in adults (Binder, 2000; Bregman, 1990, 2010, 2015; Bressler et al., 2014; Carlyon, 2004; Celsis et al., 1999; Iverson, 1992; Luo, Husain, Horwitz, & Poeppel, 2005; Nager et al., 2003; Pressnitzer, Sayles, Micheyl, & Winter, 2008; Sorokin et al., 2010; Sussman, 2004; Sussman et al., 1999; Vliegen & Oxenham, 1999; Vouloumanos et al., 2001; Yoncheva, Maurer, Zevin, & McCandliss, 2014; Zaehle, Geiser, Alter, Jancke, & Meyer, 2008), and to some extent in children (Goswami et al., 2011; Sanders et al., 2006; Sussman et al., 2001, 2015; Sussman & Steinschneider, 2009) investigating auditory discrimination in complex auditory scene in infants has been challenging (Cheour et al., 2004; Hoehl & Wahl, 2012; and see section 1.3.5 for examples on behavioural measures of infants' perception).

To address the issue of streaming in early development, Winkler et al. (2003) presented newborns with a standard oddball and two streaming paradigms. In the control condition, tones were presented with intensity oddball within 1813 Hz tones. The second, streaming paradigm consisted of the control oddball high-frequency stream, while in the second stream, low-frequency tones were equiprobable and fluctuating between 250 and 300 Hz. In the final streaming paradigm, the high-frequency tones with an oddball change were accompanied by the low-frequency stream with deviance represented by increasing versus decreasing frequency between 250 and 300 Hz. Infants produced MMR to the oddball change in all conditions, but its incline was less pronounced in the streaming than in the control paradigm. Nevertheless, the findings indicated that newborns were able to separate the two streams, process change in one of them and either ignore or process the other. Unfortunately, MMR to the low-frequency stream was not reported, so the ability to process change in two competing streams was not assessed.

Others have reported that newborns selectively discriminate frequency deviance in a stream, even in the presence of a salient distractor, such as white noise (Kushnerenko et al., 2007, 2013c; Micheyl, Hanson, Demany, Oxenham, & Shamma, 2013; Smith & Trainor, 2011). Furthermore, older infants process target sounds even if they are masked with background noise (Newman et al., 2013; Polka, Rvachew, & Molnar, 2008; Schneider, Trehub, & Bull, 1979; Schneider et al., 1989).

Section 1.1.1 outlines the theory of auditory scene analysis and demonstrates attempts to assess stream segregation in infants. Overall, despite the increasing interest in the early development of perception of the auditory scene (Snyder & Alain, 2007), little is known about neural correlates of processing competing sounds in the auditory environment in infants.

4.1.2 Stimulus type and its effect on the MMR in infants.

In a natural auditory scene, speech and other relevant sounds are rarely isolated, and so listeners must separate them from the background noise. Research shows that adults can differentiate speech from other environmental sounds (Binder, 2000; Celsis et al., 1999). MMR differences in processing phonemes /da/ and /ba/ and tones of 700 and 770 Hz frequency in a block design were found in 8-11-year-olds (Lachmann et al., 2005). Although there was a difference between dyslexic and typically developing children, both groups generated larger MMR to deviance in tones than to phonemes.

Similar findings were reported by Zhao and Kuhl (2016) who assessed the effect of music training in 9-month-old infants on the ability to process change in speech and nonspeech sounds, measured by magnetoencephalography (MEG). Infants in the intervention group increased their sensitivity to acoustic change in tones and syllables in the temporal area (although magnetic MMR was larger overall for speech than tones), but only tones increased activity in the prefrontal cortex, although overall magnetic MMR to phonemes in the intervention and control groups was as large as to tones. The data resembled findings by Putkinen, Tervaniemi and Huotilainen (2013) in 2- to 3-year-old children exposed to music at home.

In contrast, in dichotic listening studies, when children were instructed to listen to a story in one ear and ignore the other, linguistic stimuli on the unattended side provided more considerable interference than non-linguistic probes in children at 10 years and younger (Karns et al., 2015; Sanders et al., 2006).

Furthermore, three-month-old infants preferred looking towards speech than to other environmental sounds, in research by Shultz and colleagues (Shultz & Vouloumanos, 2010; Shultz et al., 2014). Infants from English-speaking families were presented with Japanese words, plus non-speech human vocalisations, such as a sneeze or a yawn, rhesus monkeys vocalisations (e.g., grunts and coos) and environmental sounds such as breaking the glass and running water. With the preference looking method in eye tracking, the researchers recorded longer fixations towards the screen during speech than noncommunicative human and monkey vocalisations and environmental sounds. Polka et al. (2008) found the same effect for speech versus bird song.

In fact, various auditory studies in early language development claim their results support language preference both at the behavioural (Marcus, Vijayan, Bandi Rao, & Vishton, 1999; Morse, 1972; Shultz & Vouloumanos, 2010; Smith & Trainor, 2011) and neural level (Gervain et al., 2008; Polka et al., 2008). However, most do not compare responses to speech versus nonspeech auditory stimuli, and in those that somehow address this issue, the nonspeech stimuli are presented as background noise rather than equally relevant stimuli (Molfese & Molfese, 1985). No study to date has systematically investigated whether infants process speech among non-speech sounds. Therefore, the current study aimed to examine infants' ability to process competing deviances in either or both of two alternating streams: a phoneme and a tone pair stream.

4.1.3 Rationale for the study.

The purpose of Study 2 was to investigate MMR in a complex auditory scene in infants. In order to do so, the stream and stimulus modulations and their effects on the MMR were examined. The paradigms employed in the study consisted of the phoneme oddball and the long ITI tone pair paradigms developed in Study 1. They were treated as control paradigms. The third streaming paradigm was new and comprised phoneme and tone pair streams, which were the control paradigms plotted alternately in streaming design. The paradigm represented two competing contrasts embedded in the linguistic and non-linguistic streams. The ability to process contrast in one of the streams indicated stream segregation, whereas discriminating both contrasts signified processing both of the competing streams independently.

4.1.4 Experimental predictions.

In line with previous literature, the stream modulation was expected to influence the temporal and spatial distribution of the MMR (H.2.1). This would explicitly relate to the phoneme stream in streaming paradigm, versus phoneme paradigm and tone pair stream in the streaming paradigm versus the tone pair paradigm. Moreover, consistently with the findings in Study 1, stimulus type was expected to have a differential effect on the temporal and spatial distribution of the MMR in infants (H 2.2). Specifically, MMR would be affected by deviance in phonemes and tone pairs in the streaming and the control phoneme and tone pair paradigms.

4.2 Methods

The general methodology is presented in Chapter 2. Any changes or further methodology for Study 2 are provided below.

4.2.1 Participants.

Forty-three infants participated in the study. However, three participants did not complete at least one of the paradigms due to fussiness and were excluded from the sample. The final sample included 40 infants (19 males). Their ages ranged between 5-11 months (159 and 337 days), M=7.30 SD=1.52 months (M=236, SD=46 days). The infants were born at term, M=9.13, SD=0.36, between 8-9 months of gestation (M=278, SD=11 days, range 253-294 days). Infants' ethnicity was predominantly Caucasian – 25 participants, the remainder was of Asian – 4, Afro-Caribbean – 4 and mixed ethnicity – 7.

Twenty-eight infants were monolingual, and the remaining 12 were exposed to at least one other language than English at home. Household income of the thirty-five families who agreed to disclose the value, ranged between £7,200 and £239,200 with mean of £69,996 (SD=£49,097), indicating wide socioeconomic background. Maternal qualification included 2 parents holding A-Levels, 16 mothers had a first degree, 4 had a master's degree, and 1 parent acquired a doctoral level qualification, signifying the overall higher educational status of the families in the sample.

4.2.2 Design.

It was a within-participants design. There were two experimental paradigms: the streaming paradigm and phoneme and tone pair paradigms, which were the same as the phoneme oddball and the long ITI tone pair paradigm in Study 1 and so were treated as control (see section 3.2.3). Figure 4.1 demonstrates the two manipulations used in Study 2.

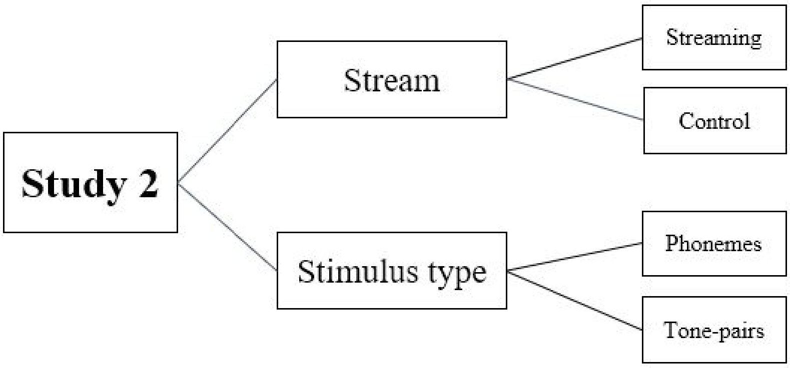

Figure 4.1 Schematic representation of modulations in Study 2.

The stream modulation.

The manipulation was designed to investigate the differential effect of the number of streams in a paradigm on the MMR in infants. The two control paradigms consisted of the phoneme oddball paradigm and the tone pair paradigm with the long trial duration. They were selected for Study 2 based on their reliability to evoke large MMR in Study 1 (see the results in section 3.3). Each of the control paradigms contained one type of deviance.

Stimulus type modulation.

The effect of phonetic (phonemes /ba/ and /da/) and tonal (tone pairs of 100-100 Hz and 100-300 Hz frequency) contrasts on the MMR was examined both in the control design (in the same manner as in Study 1, see section 3.2.2 and in the streaming paradigm.

4.2.3 Stimuli and apparatus.

The tasks used in Study 2 were three EEG paradigms, two of which consisted of a single stream: the phoneme and tone pair paradigms. They had been developed in Study 1 and were treated as a control in the current study. The third paradigm combined the two types of sounds in a streaming design. Section 2.4.1 in

General Methods provides general information on the phoneme oddball and the long ITI tone pair paradigms, while detailed description is enclosed in section 3.2.3. Any deviations or information relevant specifically for Study 2 are presented below.

The control paradigms.

The phoneme and tone pair paradigms, selected in Study 1 due to their reliability in producing large MMR deflections, included the phoneme oddball deviance and the long ITI duration (see section 3.2.3). Consequently, the control paradigms in Study 2 included oddball deviance and longer trial duration.

Streaming paradigm.

It was designed to examine the effect of streaming, i.e., one or two streams in a paradigm on the MMR in children. The two control paradigms consisted of the phoneme oddball paradigm and the tone pair paradigm with the long trial duration. They were selected for Study 2 based on the findings in Study 1 in infants (see section 3.3.4 for MMR results in the phoneme oddball and long ITI tone pair paradigms). Each of the control paradigms comprised a single stream of sounds with one type of oddball deviance.

The streaming paradigm was a combination of the control phoneme and tone pair paradigms, plotted alternately by the stimulus type (phoneme, tone pair, phoneme, tone pair, and so on) while retaining the pseudorandomised order of deviants and standards within each stream. Each of the streams therefore contained separate deviance. Significant MMR to one of the streams would infer stream segregation whilst MMR to both deviances signified that both competing streams were processed. Section 3.2.3 in General Methods provides general information on its design, which is also relevant for Study 5 in children (section 7.2.3).

Overall, there were two differences between the tone pair and the phoneme streams. The first one was that tones were presented in pairs while a single phoneme comprised one trial. However, the overall duration of both stimuli was similar, i.e., the tone pair duration (including 70 ms pause between them) was 210 ms, whilst the phoneme duration was 200 ms. Secondly, oddball change in tone pairs was a change of frequency by 200 Hz in the second tone in the deviant pair, while in the phoneme task the change was spectral, that is the first formant of phonemes /ba/ and /da/ differed. Other dimensions remained constant. Although not strictly identical, they were chosen as exemplary paradigms generating large mean MMR amplitude. Figure 4.2 demonstrates the alternating sequence of the linguistic and non-linguistic stimuli in the streaming paradigm.

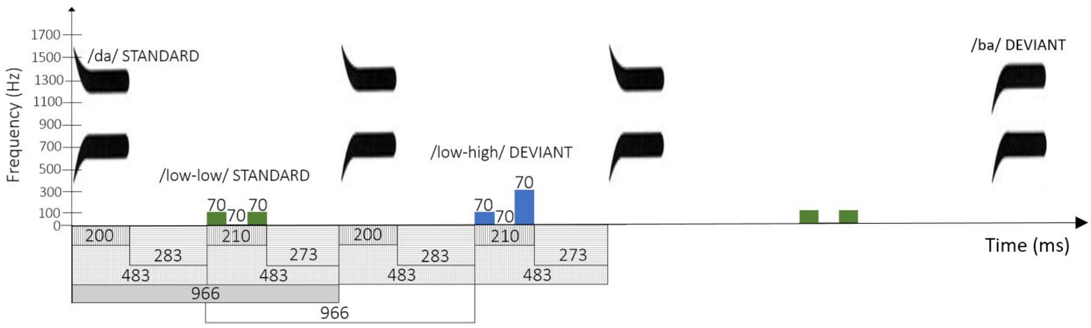

Figure 4.2 Schematic representation of a trial sequence in the streaming paradigm. The phonetic frequency distribution (the black thick horizontal double lines) represent /ba/ deviant and /da/ standard. The /low-high/ deviant (blue bars) and /low-low/ standard (green bars) tone pairs are labelled accordingly.

4.2.4 Procedure.

The full procedure is outlined in section 2.5 in General Methods. Any information specific to Study 2 is presented here. All three EEG paradigms were performed during the session. The streaming paradigm was administered first. It was followed by the control phoneme and tone pair paradigms, the order of which was counterbalanced across the participants. Each task continued for 6 minutes. Figure 4.3 illustrates the procedural timeline for Study 2. EEG data were collected with

HGSN 128-channel saline sensor net and recorded with EGI Net Station 5.2.0.2 software. Details on the EEG data recording are outlined in section 2.5.1.

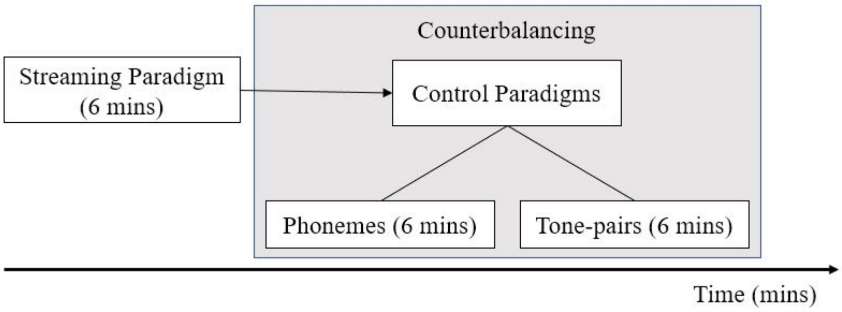

Figure 4.3 Schematic representation of the procedure in Study 2. The streaming paradigm was presented as first. Order of the following phoneme and tone pair paradigms was counterbalanced. An example is presented in the timeline with the duration of each paradigm in brackets.

4.2.5 ERP data processing and analysis.

Processing EEG data.

Section 2.6.1 in General Methods demonstrates details on the EEG data processing and analysis. Any details explicitly related to the current study are included below.

EEG data were processed with EGI Net Station 5.2.0.2 software (EGI, Eugene, OR). Following artefact rejection, the average percentage of trials for each infant accepted for further analysis was 95% (M=66.24; range: 56-70 trials) for /ba/ and /low-high/ deviant and 95% (M=265.23; range: 222-280 trials) /da/ and /low-low/ standard stimuli.

Analysis strategy.

General information on the analysis strategy is outlined in section 2.6.2. All details relevant only to Study 2 are presented below. Figure 4.4 shows a breakdown of the analytic approach into stage A and B. Analysis A represents establishing the significant MMR to each of the paradigms. Analysis B illustrates the comparison between time windows with the onset and amplitude of the MMR to each modulation: linguistic stream (deviance in phoneme paradigm versus deviance in phoneme stream in the streaming paradigm), non-linguistic stream (tone paradigms versus tone pair stream in the streaming paradigm), stimulus type within streaming (phonemes versus tone pair streams in the steaming paradigm) and stimulus type in control paradigms (phoneme versus tone pair paradigm).

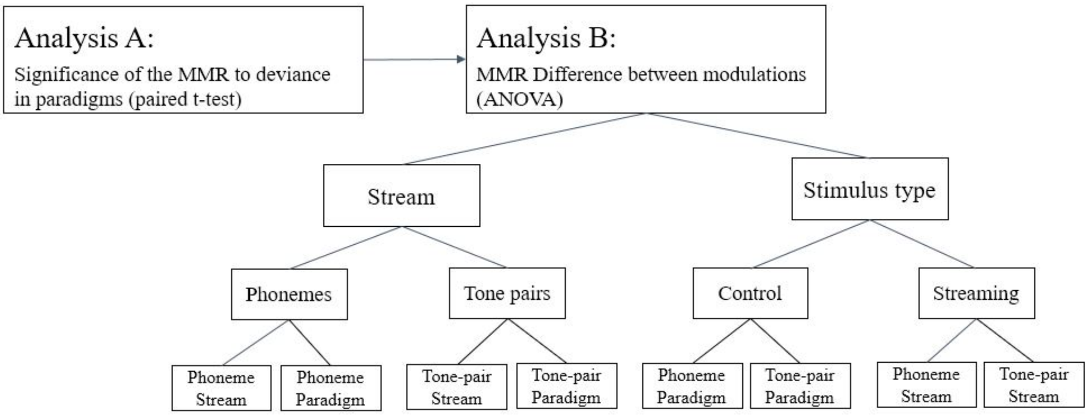

Figure 4.4 Schematic representation of analyses in Study 2. The detailed structure of a paired t-test in Analysis A is available in Figure 2.10.

4.3 Results

The purpose of Study 2 was to assess the effects of stream and stimulus modulation on the MMR to deviance in the control phoneme and tone pair paradigms and in phoneme and tone pair streams in the streaming paradigm in infants. Analyses focused first on establishing the time windows and clusters with the significant MMR onset and amplitude to each of the contrasts. Paired t-test results for MMR in response to phonetic and tone pair contrasts within streaming and control phoneme and tone pair paradigms can be found in Appendix C.

These were followed up with ANOVAs to determine the significance of the MMR difference between manipulations: stream (control single versus double stream in streaming) and stimulus (phonemes versus tone pairs). The first involved

MMR comparisons in response to stream manipulations within linguistic (deviance in phoneme stream within the streaming paradigm and in the control phoneme paradigm) and non-linguistic stimuli (deviance in tone pair stream within the streaming paradigm and in the control tone pair paradigm). The latter investigated MMR in response to stimulus modulations within streaming (deviance in phoneme and tone pair streams) and control single stream paradigms (deviance in the control phoneme and tone pair paradigms).

ANOVAs additionally included language experience (monolingual versus bilingual) as a between-subject factor and age (corrected for gestation) as a covariate, but these were excluded from the final analyses as they did not affect the relationship between manipulations (all $F<3.836$, $p>0.057$).

4.3.1 Significance of the MMR.

Table 4.1 summarises details on the timing of onset and mean MMR amplitude (as operationalised with 50 ms time windows) in all paradigms. Tone pairs elicited earlier onset and mean amplitude of the MMR than phonemes (as counted from the onset of the deviant tone in the pair). Whereas MMR to deviance in tone pair stream in the streaming paradigm was recorded frontally, deviance in the other modulations elicited the MMR in the temporal clusters.

Table 4.1

Time Windows with Onset and Mean MMR Amplitude to Deviances in the Streaming and Control Paradigms

	MMR time windows (50 ms time windows)	
MMR to deviance in:	Onset	Time of mean MMR amplitude
Phoneme stream in streaming paradigm	250-300 RT	350-400 LT & RT
Tone pair stream in streaming paradigm	250-300 (110-160) LF & RF	300-350 (160-210) LF, RF & TR
Phoneme paradigm	Not significant	Not significant
Tone pair paradigm	300-350 (160-210) RT	500-550 (360-410) LT & RT

Note. Where relevant, numbers in brackets represent time windows after the deviant tone in the tone pair. Abbreviations indicate: LF - left frontal, RT – right frontal, LT – left temporal and RT – right temporal clusters. Paired t-tests the summary is based on are available in Appendix C.

Table 4.2 summarises the MMR mean amplitude results to deviance in the assessed paradigms. All paradigms elicited positive MMR with the largest mean MMR amplitude to the tone pair paradigm. Phoneme and tone pair streams in the streaming paradigm evoked comparable responses. In contrast, deviance in the phoneme paradigm did not evoke a significant MMR.

Table 4.2

MMR at the Onset and the Mean Amplitude to Deviances in the Streaming and Control Paradigms

	MMR amplitude in μV (averaged into 50 ms time windows)	
MMR to deviance in:	Onset	Mean MMR amplitude
Phoneme stream in streaming paradigm	1.939 RT	2.142 LT
Tone pair stream in streaming paradigm	1.698 LF	2.199 LF
Phoneme paradigm	Not significant	Not significant
Tone pair paradigm	1.823 RT	4.454 RT

Note. The MMR amplitudes to all contrasts were significant at $p<0.01$. MMR values used in the analyses were absolute, i.e., there were no negative values Abbreviations indicate: LF - left frontal, RT – right frontal, LT – left temporal and RT – right temporal clusters. Paired t-tests the summary is based on are available in Appendix C.

4.3.2 The stream modulation.

The differential effects of stream modulation on the spatial and temporal distribution of the MMR in infants were assessed by employing oddball deviance in phonemes and tone pairs both in the streaming and control paradigms.

Stream modulation in phonemes.

MMR to deviance in phonemes. The series of topomaps below illustrate grand average mean differences between ERPs to /ba/ deviant and /da/ standard phonemes in the control and streaming paradigms. Figure 4.5 represents MMR to phonetic contrast within the streaming paradigm. It emerged within 250-300 ms and reached mean MMR amplitude at the end of the epoch within 350-450 ms. On the contrary, no MMR could be distinguished throughout the epoch in the phoneme paradigm (Figure 4.6).

MMR TO DEVIANCE IN PHONEME STREAM

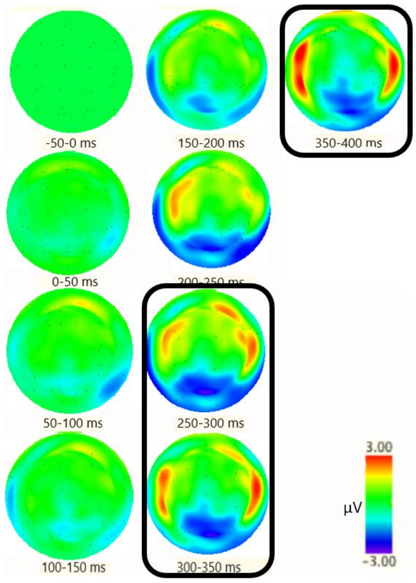

Figure 4.5 Topographic representation of the development of mean MMR amplitude to deviance in the phoneme stream in the streaming paradigm. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The encircled time windows indicate significant MMR ($p<0.01$) bilaterally in the left (channels 39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115). See Table C.1 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

MMR TO DEVIANCE IN PHONEME PARADIGM

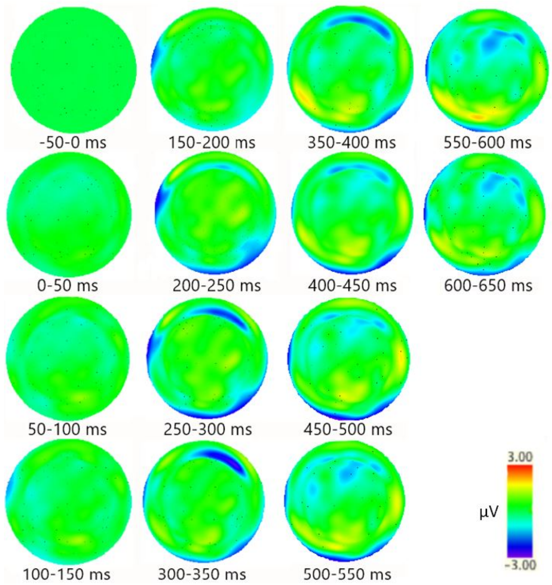

Figure 4.6 Topographic representation of the development of mean MMR amplitude to deviance in the phoneme paradigm. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts. No significant MMR was identified throughout the epoch. See Table C.3 for t-test results.

ERPs to the consonant change within the streaming and control paradigms were averaged to the left and right frontal and temporal clusters. ERPs averaged across the clusters are presented in Figures 4.7 and 4.8. Although a similar pattern of activity was generated to phonetic deviance both in the streaming paradigm and control paradigms, more significant discrimination was present in the streaming design. Distribution of individual channels on the 128-channel topomaps is available for comparison in Figures D.1 and D.3 in Appendix D, respectively.

GRAND AVERAGE ERPS TO PHONEME STREAM

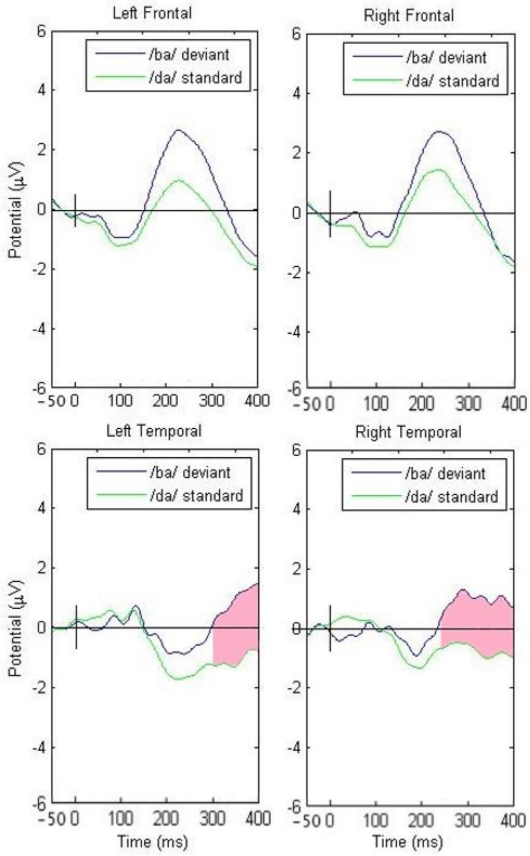

Figure 4.7 Grand average ERP amplitudes to /ba/ deviant (blue line) and /da/ standard phonemes (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in phoneme stream in the streaming paradigm. Significant MMR (based on paired t-tests) is highlighted in pink ($p<0.01$). See Table C.1 for t-test results and Figure D.1 for distribution of ERPs across the scalp in EGI 128-channel system.

GRAND AVERAGE ERPS TO PHONEME PARADIGM

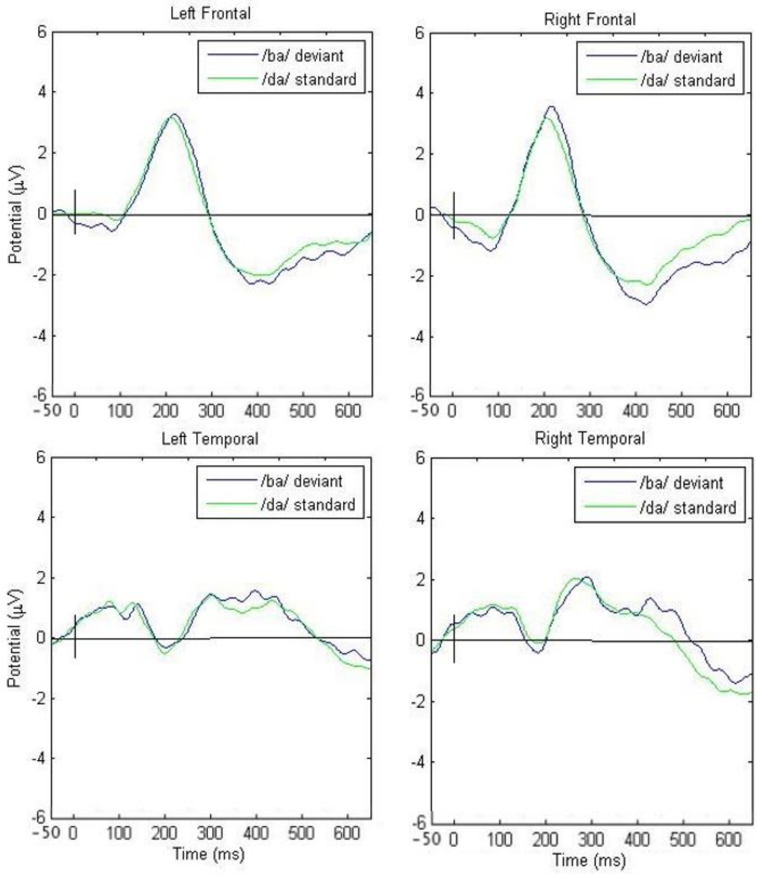

Figure 4.8 Grand average ERP amplitudes to /ba/ deviant (blue line) and /da/ standard phonemes (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in the phoneme paradigm. Based on paired t-tests between deviants and standards on 50 ms time windows within 100-650 ms post-stimulus-onset, the difference between ERPs to deviants and standards did not reach significance (at $p<0.01$). See Table C.3 for t-test results and Figure D.3 for distribution of ERPs across the scalp in EGI 128-channel system.

MMR difference between phoneme contrasts in the streaming and control paradigm. Visual comparison between MMR to both modulations (see Figure 4.9) revealed an increased positivity to phonetic contrast within the streaming paradigm than in the control phoneme paradigm. Repeated-measures three-way analysis of variance was carried out to confirm the difference. The factors were: stream (phoneme stream in the streaming paradigm versus phoneme paradigm) x hemisphere (left and right temporal) x time window (250-300 ms versus 350-400 ms). They were selected based on time windows with the onset and mean MMR amplitude to deviance in either of the modulations. However, despite significant positive MMR deflection to deviance in phoneme stream in the streaming paradigm and not in the phoneme paradigm, there was no significant difference between them, all $F<3.843$, $p>.056$.

MMR WAVEFORMS TO PHONEMES

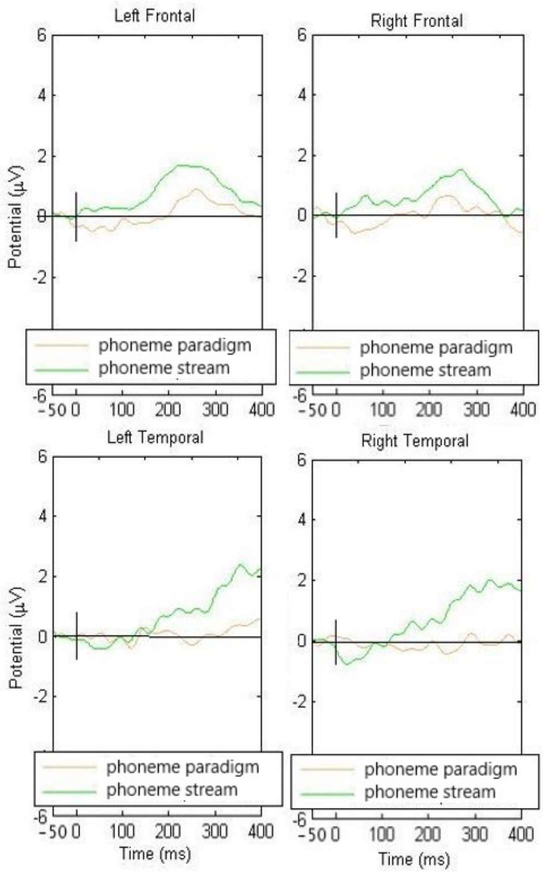

Figure 4.9 Grand average MMR waveforms generated to deviance in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in the phoneme paradigm (orange line) and in phoneme stream within the streaming paradigm (lime green line). See Table C.1 and Table C.3 for mean MMR amplitude values and Figure D.5 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

Stream modulation in tone pairs.

The stream modulation in processing tone pair contrast in tone pair stream in the streaming and control paradigms was examined in this analysis.

MMR to deviance in tone pairs. The grand average topomaps illustrate development of the MMR to tone pair contrast in the streaming (Figure 4.10) and control paradigm (Figure 4.11). MMR to deviance in tone pair stream within the tone pair paradigm emerged within the 250-300 ms (110-160 ms after the onset of the second tone in the pair) and later within 300-350 ms (160-210 ms) in the tone pair paradigm and developed to become widespread by the end of the epoch in both paradigms. Interestingly, the MMR to tone pair contrast in the streaming paradigm emerged as positive frontal deflection which spread out towards the temporal area by the end of the epoch whereas the MMR in the tone pair paradigm was established temporally throughout the epoch.

MMR TO DEVIANCE IN TONE PAIR STREAM

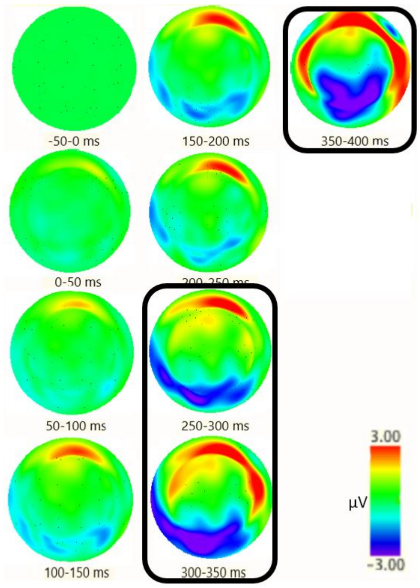

Figure 4.10 Topographic representation of the development of mean MMR amplitude to deviance in tone pair stream in the streaming paradigm. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The encircled time windows indicate significant MMR (p<0.01) bilaterally in the left (channels 19, 20, 23, 24, 27 and 28) and right frontal (3, 4, 117, 118, 123 and 124), and left (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115). See Table C.2 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

MMR TO DEVIANCE IN TONE PAIR PARADIGM

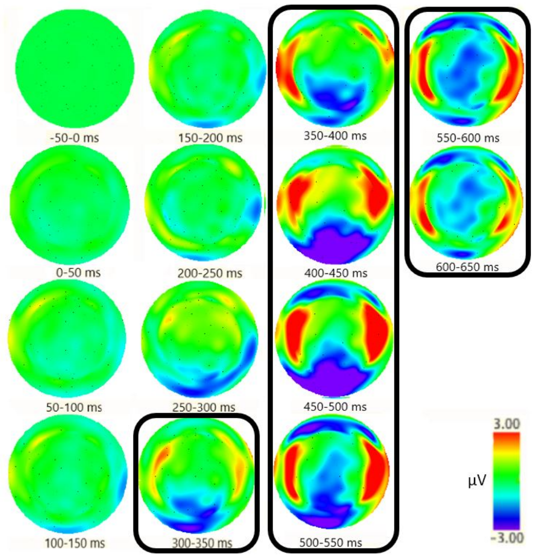

Figure 4.11 Topographic representation of the development of mean MMR amplitude to deviance in the tone pair paradigm. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The encircled time windows indicate significant MMR ($p<0.01$) bilaterally in the left (channels 39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115). See Table C.4 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

Grand average images in Figure 4.12 and Figure 4.13 demonstrate ERPs to deviant and standard stimuli in tone pair stream in the streaming paradigm and the tone pair paradigm (see also Figures D.3 and D.4 for distribution of the channels on the 128-channel system). In the tone pair paradigm, the significant MMR was recorded in the temporal clusters, while in the streaming design it was found in the frontal, followed by the temporal clusters (see Table C.4 for significant MMR results).

GRAND AVERAGE ERPS TO TONE PAIR STREAM

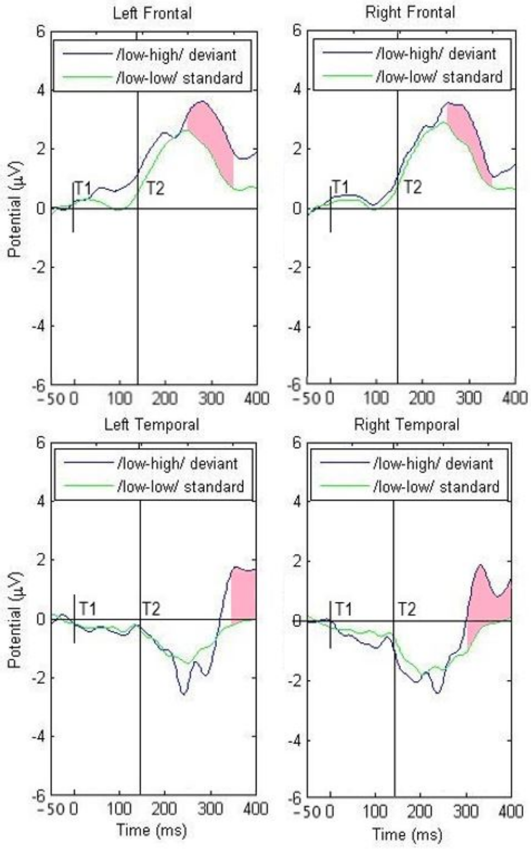

Figure 4.12 Grand average ERP amplitudes to /low-high/ deviant (blue line) and /low-low/ standard tone pairs (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) generated to deviance in tone pair stream in the streaming paradigm. T1 and T2 indicate the onset of each tone in the pair. Significant MMR (based on paired t-tests) is highlighted in pink (p<0.01). See Table C.2 for t-test results and Figure D.2 for distribution of ERPs across the scalp in EGI 128-channel system.

GRAND AVERAGE ERPS TO TONE PAIR PARADIGM

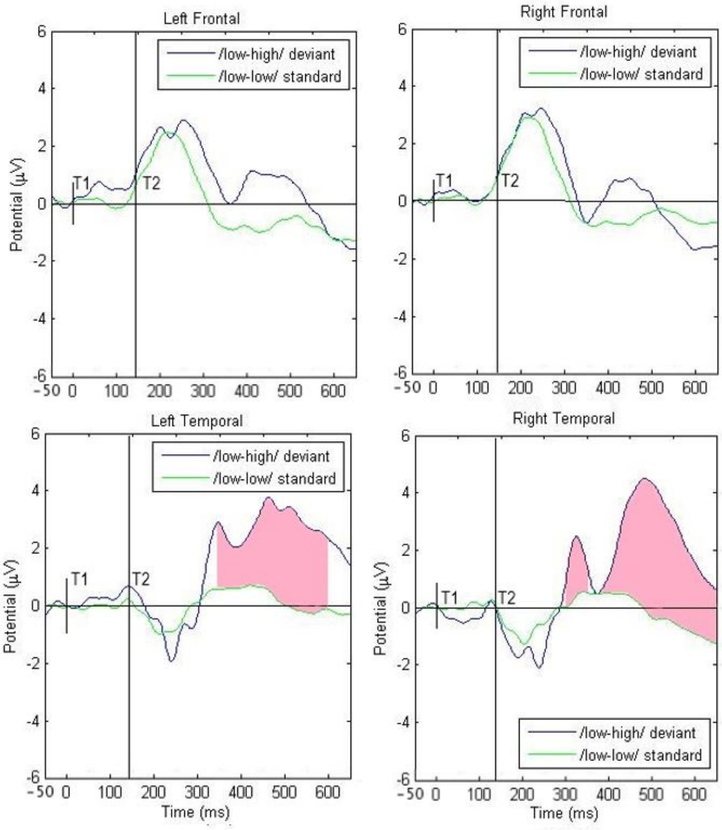

Figure 4.13 Grand average ERP amplitudes to /low-high/ deviant (blue line) and /low-low/ standard tone pairs (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) generated to the deviance in the tone pair paradigm. T1 and T2 indicate the onset of each tone in the pair. Significant MMR (based on paired t-tests) is highlighted in pink ($p<0.01$). See Table C.4 for t-test results and Figure D.4 for distribution of ERPs across the scalp in EGI 128-channel system.

MMR difference between tone pair contrasts in the streaming and control paradigm. Figure 4.14 revealed a similar pattern of activity between MMR waveforms to both modulations except for the MMR amplitude to tone pair paradigm, which was identified beyond the epoch in the streaming paradigm (i.e., 500-550 ms time window).

MMR WAVEFORMS TO TONE PAIRS

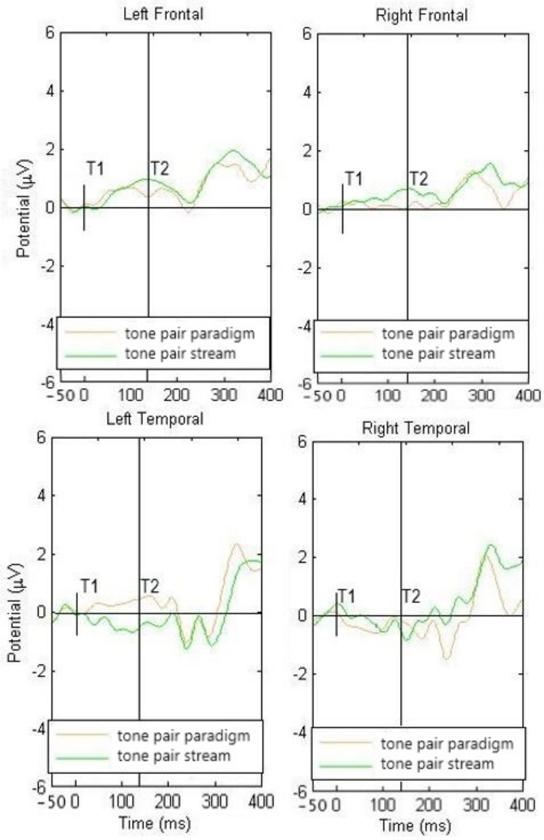

Figure 4.14 Grand average MMR waveforms generated to deviance in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in tone pair stream in the streaming paradigm (lime green line) in the tone pair paradigm (orange line). T1 and T2 indicate the onset of each tone in the pair. See Table C.2 and Table C.4 for mean MMR amplitude values and Figure D.6 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

Repeated measures four-way ANOVA with factors: stream (tone pair stream in the streaming paradigm versus tone pair paradigm) x region (frontal versus temporal) x hemisphere (left and right) x time window (250-300 ms versus 300-350 ms, i.e., 110-160 and 160-210 ms after the deviant tone in the pair)) was carried out. The included factors were based on time windows and areas with onset and mean MMR amplitude in either of the paradigms.

However, the only significant effect was found for the time window, $F_{(1,39)}=18.085$, $p<0.001$, $\eta^2=0.317$. This was expected, given that the time windows reflected the development of the MMR from emerging to its optimal level. No other effects or interactions were significant (all other $F<1.701$ and $p>0.199$). It was hence concluded that there was no significant difference between MMR to deviance in the tone pair stream in the streaming paradigm and tone pair paradigm.

4.3.3 Stimulus modulation.

MMR difference between phoneme and tone pair streams in the streaming paradigm.

MMR to deviance in phoneme and tone pair streams in the streaming paradigm was analysed as part of the stimulus comparison. The individual topomap representations of the MMR to deviance in the phoneme (Figure 4.5) and tone pair stream (Figure 4.11) are provided in section 4.3.2. Figure 4.15 shows a similar pattern of activity of the MMR to both streams.

Repeated-measures four-way ANOVA with factors: stimulus (phonemes versus tone pairs) x region (frontal and temporal) x hemisphere (left versus right) x time window (250-300 ms, 300-350 ms, 350-400 ms; which related to 110-160, 160-210 and 210-260 ms after the onset of the deviant tone in tone pairs) was carried out to systematically assess the difference between MMR to phonemes and tone pairs in the streaming paradigm. The factors were selected based on the time windows with the onset and mean MMR amplitude in at least one of the streams. The analysis revealed an interaction between stimulus and time window, $F_{(1.520,59.281)}=6.131$, $p=0.007$, $\eta^2=0.136$. Post hoc analyses confirmed larger MMR to tone pair ($M=3.307$, $SE=0.301$) than phoneme stream ($M=2.228$, $SE=0.217$) in the frontal clusters within 350-400 ms, $F_{(1,39)}=7.956$, $p=0.007$, $\eta^2=.169$.

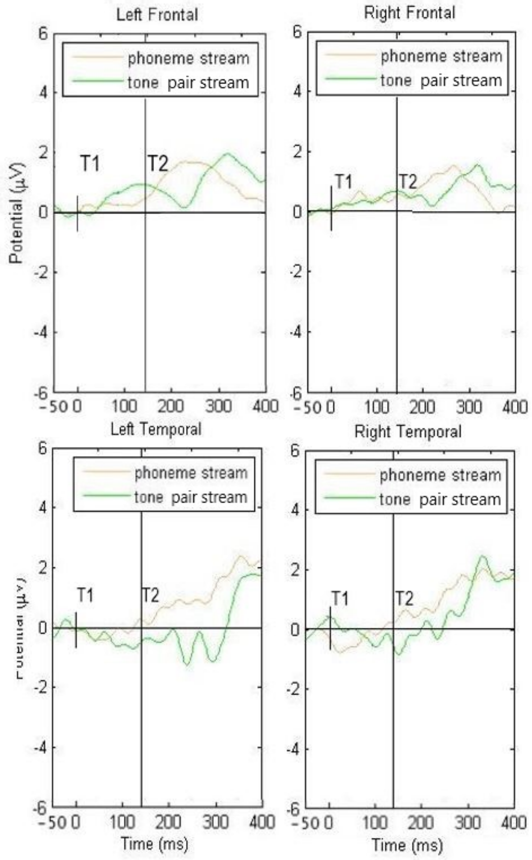

Figure 4.15 Grand average MMR waveforms generated to deviance in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in phoneme (orange line) and tone pair (lime green line) streams in the streaming paradigm. T1 and T2 indicate the onset of each tone in the pair in the tone pair stream. See Table C.1 and Table C.3 for mean MMR amplitude values and Figure D.7 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

MMR difference between phoneme and tone pair paradigms.

MMR to deviance in phonemes and tone pairs in the control paradigms was compared. As seen in Figure 4.16, MMR to tone pair contrast was strikingly more extensive than the response to phonemes, which, as confirmed earlier by paired t-tests, did not differ significantly from the baseline.

To systematically assess the difference between MMR to deviance in the phoneme and tone pair paradigms in the right temporal clusters, two-way ANOVA test was performed. The factors included: stimulus (phoneme versus tone pair paradigm) x time window (300-350 versus500-550 ms; in the tone-paradigm, this related to 160-210 and 360-410 ms after the onset of the second tone in the pair). There was the main effect of stimulus, $F_{(1,39)}=24.356$, $p<0.001$, $\eta^2=0.384$. Overall, MMR to phonetic contrast (M=2.006, SE=0.195) was weaker than to tone pairs (M=4.245, SE=0.459).

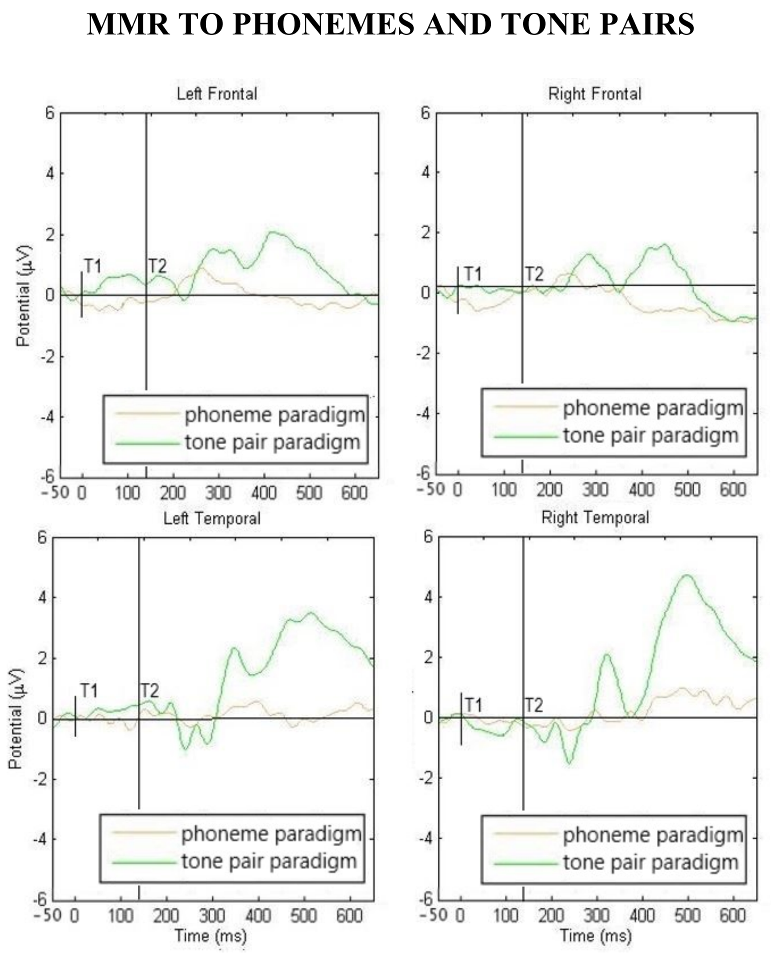

Figure 4.16 Grand average MMR waveforms generated to deviance in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in the phoneme (orange line) and tone pair (lime green line) paradigms. T1 and T2 indicate the onset of each tone in the pair in the tone pair paradigm. See Table C.3 and Table C.4 for mean MMR amplitude values and Figure D.8 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

4.3.4 Summary of the results.

Significant MMR was identified to all modulations except to deviance in the phoneme paradigm (see Table 4.2). However, MMR to phonetic contrast in the streaming paradigm did not significantly differ from that in the phoneme paradigm. Also, a comparable pattern of activity as to phoneme stream was identified to tone pair stream in the streaming paradigm, although more positive MMR to tone pair stream was found over the frontal clusters. This was reconfirmed with even more extensive MMR to the tone pair paradigm, while phonetic contrast in the control paradigm was not discriminated. These results confirm that the stream and stimulus modulations influence the MMR in infants. Stream affected phoneme though not tone pair processing and overall, tone pairs were discriminated earlier and to a higher degree than phonemes.

4.4 Discussion

The purpose of Study 2 was to examine MMR to oddball change in phoneme and tone pair streams in the streaming design and the control phoneme and tone pair paradigms. Both the stream (the streaming versus control paradigms) and stimulus (phonemes versus tone pairs) modulations were expected to have differential effects on the MMR in infants.

In the first instance, the stream modulation did not appear to convey a difference in MMR in phonemes or tone pairs. Comparison between phoneme stream in the streaming paradigm and the phoneme paradigm revealed no difference in absolute MMR despite significant, albeit weak MMR to phoneme stream but absent MMR to the phoneme paradigm. Moreover, no distinction was found between MMR to tone pair stream in the streaming paradigm and the tone pair paradigm, although both components were large and clearly defined. Hypothesis one, which stated that the number of streams in a paradigm would influence the MMR, was not supported (H.2.1), although there was a trend within the phoneme contrasts.

Still, tone pairs were found to generate larger mean MMR than phonemes both in the streaming and control paradigms. As expected, the stimulus modulation had a differential effect on the spatial and temporal distribution of the MMR, and so hypothesis two was supported (H.2.2).

4.4.1 Stream modulation and its effect on the MMR in infants.

The most striking finding was that the stream modulation did not have a differential effect on the MMR in infants. There are several possible explanations for these results. One interpretation is that phonetic and tonal discriminations represent preattentive sensory adaptation (see section 1.3.3 for theories explaining the MMR) and as that are not influenced by streaming, which is thought to be a later attentional mechanism (Carlyon, 2004; Nie, Zhang, & Nelson, 2014; Sussman, 2005; see also section 1.1.2 for details for neurophysiological theory of stream segregation).

Another possibility is that the deviant and standard stimuli in each modulation were so distinct that the MMR would be significant regardless of modulation. In other words, the contrast was so considerable that it was too easy to process, resulting in the ceiling effect (Chen et al., 2016; Hoonhorst et al., 2012). A large and early MMR would be a sign of such a design flaw (Campbell et al., 2007; Näätänen et al., 1978; Näätänen & Picton, 1987). Admittedly, this could perhaps explain the MMR to tone pairs but not the weak MMR to phoneme stream or even absence of the MMR to deviance in the phoneme paradigm.

Finally, the stream modulation may be somewhat limited by the differences in trial duration between the streaming and control paradigms (Andreou et al., 2011; Escera et al., 2000; Sussman et al., 2008; Wunderlich & Cone-Wesson, 2006; Wunderlich et al., 2006; Xu & Ma, 2009). The 932 ms in the phoneme and tone pair paradigms was long enough to encompass obligatory ERPs the MMR was based on (section 1.3.3 outlines origins of the MMR). However, the shorter 483 ms trial in the streaming paradigm may not suffice for the full development of the ERPs or if they were present, they could be attenuated and with earlier peaks than in the longer trial, rendering the modulations quantitatively incomparable (Escera et al., 2000). On the contrary, no such differentiation was found between the modulations. Visualisations. Figures 4.9 and 4.14 indicate that the MMR waveforms did not differ between the streaming and control paradigms and instead followed the same pattern.

This observation weakens the claim for another limitation which may accompany a shorter trial duration. If obligatory responses to the stimulus do not have sufficient time to develop before the end of the trial, they may overlap with and as a result inflate the baseline correction and ERP to the next trial (Luck, 2014, pp. 255-258; Luck & Gaspelin, 2017; see also section 1.3.6 . This can be easily observed on grand average images as large deflections of ERP waveforms within baseline correction (here within 50 ms before the stimulus onset) and up to 100 ms after stimulus. No such deviations were found in the current data (see Figure 4.7 and Figure 4.8 for ERPs to phoneme and Figures 4.12 and 4.13 to tone pair modulations).

Stream modulation in phonemes.

The number of streams in a paradigm did not affect the linguistic MMR in infants (see Figure 4.9). This is despite the MMR observed in response to phonetic contrast in the streaming (Figure 4.7), but not in the case of the phoneme paradigm (Figure 4.8). While the linguistic stream segregation has been found previously in infants (Barker & Newman, 2004), this is in opposition to findings by Polka et al. (2008). They reported that 6- to 8-month-old infants were more likely to discriminate

/bu/ and /gu/ phonemes when the stream was presented against a silent background than when it was placed among nonspeech sounds such as a bird and cricket song. However, the preferential looking technique used in their study is prone to attentional bias (Delle Luche, Durrant, Poltrock, & Floccia, 2015). Also, in another preferential looking study by Smith and Trainor (2011) infants performed just as well when identifying target sounds in one stream as in the presence of an additional one.

The result is, however, surprising in the light of Study 1, in which the same phoneme paradigm generated significant MMR (see section 3.3.2 for the MMR generated to the phoneme oddball paradigm in Study 1). Age and language experience could (Choudhury & Benasich, 2011; Kushnerenko et al., 2002a; Garcia, Guerrero-Mosquera, Colomer, & Sebastian-Galles, 2018; Shafer, Yu, & Datta, 2011) but did not appear to affect the responses to modulations in Studies 1 and 2. Overall the age range (5-10 and 5-11 months, respectively) was found to be similar in both studies (see section 1.3.4 for maturation changes in the MMR) and proportion of monolingual participants even larger in the current study (53% and 70%; see section 1.2.2. Therefore, additional factors may have contributed to the difference in the MMR to the phoneme paradigm between the studies, despite a similar pattern of activity.

The order of paradigms in the current study may have inadvertently caused attenuation of the MMR in the phoneme paradigm when compared to the significant result in Study 1. While all paradigms in Study 1 were counterbalanced, here, the streaming paradigm was played first, followed by the phoneme and the tone pair paradigms, which were counterbalanced. The reason for this arrangement was to avoid priming effect for the streaming design, i.e., if infants had been exposed to either or both control paradigms before the streaming paradigm, potential enhanced discrimination in the streams would have been expected (Angelini et al., 2009; Garrido et al., 2008).

Whilst every effort was taken to avoid enhancing the MMR in the streaming paradigm (Dehaene-Lambertz & Gliga, 2004; Dehaene-Lambertz et al., 2010b), this may have led to the opposite priming effect. By presenting the streaming paradigm first, it may have negatively impacted the MMR to the phoneme paradigm, which was performed afterwards. Such priming could increase neural sensitivity to both frequent and rare phonemes (Guiraud et al., 2011; Müller et al., 2005). Therefore, absence of significant MMR to deviance in the phoneme paradigm may have been caused by reduced habituation to the standard phonemes, not by decreased response to deviants (Angelini et al., 2009; Budd et al., 2013; Carbajal & Malmierca, 2018; Garrido et al., 2008; Nordt et al., 2016; Turk-Browne et al., 2008). Indeed, the ERP pattern reflected responses to the roving paradigm in Study 1, where also clear P1 and N2 components emerged both to deviant and standard phonemes in the roving design (Kushnerenko et al., 2002a). The phonetic contrast may have been processed, but habituation did not take place (Demany, 1982; Muenssinger et al., 2013a). Indeed, the ERP pattern to the current phoneme paradigm more closely resembles neural activity to the roving than oddball deviance in Study 1 (see section 3.3.2 for comparison between MMR to both types of deviance).

Stream modulation in tone pairs.

The current MMR waveforms to deviance in tone pair stream in the streaming paradigm and the tone pair paradigm (Figure 4.14) did not differ significantly and in that resembled MMR difference to phonemes in both modulations. However, in contrast to phonemes, MMR to tone pairs was significant and indeed displayed broad spatial and temporal distribution to both tonal contrasts (Figures 4.12 and 4.13).

The results corroborated findings by Polka et al. (2008) as well as by Winkler and colleagues (2003), in which both the streaming and control paradigms evoked the MMR, but it was more pronounced in the control tone pair than streaming design. It is also encouraging to compare the current MMR to the tone pair paradigm to the very similar pattern of activity to the long ITI tone pair paradigm in Study 1 (section 3.3.3).

Notably, MMR to tone pair contrast in the streaming paradigm was initially observed in the frontal clusters and appeared slightly attenuated in comparison to that in the tone pair paradigm, which was elicited temporally from the onset. Despite the nonsignificant effect of the stream modulation, some maturational differences could be inferred, with MMR in the streaming design less mature than the control tone paradigm.

Support for this deduction comes from studies by Benasich and team (Benasich et al., 2002, 2006; Cantiani et al., 2016a; Choudhury et al., 2007; Choudhury & Benasich, 2011; Musacchia et al., 2013; Ortiz-Mantilla et al., 2016), who assessed MMR to the tone pair paradigm in younger infants (up to 7 months) than in the current sample. In their studies, MMR was observed frontally and could, as in processing contrasts in the complex streaming design in the current study, reflect immature central auditory discrimination (Banai & Kraus, 2006; Näätänen & Alho, 1997; Woldorff & Hillyard, 1991). The larger and temporal MMR in response to the tone pair paradigm could be interpreted as a more mature response to simple acoustic contrast.

Overall, these observable, although not statistically significant distinctions between stream modulations both in phonemes and tone pairs highlight the hierarchy of cognitive involvement in processing one versus two competing streams (Choudhury & Benasich, 2011; Kushnerenko et al., 2002a) and raise awareness of how the study design may impact the response.

4.4.2 Stimulus modulation and its effect on the MMR in infants.

Across the streaming and control paradigms, tone pairs elicited larger MMR than phonemes (see Figures 4.15 and 4.16), although the difference was more significant between the control paradigms than between the streams. This is partly due to the absence of the MMR in the phoneme paradigm (see Table 4.1 for a summary of the MMR results). In accordance with the result in Study 1, non-linguistic MMR had an advantage over linguistic discrimination (see section 3.4.3). As found in previous literature infants were more efficient in discriminating the narrowband frequencies in tones than broadband phonemes (Gerber, 1985; Irwin et al., 1985; Schneider, Morrongiello, & Trehub, 1990; Teas, Klein, & Kramer, 1982).

MMR difference between phoneme and tone pair stream in the streaming paradigm.

Notwithstanding the robust MMR to tone pair contrast, the more relevant finding is that infants processed phonetic deviance as well as the more salient non-linguistic contrast in the streaming paradigm (Figure 4.14). Therefore, infants did not only ignore irrelevant sounds in the background as previously reported (Barker & Newman, 2004; Bergmann, Bosch, Fikkert, & Boves, 2015; Kushnerenko et al., 2013c; Newman, 2005, 2011, 2013; Nozza, Miller, Rossman, & Bond, 1991; Nozza, Rossman, Bond, & Miller, 1990; Nozza & Wilson, 1984; Tharpe & Ashmead, 2001;

Werner, 2013) but processed competing speech and non-speech sounds when they were presented together in an alternating sequence.

Furthermore, the spatial distribution of the MMR demonstrated the differentiation between the linguistic and non-linguistic contrast (see section 4.3.3). MMR to phoneme stream was distributed temporally (Figure 4.5), while MMR to tone pair stream was observed over the frontotemporal portion of the scalp (see Figure 4.10). Considering referential bias of the EEG (see section 1.3.7) to phonetic contrast is likely to have originated in the primary auditory area and tonal discrimination was probably generated in the centrally located subcortical areas, possibly surfaced cortically through thalamic projections (section 1.1.1 outlines neuroanatomy of the auditory network), reflecting localisation of the speech specific and primary acoustic processing networks.

Although admittedly, source localisation of the EEG signal remains speculative (Hallez et al., 2007; Justen & Herbert, 2018; Odabaee et al., 2014), in accordance with the current findings, differences in the spatial distribution in response to speech versus nonspeech stimuli have also been found using fMRI in adults (Vouloumanos et al., 2001; Zaehle et al., 2008). Responses to speech sounds were localised to temporal regions while the nonspeech sound bursts were processed both in the temporal and prefrontal cortex. Differentiation within the auditory cortex has also been reported (Alho et al., 2014; Whalen et al., 2006).

MMR difference between the phoneme and tone pair paradigms.

Overall, current results demonstrate that MMR to deviance in the tone pair paradigm was more significant than in the phoneme paradigm (Figure 4.16). The current pattern of the MMR generated to tone pair paradigm closely resembles the findings of Study 1 (see section 3.3.3). Although MMR in the phoneme paradigm was too weak to reach significance, the pattern of activity was similar to responses to phoneme paradigms in the earlier section 4.3.3 and within the streaming paradigm in the current study.

In support of the present results, the larger MMR amplitude was found to deviance in tones than in phonemes in 8- to 11-years-old children (Lachmann et al., 2005). Larger MEG responses to nonspeech than speech stimuli were likewise found in typically developing 6- to 14-year-olds (Yau, Brock, & McArthur, 2016). No difference was however identified in the MMR amplitude in adults in another study, but hemispheric lateralisation indicated differences in spatial distribution between regions processing speech sounds and matched nonspeech bips (Sorokin et al., 2010).

Contrasting results were reported in 1- to 4-month-old infants, whose data highlighted preference for speech over human noncommunicative vocalisations, rhesus monkey vocalisations or environmental sounds (Shultz & Vouloumanos, 2010; Shultz et al., 2014) or when the other sounds were associated with background noise, such as a bird song (Polka et al., 2008). However, the study employed the behavioural preferential looking technique, which though useful, can be biased towards familiarity or novelty (Delle Luche et al., 2015), so the results may not reflect a preference for speech per se. Some advantage of speech over tones was also found in 9-month-old infants (Zhao & Kuhl, 2016), but when the ITI rather than frequency modulation was implemented, so the sounds did not differ within the phoneme and tone blocks.

As demonstrated in both Study 1 and partly replicated in the current study, despite the ongoing controversy, this finding offers some insight into whether linguistic or non-linguistic contrast has processing advantage and whether different processing mechanisms are engaged in processing speech and nonspeech stimuli. This further highlights the importance of the careful selection of the paradigm features while designing a study.

4.4.3 Conclusion.

The effect of stream and stimulus modulations was investigated in Study 2. The stream modulation did not have a differential effect on processing phonemes or tone pairs. Furthermore, the stimulus manipulation confirmed tone pairs as more reliable in eliciting large absolute mean MMR amplitude than phonemes. The finding replicated the account from Study 1.

A more in-depth exploration of the data shed light on the differential processing of speech and nonspeech stimuli in the streaming and control single stream design. Infants produced MMR both to phoneme and tone pair streams in the streaming paradigm. It showed that infants were able to stream out two simultaneous sound sequences, i.e., they did not only segregate but processed both competing streams. In other words, they discriminated linguistic and non-linguistic contrasts simultaneously. This the first report of infants' ability to process the complex auditory scene and this finding has important implications for understanding auditory and specifically speech processing in a more naturalistic setting.

Chapter 5. Study 3 – Associations between the MMR and language in infants.

5.1 Introduction

Recent trends in early auditory processing have led to the proliferation of studies that seek the origins of language development in basic auditory mechanisms in infancy and stream segregation presents as a potential candidate. This could be due to the complexity of the neural processing involved in the task and associations with language (Fiveash, Thompson, Badcock, & McArthur, 2018; Helenius, Uutela, & Hari, 1999; Sussman et al., 2015).

Stimuli such as tones (Benasich & Tallal, 2002; Benasich et al., 2002; Choudhury & Benasich, 2011; Dehaene-Lambertz & Gliga, 2004; Friederici, 2005; Guiraud et al., 2011; Heim et al., 2013; Kraus et al., 1996; Steinbrink, Zimmer, Lachmann, Dirichs, & Kammer, 2014) and phonemes (Kushnerenko et al., 2013b; Nath, Fava, & Beauchamp, 2011) have been employed in research exploring early language development.

However, the newly designed streaming paradigm (in Study 2), as an attentionally and potentially cognitively demanding task could be more effective in identifying infants at risk of developing language deficits than the less challenging paradigms (Snyder & Alain, 2007). In addition, this raises a question whether infants are as efficient in processing two competing auditory streams, as they are in isolating speech from other sounds. They may be required to do so in a home environment, for example when the infant is presented with an attractively sounding toy as the parent is talking to her/him about it.

The efficiency of paradigms assessing auditory processing can be confirmed with the use of behavioural assessment of language proficiency within the same individuals. Although it is difficult to test an infant on their language skills, measures such as Bayley-III (Bayley, 2005) have been shown to reliably assess the level of communication in prelinguistic children. This may involve discrimination of sounds or turning towards voice as examples of auditory comprehension, or crying for food, or the toy and giggling or bubbling when in a happy mood as signs of expressive communication.

5.1.1 MMR vs language in infants.

Associations between auditory discrimination and linguistic ability in the first year of life have been found in a number of studies (Benasich et al., 2016; Chonchaiya et al., 2013; Horowitz, 1974; Molfese, 1989, 1990; Molfese & Molfese, 1985). For instance, in a study by Fenson et al. (2000), infants aged between 6 and 9 months with familial autoimmune disease or language impairment were worse at receptive and expressive language than matched controls. They were less likely to recognise (i.e., look longer towards a screen with no related visual stimulus) novel syllable when habituated to one consonant-vowel structure (/ba/ versus /da/ or the opposite).

Moreover, 6-9-month-old infants who produced larger MMR to audiovisual speech stimuli, have been reported to display differential looking pattern to speakers, i.e., looking less to mouth and more to eyes (Kushnerenko et al., 2013b). This in turn, was related to increased receptive language at 14-16 months (Kushnerenko et al., 2013a). However, the most significant difference between the groups has been demonstrated by discrimination of the novel rapidly changing tone pairs (i.e., low-high versus high-low, at 100 and 300 Hz), most notably when the inter-stimulus-interval is set at 70 ms (Benasich, 2002), as indicated by the head-turn familiarisation procedure. The MMR amplitude was also attenuated in infants born to families with a history of language impairments (Benasich et al., 2006; Choudhury & Benasich, 2011). Overall, the link between sound discrimination and linguistic proficiency in early childhood appears to be strong so a more in-depth investigation of this relationship would provide insight into its trajectories in early development.

5.1.2 Rationale for the study.

This study aimed to assess the relationship between auditory processing and linguistic performance in infants. The EEG streaming and control phoneme and tone pair paradigms elicited MMR in Study 2 (except for the phoneme paradigm). Time windows with significant MMR in response to deviance in those paradigms were compared with the receptive and expressive communication scores on Bayley-III (Bayley, 2005), which is an objective assessment of infant language ability.

However, it is designed and standardised on North American monolingual cohorts of infants. Based on previous literature, this could cause some discrepancies in responses of British monolingual and bilingual infants. Evidence suggests that British infants underperform on language assessments standardised to responses by monolingual North American participants (Buckler & Johnson, 2019; Hamilton, Plunkett, & Schafer, 2000). Furthermore, infants from bilingual families tend to score lower on English language tests (Byers-Heinlein & Lew-Williams, 2013; Cattani et al., 2014; Werker, Byers-Heinlein, & Fennell, 2009), although for most this difference disappears by the time they enter primary school (Hoff, 2013). Nonetheless, to date Bayley-III is the most comprehensive language assessment carried out with infants in the first year of life exposed to the English language. It was therefore selected to be administered to assess receptive and expressive communication in monolingual and bilingual infants participating in the current study.

5.1.3 Experimental predictions.

In accordance with the outlined research, MMR to deviance in auditory paradigms was hypothesised to be associated with language ability in infants (H.3.1), as operationalised by the phoneme and tone pair paradigms and phoneme and tone pair streams in the streaming paradigm and standardised scores on the receptive and expressive communication subtests in Bailey-III behavioural assessment (Bayley, 2005).

5.2 Methods

The general methods are outlined in Chapter 2. See section 4.2.1 for the demographics of the sample. Any additional information is provided below.

5.2.1 Participants.

Forty-three infants participated in Study 2. All of them performed the behavioural Bayley-III (Bayley, 2005) battery and all attempted to participate in the stream and the control EEG tasks. However, three subjects were excluded as they failed to complete at least one of the EEG paradigms due to restlessness. The final sample included in the analysis consisted of 40 infants (19 males).

5.2.2 Design.

It was a correlational study of within-subject design. The relationship between MMR to deviance in the streaming and control phoneme and tone pair paradigms from Study 2 and behavioural language ability was assessed in infants (see section 4.2.2 for details). Figure 5.1 illustrates the modulation and tasks performed by the infants.

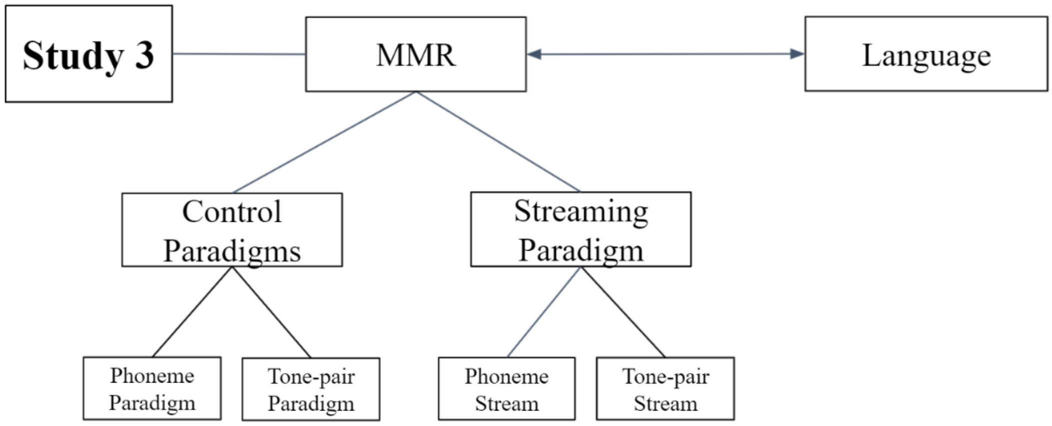

Figure 5.1 Schematic representation of the manipulations in Study 3. The arrow demonstrates the relationship between MMR to deviance in the control paradigms and phoneme and tone pair streams in the streaming paradigm and language in infants.

5.2.3 Stimuli and apparatus.

The tasks used in the study were three EEG auditory paradigms and a behavioural assessment of receptive and expressive communication.

EEG Paradigms.

General information on the paradigms is presented in section 2.4.1 with the detailed description in section 4.2.3 The control paradigms included the phoneme and tone pair paradigm. The streaming paradigm comprised phoneme and tone pair stream, which were essentially the two control paradigms plotted sequentially in an interweaving manner.

Behavioural language assessment.

Bayley-III (Bayley, 2005) receptive and expressive communication subtests were used in the study. The subtests assessed responding and turning to different sounds, differentiating speech from other sounds, interacting with parent, and producing vowels and consonants as well as communicating pleasure and displeasure. The tasks within each subtest increased in difficulty, following developmental milestones. The higher the raw scores on the assessment, the most proficient the infant was at communicating with the environment. Details on the assessment are provided in section 2.4.2.

Receptive communication. Infants in the current study were expected to calm down when spoken to and respond to surroundings at 5 months and play with a toy for an at least 60 seconds and respond to their name at 11 months at the least.

Expressive communication. The youngest infants were predicted to produce a social smile and vocalise mood while the oldest were expected to attempt to draw the attention of another person and produce consonants.

5.2.4 Procedure.

General procedure related to the experimental session with infants is outlined in section 2.5.2. Procedural timeline and counterbalancing the order of all the tasks in Study 3 are outlined in Figure 5.2.

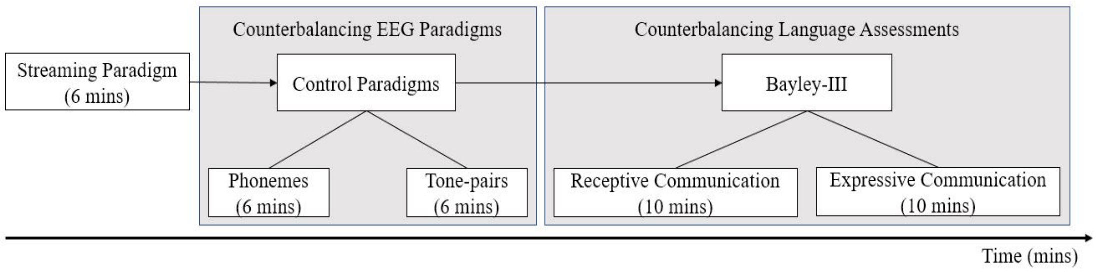

Figure 5.2 Schematic representation of the procedure in Study 3. Within the EEG tasks, the streaming paradigm was presented as first. Order of the following phoneme and tone pair paradigms was counterbalanced. The second part of the experimental session involved Bayley-III receptive and expressive communication subtests, which were also counterbalanced. An example timeline is presented with the duration of each task in brackets.

5.2.5 Data processing and analysis.

EEG data processing.

The EEG data were collected and processed using Net Station 5.2.0.2 software (EGI, Eugene, OR). Additional information is recorded in section 2.6.1 and details relevant only to Study 2 within section 4.2.5.

Processing language scores.

The acquired scores on Bayley-III receptive and expressive language subtests (Bayley, 2005) were standardised using the provided tables to each infant's age, which was corrected for gestation. The standardised scores were summed up and then transposed into a total language composite. Details on the processing of scores can be found in section 2.5.2.

Analysis strategy.

General information on the analysis strategy is outlined in section 2.6.2. Figure 5.3 demonstrates the specific analyses in Study 3. The model demonstrates Pearson correlations between MMR to modulations in the phoneme and tone pair paradigms and the phoneme and tone pair streams in the streaming paradigm and language composite scores on Bayley-III.

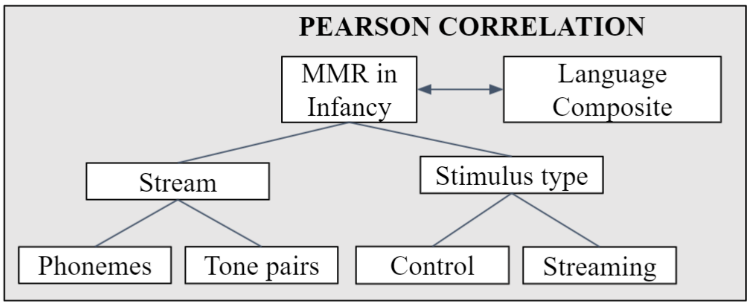

Figure 5.3 Schematic representation of analyses in Study 3. The detailed structure of paired t-tests used to identify significant MMR to the EEG modulations can be found in Figure 2.10.

5.3 Results

MMR to phoneme and tone pair stream in the streaming paradigm and the phoneme and tone pair paradigm was expected to be associated with receptive and expressive communication scores on Bayley-III language subtests (Bayley, 2005) in infants.

5.3.1 Language ability in infants.

Infants' language ability was assessed with Bayley-III (Bayley, 2005) receptive and expressive communication. Behavioural raw scores were standardised and corrected for gestation in order to remove the effect of age between participants, using Bayley-III standardisation tables. Table 5.1 demonstrates the breakdown of the raw and standardised scores in monolingual and bilingual participants.

Table 5.1

Language Results in Infants

	Bayley scores	Language experience	Mean	SD	Minimum	Maximum	Scale range	Part. no.
Raw	Receptive communication	Monolingual	8.607	1.315	7	13	0-49	28
		Bilingual	7.833	0.937	6	9		12
	Expressive communication	Monolingual	7.929	2.523	5	14	0-48	28
		Bilingual	8.917	2.353	5	12		12
Standardised	Receptive communication	Monolingual	6.250	1.456	4	11	1-19	28
		Bilingual	4.667	1.670	2	8		12
	Expressive communication	Monolingual	7.964	1.953	5	11	1-19	28
		Bilingual	8.500	1.977	6	12		12
Total language	Sum of scaled scores	Monolingual	14.214	2.685	10	21	2-38	28
		Bilingual	13.167	2.657	10	19		12
	Language composite	Monolingual	83.286	7.850	71	103	47-153	28
		Bilingual	90.417	7.775	71	97	47-153	12
	Percentile rank	Monolingual	-	-	3	58	0.1-100	28
		Bilingual	-	-	3	42		12

Note. The raw and standardised scores (Bayley, 2005) were divided by language experience (monolingual and bilingual) in infants. The scores were standardised to age, which was corrected for gestation. See the distribution of the standardised scores in scatterplots in Figure E.1 for receptive communication, Figure E.2 for expressive communication and Figure E.3 for the language composite scores.

Performance varied between 3rd and 58th percentile, which is indicative of a diverse population. Overall, infants performed in the lower than the expected range on both receptive and expressive communication. Distribution of the scores across age in scatterplots, with division by language experience, can be found in Appendix E.

The difference between scores in monolingual and bilingual infants was assessed with an independent t-test to identify the contribution of language experience to the main analysis investigating the relationship between language and linguistic and non-linguistic MMR in infants. Independent t-tests confirmed the difference on the standardised scores. Overall bilingual participants had lower scores on receptive communication than monolinguals, $t_{(38)}=3.017$, $p=0.005$. However, there was no significant difference between scores in the bilingual and monolingual participants on expressive communication, $t_{(38)}=0.792$, $p=0.433$. Furthermore, analysis of the language composite scores also did not render significant difference, $t_{(38)}=1.062$, $p=0.295$. The descriptive statistics are provided in Table 5.1 for reference.

5.3.2 Relationship between MMR and language in infants.

The behavioural correlates of the MMR and verbal communication were investigated within Study 3. Specifically, the relationship between MMR to deviance in phoneme and tone pair stream in the streaming paradigm and in the tone pair paradigm and language composite scores (standardised to gestational age) on Bayley-III assessment (Bayley, 2005) were assessed. As significant MMR to the phoneme paradigm was not identified in Study 2, this correlation was not conducted. Pearson correlations between the MMR and language composite were performed (see Tables 5.2, 5.3 and 5.4 below for results on all correlations) and their significance tested against Bonferroni correction for multiple comparisons to reduce the probability of Type I error. Following the correction, none of the correlations was significant. Therefore, MMR to auditory deviance was not associated with behavioural language in infants.

Table 5.2

Pearson Correlation Results Between MMR to Deviance in Phoneme Stream in the Streaming Paradigm and Language Composite in Infants

Phoneme Stream			Language Composite	
Bin (ms)	Region	Hemisphere	Pearson	Sig. (2-tailed)
250-300	Temporal	Right	0.176	0.277
300-350	Temporal	Left	0.145	0.372
		Right	-0.131	0.421
350-400	Temporal	Left	-0.064	0.693
		Right	0.090	0.581

Note. Bayley-III (Bayley, 2005) language composite scores were standardised to participants' age, which was corrected for gestation. Time windows were selected based on the significant MMR to deviance in phoneme stream in the streaming paradigm in infants in Study 2 (N=40). See Table C.1 in Appendix C for details. The correlations were tested against a Bonferroni-adjusted alpha level of 0.01 (0.05/5) and none was significant.

Table 5.3

Pearson Correlation Results Between MMR to Deviance in Tone Pair Stream in the Streaming Paradigm and Language Composite in Infants

Tone Pair Stream			Language Composite	
Bin (ms)	Region	Hemisphere	Pearson	Sig. (2-tailed)
250-300	Frontal	Left	0.085	0.600
		Right	-0.059	0.723
300-350	Frontal	Left	0.192	0.236
		Right	-.050	0.761
	Temporal	Right	0.184	0.255
350-400	Temporal	Left	-0.016	0.920
		Right	0.276	0.085

Note. Bayley-III (Bayley, 2005) language composite scores were standardised to participants' age, which was corrected for gestation. Time windows were selected based on the significant MMR to deviance in tone pair stream in the streaming paradigm in infants in Study 2 (N=40). See Table C.2 in Appendix C for details. The correlations were tested against a Bonferroni-adjusted alpha level of 0.007 (0.05/7) and none was significant.

Table 5.4

Pearson Correlation Results Between MMR to Deviance in the Tone Pair Paradigm and Language Composite in Infants

Tone Pair Paradigm			Language Composite	
Bin (ms)	Region	Hemisphere	Partial R	Sig. (2-tailed)
300-350	Temporal	Right	-0.071	0.663
350-400	Temporal	Left	-0.217	0.178
400-450	Temporal	Left	-0.073	0.653
		Right	0.044	0.787
450-500	Temporal	Left	0.153	0.346
		Right	-0.226	0.161
500-550	Temporal	Left	0.213	0.187
		Right	-0.228	0.158
550-600	Temporal	Left	0.325	0.040
		Right	0.080	0.622
600-650	Temporal	Right	0.004	0.980

Note. Bayley-III (Bayley, 2005) Language composite scores were standardised to participants' age, which was corrected for gestation. Time windows were selected based on the significant MMR to deviance in the tone pair paradigm in infants in Study 2 (N=40). See Table C.4 in Appendix C for details. The correlations were tested against a Bonferroni-adjusted alpha level of 0.004 (0.05/11) and none was significant.

5.3.3 Summary of the results.

Analysis of the behavioural and neural associations in language in infants did not render any significant results.

5.4 Discussion

This study aimed to assess the relationship between MMR to deviance in phonemes and tone pairs in the control and streaming design and language composite in infants. The MMR to deviance in the phoneme or tone pair stream in the streaming paradigm or the tone paradigm was not found to be associated with behavioural language performance, and so the hypothesis (H.3.1) was not supported. Essentially, auditory MMR was not linked to language proficiency.

5.4.1 Relationship between MMR and language in infants.

In contrast to the expectations, the current data did not confirm the association between auditory discrimination and behavioural markers of language in infants. The results are contrary to the previous work in this area linking frequency discrimination in tones with language outcomes (Ahmmed et al., 2008; Benasich et al., 2002, 2006, 2016; Cantiani et al., 2016b; Choudhury & Benasich, 2011; Kolesnik et al., 2019), including linguistic tones (Chen et al., 2016; Hua & Dodd, 2000), as well as the ability to discriminate linguistic stimuli such as vowels (Guttorm et al., 2010; Shafer et al., 2012), phonemes (Cheour et al., 1998b; Conboy et al., 2008; Espy & Cwik, 2004; Guttorm et al., 2005, 2010; Kuhl et al., 1983, 2005; Leppänen et al., 2004; Leppänen & Lyytinen, 1997; Lyytinen et al., 2001; Marcus et al., 1999; Molfese, 1989, 2000; Molfese & Molfese, 1985; Molfese & Searock, 1986; Molfese et al., 2001, 2003; Puolakanaho et al., 2008; Seery et al., 2014) and pseudowords
(Leppänen et al., 2002). However, a review by Kujala and Leminen (2017) indicates that this relationship may be stronger in children with language difficulties rather than the general population. As such division was not performed in the current study the effect may have disappeared.

Nonetheless, it is peculiar that no significant relationship was observed between phonetic discrimination and language scores in infants in this study. Closer inspection of the literature, however, reveals very little evidence on the associations between linguistic MMR and language ability in infancy. This could be partly attributed to rapid maturational changes in the MMR in the first year of life (see section 1.3.4). However, the behavioural assessment of communication is due critical evaluation here. Behavioural language assessments are generally less reliable in infants than in older children, since the younger the infant, the fewer the exhibited behavioural indicators of receptive and expressive communication (see section 1.2.2 for details).

Additionally, performance on the assessment is subject to the child's alertness and emotional state, which may be varied due to a number of factors, such as teething or fever. Environmental contributors, such as a change to daily routine or unfamiliar people (which experimenters tend to be) or setting (e.g., a lab or children's centre) or even unfamiliar toys and other objects may also be important. Above which, individual differences in the development of receptive and expressive communication may be affecting the relationship with the MMR (Karousou & López-Ornat, 2013; Marchman, Adams, Loi, Fernald, & Feldman, 2016). As a result, collapsing the language data into a composite variable may have dissolved the effect (Kidd & Donnelly, 2020; Nelson, 1981).

By the same token, combining the responses of infants growing up in monolingual and bilingual environments may have further diluted the relationship. This is likely in the current sample as the initial results showed more advanced receptive language in monolingual than bilingual participants but not in expressive communication and the overall composite language score (Hoff, 2013; Nacar Garcia, Guerrero-Mosquera, Colomer, & Sebastian-Galles, 2018; Williams, 1977).

Finally, as generally large numbers of participants are required to show the associations between neural and behavioural correlates, and considering that some of the showed trends were indicative of this relationship (specifically between discrimination of simple acoustic contrast and language performance), a larger sample could have evidenced it more clearly (Bujang & Baharum, 2016).

5.4.2 Conclusion

To conclude these findings, neural responses to acoustic contrast were not associated with language proficiency in 5- to 11-month-old infants. Considering the scarcity of literature on the topic, this was the first attempt to assess potential associations between auditory MMR and behavioural language performance in infancy.

Chapter 6. Study 4 – The MMR in infancy and language at 2 years

6.1 Introduction

In the United Kingdom, on average two children within a classroom will have some form of language deficits. This is approximately 5 - 8% of children but increases within the more impoverished socioeconomic areas to between 20 and 50% (Farah et al., 2006; Ginsborg, 2006; Lindsay & Strand, 2016; Locke et al., 2002). However, by the school age, the language networks in the brain have been consolidated (see section 1.1.4 for details) and speech and language interventions are less effective (Benasich et al., 2016; Botting, Gaynor, Tucker, & Orchard-Lisle, 2016; Koegel, Koegel, Ashbaugh, & Bradshaw, 2014; Olswang, Rodriguez, & Timler, 1998) . Therefore, there is a need to identify and address neural precursors to language and communication before then in order to prevent their potential damaging long-term effects in school and later in employment.

Traditionally, MMR presence has been sought when assessing the relationship between the ability to discriminate the vowel (Lyytinen et al., 2004; Molfese & Searock, 1986) or consonant contrast (Jansson-Verkasalo et al., 2010; Molfese et al., 1992; Molfese, 1989, 2000; Molfese & Molfese, 1985) and language development. Previous research has linked the MMR latency and amplitude in infancy with language outcomes in childhood (de Haan & Thomas, 2002; Guzzetta et al., 2011; Jansson-Verkasalo, et al., 2004).

More recently, MMR to deviance in linguistic tones in tonal languages has been associated with language development (Chen et al., 2016; Lee et al., 2012;

Xi et al., 2010a; Zhang et al., 2012) and MMR to harmonic tone pairs has been reported to predict language outcomes in children with familiar risk of language disorders (Benasich et al., 2002, 2006; Carral et al., 2005; Choudhury & Benasich, 2011; Choudhury et al., 2007; de Haan & Matheson, 2009).

Phonemes (Kushnerenko et al., 2013; Nath, at al., 2011; Tomalski et al., 2012) are also commonly employed as stimuli in research exploring early language development. ERPs to auditory stimulus and specifically the MMR component, have been implicated in predicting language outcomes. Auditory MMR in adults (Rihs, et al., 2013; Prakke & Romanski et al., 2014) and children (Kuhl & Rivera-Gaxiola, 2008) has been associated with language performance. However, this relationship is not as straightforward when applied to infants.

6.1.1 Predicting from MMR in infancy to language ability at 2 years.

There are considerable volumes of published studies describing the role of neural auditory processing in assessing early language development (Banaschewski & Brandeis, 2007; Benasich et al., 2002; Conboy & Kuhl, 2011; Dehaene-Lambertz & Gliga, 2004; Gilley et al., 2017; Key et al., 2007; Kudo, Nonaka, Mizuno, Mizuno, & Okanoya, 2011; Parise & Csibra, 2012; Rivera-Gaxiola et al., 2005; Shafer et al., 2011, 2012; Wanrooij et al., 2014; Weber, Hahne, Friedrich, & Friederici, 2004).

For example, the ability to process change in frequency of tone pairs between 6 months and 4 years predicted language outcomes up to 4 years of age in typically developing children and those with a familiar risk of language disorders (Choudhury & Benasich, 2011). A similar effect was found by assessing the relationship between ERPs at 6 months and verbal ability at 20 months of age in Italian infants (Cantiani et al., 2016b, 2019; Riva et al., 2018).

This research is in line with other ERP prediction studies showing that infant ERPs can be used to estimate later language outcomes (Benasich et al., 2006; Friedrich & Friederici, 2006; Molfese, 2000; Molfese & Molfese, 1985, 1997). This includes a study by Guttorm and colleagues (2005) of newborn ERPs predicting later receptive language skills at 2.5 and 5 years of age. The authors argued that infants' processing of phonetic contrast in the right hemisphere, manifested behaviourally as reduced performance on receptive language tests when they were older (see also Bailey & Snowling, 2002).

Other EEG studies by Molfese and Molfese and team took the longitudinal approach with preterm and full-term born infants (Key et al., 2007; Molfese, 1989, 1990; Molfese et al., 2001; Nelson & Franzen, 1997). The studies identified EEG responses in infants that distinguished between those with appropriate and poor for age language skills at 3, 5, and 8 years of age. They demonstrated that individual differences in neonatal ERP waveforms bilaterally in response to consonant sounds predict verbal ability at 3 (Molfese & Molfese, 1985; Molfese & Searock, 1986) and 5 years of age (Molfese & Molfese, 1997). Literacy skills were moreover predicted from infant responsiveness to consonant contrasts, successfully discriminating between poor and typical readers at age 8 years (Molfese, 2000, 2003; Schaadt et al., 2015).

In view of all that has been mentioned so far, one may suppose that the predictive properties of the ERPs in infants and language outcomes are established. However, the relationship between linguistic and non-linguistic MMR in infancy and receptive and expressive communication at 2 years of age has not been systematically assessed in the control phoneme and tone paradigms as well as deviance in phoneme and tone pair stream in the streaming paradigm.

6.1.2 Rationale for the study.

Study 4 set out to evaluate the relationship between auditory processing in infancy and language ability at 2 years. The control phoneme and tone pair paradigms were developed in Study 1, and the streaming paradigm was designed in Study 2. Time windows with significant MMR to deviance in the tone pair paradigms and phoneme and tone pair streams in the streaming paradigm were compared with the receptive and expressive communication scores on Bayley-III (Bayley, 2005).

It is an objective assessment of infant language ability, although some developmental differences between monolingual participants and infants who regularly engage with at least two languages could be expected (see section 1.2.2 . However, assessing the relationship between MMR in infancy and language ability at 2 years based on language experience was beyond the scope of this thesis and so was not explored in this study beyond being included in the initial analysis.

6.1.3 Experimental predictions.

Consistently with the literature, MMR to deviance in auditory paradigms in infancy was hypothesised to predict language ability at 2 years (H.4.1), as operationalised by the phoneme and tone pair paradigms and phoneme and tone pair streams in the streaming paradigm and standardised scores on the receptive or expressive communication subtests in Bailey-III (Bayley, 2005) behavioural assessment.

6.2 Methods

See section 2.2 on information regarding recruitment of the participants and 3.2.1 Any deviation or additional details are provided below.

6.2.1 Participants.

A subset of families with infants from the 2015-2017 birth cohort, who participated in Study 1 or 2, were invited for the second visit to UEL Babylab when the participants reached two years of age. Nineteen families agreed to attend the testing session (12 males). Fifteen participants were from Study 1 and 4 from Study 2. There were 12 bilingual infants. The mean age of the children was M=24.12, SD=0.39 months (M=734, SD=12 days) and ranged between 23-25 months (713-758 days).

6.2.2 Design.

It was a correlational study of within-subject design. The relationship between MMR to deviance in the control paradigms in a subset of infants from Studies 1 and 2 and their behavioural language ability when they reached their second birthday was investigated. Figure 6.1 illustrates the structure of the study.

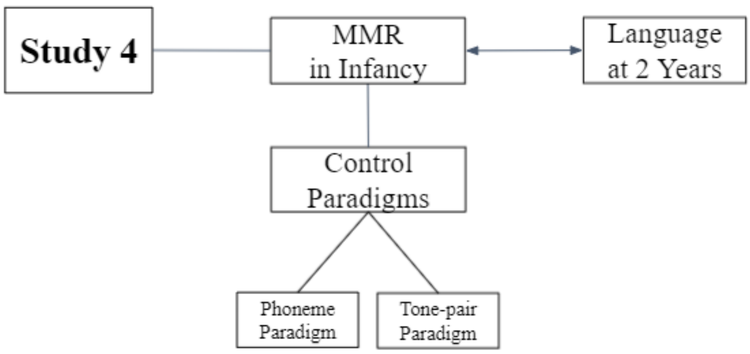

Figure 6.1 Schematic representation of the manipulations in Study 4. The arrow demonstrates the relationship between MMR to deviance in the control paradigms and phoneme and tone pair streams in the stream paradigm in infancy and behavioural language performance at 2 years.

EEG Paradigms.

Two EEG paradigms were conducted both in Study 1 and 2 and they were employed for correlations in the current study: phoneme and tone pair paradigms. They were of a single stream phoneme and tone pair design. The phoneme and tone pair paradigms were counterbalanced. Each contained 350 trials, 70 of which were deviant (20% of all trials) and 280 standard stimuli. They were presented in pseudorandomised order in that no two deviants followed each other.

Language assessment.

Language ability in a subset of participants from Studies 1 and 2 was assessed with Bayley-III (Bayley, 2005) receptive and expressive communication subtests around their second birthday. The tasks within each subtest increased in difficulty, following developmental milestones.

6.2.3 Stimuli and apparatus.

Study 4 comprised two EEG auditory paradigms conducted in infancy and a behavioural assessment of receptive and expressive communication carried out when participants turned 2 years.

EEG Paradigms.

Information on the paradigms is presented in section 2.4.1, with the detailed description in section 4.2.3

Behavioural language assessment.

Bayley-III (Bayley, 2005) receptive and expressive communication subtests were used in Study 4. Detailed information on the assessment is provided in section 2.4.2.

Receptive communication. At two years of age, participants were expected to identify a label for at least one familiar object and a picture of an object by pointing to it. Understanding two-part instructions was considered one of the most advanced skills for this age group.

Expressive communication. Upon turning 2 years of age, participants in Study 4 were expected to name at least one familiar object and combine words and gestures at the very least. Producing from 3- to 5-word sentences was regarded as an advanced verbal ability for 2-year-olds.

6.2.4 Procedure.

General information on experimental sessions is recorded within section 2.5.2. Figure 6.2 illustrates counterbalancing of the tasks with the age division.

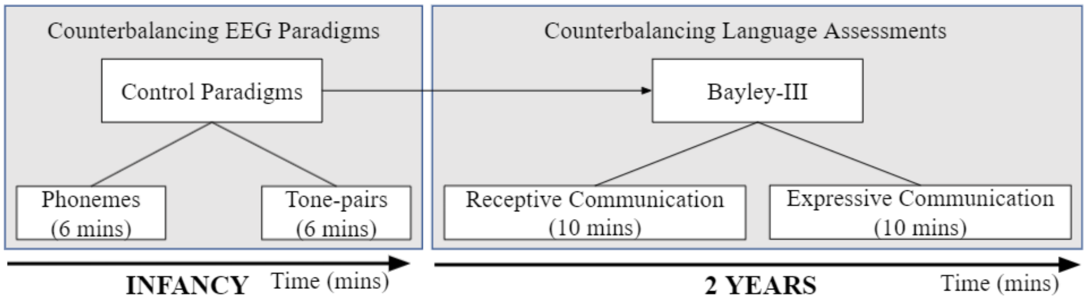

Figure 6.2 Schematic representation of the procedure in Study 4. The EEG tasks were conducted at the first session in infants, while the language assessment when participants turned 2 years. Within the EEG tasks, the streaming paradigm was presented first. Order of the following phoneme and tone pair paradigms was counterbalanced. Bayley-III receptive and expressive communication subtests were also counterbalanced. The EEG timelines for each age are presented with the duration of each task in brackets.

6.2.5 Data processing and analysis.

EEG data processing.

The EEG data were collected from participants as part of Study 1 or 2 in their infancy. Data processing was carried out using Net Station 5.2.0.2 software (EGI, Eugene, OR). General information about the process is provided in section 2.6.1 and details relevant only to Study 2 in section 4.2.5.

Processing language scores.

The scores on Bayley-III receptive and expressive language subtests (Bayley, 2005) were acquired within 2 weeks of participants' second birthday. They were standardised using the provided tables to each infant's age, which was corrected for gestation. The total scaled score was calculated by adding the standardised scores. This value was represented on the language composite scale and the latter was used in the analysis. General information on processing behavioural data can be found in section 2.5.2.

Analysis strategy.

The analyses relevant to all studies are presented in section 2.6.2. In the current study, Pearson correlations were carried out between clusters and time windows with significant MMR to phoneme and tone pair paradigms collected from infants and the language composite scores in Bayley-III when participants reached 2 years of age. Figure 6.3 demonstrates the analysis strategy.

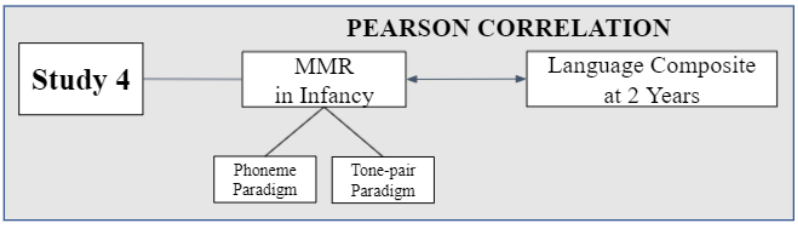

Figure 6.3 Schematic representation of analyses in Study 4. The detailed structure of paired t-tests used to identify significant MMR for the correlations can be found in Figure 2.10.

6.3 Results

MMR to the phoneme and tone pair paradigms in infancy were expected to be associated with the language composite scores on Bayley-III language assessment (Bayley, 2005) at 2 years of age.

6.3.1 Assessment of linguistic proficiency in 2-year-olds.

Linguistic performance of a subset of the children from 2015-2017 cohort was assessed at a second session at 2 years of age. The sample comprised fifteen participants from Study 1 and four from Study 2. Behavioural raw scores were standardised and corrected for gestation, using Bayley-III (Bayley, 2005) standardisation tables. Appendix G. illustrates the distribution of the standardised and corrected for gestation the receptive (Figure G.1), expressive communication (Figure G.2) and the language composite (Figure G.3) scores as a function of participants' age. Behavioural performance by the 2-year-olds was variable but generally evenly distributed. Monolingual participants scored significantly higher than bilinguals on receptive ($t_{(17)} = 2.219$, $p=0.04$) and expressive communication ($t_{(17)} = 3.114$, $p=0.006$). Analysis of the language composite scores confirmed the difference, $t_{(17)} = 2.753$, $p=0.014$. The descriptive statistics are provided in Table 6.1 for reference.

Table 6.1

Language Results in 2-Year-Olds

	Bayley scores	Language experience	Mean	SD	Minimum	Maximum	Scale range	Part. no.
Raw	Receptive communication	Monolingual	29.571	4.791	25	38	0-49	7
		Bilingual	23.417	6.501	14	37		12
	Expressive communication	Monolingual	35.143	5.305	28	45	0-48	7
		Bilingual	26.333	6.457	16	36		12
Standardised	Receptive communication	Monolingual	12.000	3.215	9	18	1-19	7
		Bilingual	8.500	3.371	4	16		12
	Expressive communication	Monolingual	13.000	3.215	9	19	1-19	7
		Bilingual	8.500	2.939	4	13		12
Total language	Sum of scaled scores	Monolingual	25.000	5.972	18	37	2-38	7
		Bilingual	17.000	6.135	8	29		12
	Language Composite	Monolingual	114.857	17.583	94	150	47	7
		Bilingual	91.500	17.977	65	127	153	12
	Percentile rank	Monolingual	-	-	34	>99.9	0.1-100	7
		Bilingual	-	-	1	96		12

Note. The raw and standardised scores (Bayley, 2005) were divided by language experience (monolingual and bilingual) in 2-year-olds. The scores were standardised to age, which was corrected for gestation. See the distribution of the standardised scores in scatterplots in Figure G.1 for receptive communication and Figure G.2 for expressive communication and Figure G.3 for the language composite scores.

6.3.2 Relationship between MMR in infancy and language at 2 years.

The EEG results for the phoneme and tone pair paradigms between 2-year-olds who previously participated in Study 1 (15 infants) or Study 2 (4) were combined for analysis into the concluding sample of 19 participants. Pearson correlations were carried out to establish the relationship between language ability and time windows with significant MMR to deviance in the tone pair paradigm based on clusters and time windows in either Study 1 (Table 3.1) or Study 2 (Table 4.1) where relevant. As no significant MMR was found in response to the phoneme paradigm in Study 2, this data was not used for the corelation analysis. All the results are available in Table 6.2 below. Their significance was corrected with Bonferroni-adjusted alpha level of 0.004 (0.05/11) for multiple comparisons to reduce the probability of Type I error. Following the correction, none of the correlations was significant. Therefore, MMR to auditory deviance in infancy was not associated with behavioural language at 2 years.

Table 6.2

Pearson Correlation Results Between MMR to Deviance in the Tone Pair Paradigm in Infancy and Language Composite at 2 Years

Tone Pair Paradigm			Language Composite	
Bin (ms)	Region	Hemisphere	Pearson R	Sig. (2-tailed)
300-350	Temporal	Right	0.421	0.073
350-400	Temporal	Left	-0.361	0.128
400-450	Temporal	Left	-0.003	0.992
		Right	0.320	0.182
450-500	Temporal	Left	0.280	0.246
		Right	0.473	0.041
500-550	Temporal	Left	-0.009	0.972
		Right	0.031	0.899
550-600	Temporal	Left	0.029	0.907
		Right	-0.169	0.490
600-650	Temporal	Right	0.041	0.808

Note. Bayley-III (Bayley, 2005) language composite scores were standardised to participants' age, which was corrected for gestation. Time windows were selected based on the significant MMR amplitude to deviance in the tone pair paradigm in infants in Studies 1 and 2 (N=19). See Table A.3 in Appendix A and Table C.4 in Appendix C for details. The correlations were tested against a Bonferroni-adjusted alpha level of 0.004 (0.05/11) and none was significant.

6.3.3 Summary of the results.

MMR to oddball change in the tone pair paradigm in infancy did not correlate with Bayley-III language composite at 2 years.

6.4 Discussion

This study aimed to assess the relationship between neural responses to speech sounds in infancy and communication skills at 2 years. Contrary to the expectations, auditory MMR was not associated with language performance at 2 years of age, and thus the hypothesis (H.4.1) was not supported.

6.4.1 MMR in infancy versus language at 2 years.

In the current study, the ability to discriminate acoustic contrast was not linked to communication at 2 years (Bayley, 2005). This outcome is contrary to the previous literature, in which the proficient acuity and neural sensitivity to frequency contrast has been positively associated with language development (Bitz et al., 2007; Jansson-Verkasalo et al., 2004a; Shankarnarayan & c, 2007; Sharma et al., 2006; Mridula Sharma, Purdy, Munro, Sawaya, & Peter, 2013). In addition, a wealth of literature supports this concept (Cantiani et al., 2019; Castro-Camacho et al., 2015; D'Souza et al., 2017; Espy & Cwik, 2004; Fernald & Marchman, 2012; François et al., 2017; Garcia-Sierra et al., 2011; Guttorm et al., 2001, 2010; Kuhl et al., 2005; Kushnerenko, Tomalski, Ballieux, Potton, et al., 2013; Molfese, 1989, 2000; Molfese & Molfese, 1985, 1997; Molfese & Searock, 1986; Ortiz-Mantilla et al., 2012, 2013, 2016; Shafer et al., 2012).

Admittedly, the link between auditory processing and behavioural language outcomes in early development, while present, may have been diluted by the limitations of the study. Individual differences in language experience and undiagnosed prospective language difficulties could be the major moderating factors in this relationship. Their potential contribution is discussed in Study 3 (see section 5.4.1 for details).

6.4.2 Conclusions.

The purpose of the current study was to assess the predictive potential of the linguistic and non-linguistic MMR in infancy in determining language proficiency at 2 years of age. The current investigation has not confirmed such associations. Nevertheless, this study raises important questions about the mechanisms behind Auditory processing excellent language development in infants and toddlers. A natural progression of this work is to analyse the association between MMR and specific language mechanisms in older children.

Chapter 7. Study 5 – The effect of stream modulation on the MMR in children.

7.1 Introduction

Auditory scene analysis and segregation of sounds are essential for language processing in a complex environment (Bregman, 1990; Snyder & Alain, 2007; Sussman, 2004; Woods & McDermott, 2015). Researchers turned their attention towards auditory processing in a more environmentally viable setting, as opposed to the silent background, in the second half of the 20th century (Bregman & Rudnicky, 1975; Snyder & Alain, 2007).

Early attempts at studying speech processing in a natural scene involved dichotic design. In the first such study by Cherry (1953), participants were exposed to two different speech samples played simultaneously but were instructed to listen and repeat ('shadow') only one of them. When subsequently asked about the unattended stream of speech, they could identify only the more salient features such as timbre (male versus female voice) and 400 Hz tone distractor. The contents of the unattended speech, or even that it was reversed went unnoticed. Similar results were produced, when participants were given headphones that played a different story into each ear (the 'dichotic listening' paradigm). Participants were able to segregate the stories based on location and attend to the relevant stream while ignoring the other.

7.1.1 Stream modulation and its effect on MMR in children.

This paradigm has been recently explored in a longitudinal design. Behavioural and ERP comparisons were made between three age groups: 3- to 5- and 6- to 8-year-old children and adults (Sanders, Stevens, & Neville, 2006). The youngest age group of 3- to 5-year-old children processed both speech streams. When exposed to two different stories played concurrently in each headphone, but instructed to listen to one story only, afterwards they could answer questions about the story played on the supposedly unattended side. The ERPs to the attended and unattended stimuli embedded in the stories: /ba/ phoneme representing the linguistic and scrambled /ba/ as the non-linguistic deviants were recorded. There was no effect of the attended side, and both types of probes were processed, but linguistic stimuli had the advantage.

Behavioural and ERP responses from 6- to 8-year-old children resembled those of adults rather than younger children's performance, with more errors while answering questions about the unattended story and larger MMR amplitudes to the attended than the unattended deviants. It could be implied that selective attention developed and becomes more efficient with age (Gomes et al., 2000, 2007; Werner, 2007). In addition, linguistic deviants elicited larger MMR than non-linguistic contrast in all three age groups.

Karns et al. (2015), investigated this phenomenon across development in 3 to 5, 10, 13, 16-year-olds and adults. They were assessed on their ability to process speech and nonspeech probes within a story. In a similar manner as the 'cocktail party' design (Cherry, 1953), two stories were played from loudspeakers located to the left and right of the participant, one from each direction, but they were instructed to listen to only one of them and ignore the other. The deviants to the continuous speech, either phoneme /ba/ or a buzz were played from each speaker, randomly within each story. The ability to process the interfering sounds was tested with EEG. The 3- to 5- and 10-year-olds were more likely to process deviants on the unattended side, but the effect was more significant for the linguistic than non-linguistic deviants (also in Coch, Sanders, & Neville, 2005). The older age groups showed attendance effect but no linguistic advantage.

Others have reported attentional bias in processing auditory streams (Downes, Kirkham, Telfer, & de Haan, 2017; Olguin, Bekinschtein, & Bozic, 2018; Paavilainen, Saarinen, Tervaniemi, & Näätänen, 1995; Sanders et al., 2006; Courtney Stevens, Fanning, Coch, Sanders, & Neville, 2008; Sussman, 2017; Sussman et al., 1998; Sussman, Horváth, Winkler, & Orr, 2007), despite the general consensus that the MMR is preattentive (Alho et al., 1998a, 1998b; Allen, Kraus, & Bradlow, 2000; Čeponiené et al., 2004; Cheour et al., 2002b; Gomes, Ritter, & Vaughan, 1995; Gumenyuk et al., 2003; Paavilainen, 2013; Schröger, 1997; Winkler et al., 1996).

According to the auditory scene analysis theory outlined in section 1.1.2, when an individual is exposed to a streaming design, initially all sounds in the sequence are processed as one stream, but with an increased number of repetitions, neural memory traces accumulate information about a pattern of deviants and standards in each of the streams separately (Bregman, 1978). Researchers propose that sufficient frequency contrast between the streams is required to distinguish them (Aslin, Saffran, & Newport, 1998; Deike et al., 2012; Denham & Winkler, 2006; Fishman, Arezzo, & Steinschneider, 2004; Haywood & Roberts, 2010; Sussman et al., 2015; Vliegen & Oxenham, 1999) and that mechanisms underlying neural streaming involve switching between the streams in order to process deviance within each (Bendixen, Denham, Gyimesi, & Winkler, 2010; Coensel & Botteldooren, 2010; Gutschalk et al., 2005; Moore & Gockel, 2012).

Processing acoustic change in the simple single stream design is thought to generate larger MMR than processing the same deviance when plotted along another stream (Almonte et al., 2005; Cusack, 2005; Deike et al., 2012; Haywood & Roberts, 2010; Moore & Gockel, 2012; Shaw, Baart, Depowski, & Bortfeld, 2015; Szycik, Stadler, Brechmann, & Münte, 2013; Tóth, Kocsis, Urbán, & Winkler, 2016)

Koerner and colleagues (Koerner, Zhang, Nelson, Wang, & Zou, 2017) investigated sentence processing against the silent background and in noise in adults and found earlier onset and larger MMR amplitude in the silence than in noise conditions. In a manner akin to adults, 9-10 years of age children selectively attended to speech, which had to be filtered out from masking sounds (Jones, Moore, & Amitay, 2015). This indicated that older children and adults are efficient in attending to the task-relevant stimuli while ignoring the distractors.

More recently, literature has emerged that offers some explanation of the relationship between the MMR and selective attention (Dykstra & Gutschalk, 2015; Gomes, Molholm, Christodoulou, et al., 2000; Sussman et al., 1999, 2014; Winkler, Sussman, et al., 2003) but the debate continues. The streaming paradigm has the potential to reveal the underlying mechanisms of MMR in the linguistic and non-linguistic setting and the relative contribution of selective attention to these mechanisms in early development. No study has however directly explored these patterns as yet.

7.1.2 Stimulus type and its effect on MMR in children.

There is some controversy over whether linguistic or non-linguistic contrast generates a larger MMR (Rauschecker, 1998). Whereas in infancy larger MMR is produced to narrowband tone frequency than to phonetic contrast (Kozou et al., 2005; Xi et al., 2010a), this may reverse in primary school, presumably due to emphasis on phonics and phonological processing as well as learning to read (Shafer et al., 2010; Tallal, 1980). Indeed, this phenomenon has been reported in typically developing 4-7 years old children (Pirjo Korpilahti, Krause, Holopainen, & Lang, 2001), although no differences were found (due to attenuated MMR to phonemes) in children at risk of dyslexia (Bitz et al., 2007) except for the earlier onset of the MMR to sine tones than vowels in all children (also Lohvansuu et al., 2013). By contrast, in a study by Čeponiené and colleagues (2003), 6-12-year-old typically developing, and children on autistic spectrum processed vowel and complex tone contrast but did not discriminate sinusoidal tones. The debate over advantage of speech or nonspeech stimuli in auditory processing is still open with even more controversy surrounding it in younger children and infants. Further information on the topic is available in sections 3.1.3 and 4.1.2.

7.1.3 Rationale for the study.

Study 5 investigated MMR in a complex auditory scene in children. In order to do so, the stream and stimulus modulations and their effects on the MMR were examined. The paradigms employed in the study consisted of the phoneme oddball and the long ITI tone pair paradigms developed in Study 1. They were treated as control paradigms. The third, streaming paradigm was new and comprised phoneme and tone pair streams, which were the control paradigms plotted alternately in streaming design. The paradigm represented two competing contrasts embedded in the linguistic and non-linguistic streams. The ability to process contrast in one of the streams indicated stream segregation, whereas discriminating both contrasts signified processing both of the competing streams independently. All three paradigms were used earlier in Study 2 in infants.

7.1.4 Experimental predictions.

Based on previous literature, streaming was hypothesised to affect the temporal and spatial distribution of the MMR. This would explicitly relate to absolute mean MMR amplitude to the phoneme paradigm versus phoneme stream in the streaming paradigm and the tone pair paradigm versus tone pair stream in the streaming paradigm (H.5.1). Moreover, the stimulus type modulation was expected to influence the temporal and spatial distribution of the MMR in 4- to 6-year-old children. Specifically, MMR would be differentially affected by deviance in the phoneme and tone pair paradigms and between phoneme and tone pair streams within the streaming paradigm (H.5.2).

7.2 Methods

The general methods are outlined in Chapter 2. Any differences or further details included in Study 5 are presented below.

7.2.1 Participants.

Fifty-two children (of which 25 were males) participated in the sessions. However, 11 participants were removed from the sample: 2 participants refused to take part in the EEG testing, and 9 produced large noise artefacts in at least one of the three paradigms.

The final sample comprised of 41 participants. There were 14 monolingual English-speaking families, whilst the remainder were exposed to at least one additional language at home. Their age varied between 4 and 6 years when corrected for gestation (52-82 months), M=5.57, SD=0.55 years (M=67, SD=7 months). Mean gestational age of all participants at birth was M=9.10, SD=0.36

months. Their ethnicity was of Caucasian (17 children), Asian (17), Afro-Caribbean (4) or mixed (3) background.

Forty mothers agreed to provide their educational level. Four had GCSEs, 6 acquired A-Levels and the remainder held a higher degree: 21 at undergraduate and 9 at postgraduate level. The average gross income of 26 families who disclosed it was £65,195 (SD=92,504) and varied from £6,780 to £400,000, which represented a broad and economically diverse sample set of households.

7.2.2 Design.

The study was of a within-participant design and resembled Study 2 in infants (see section 4.2.2 in Chapter 4). There were three experimental paradigms: one streaming and two control paradigms. Figure 7.1 demonstrates the structure of the manipulations.

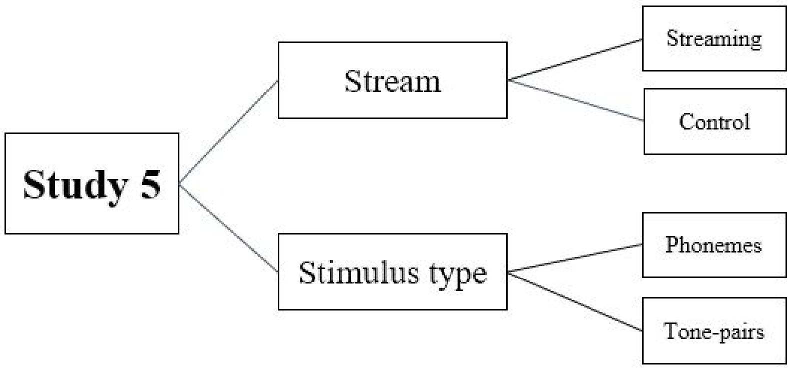

Figure 7.1 Schematic representation of manipulations in Study 5.

Stream modulation.

The streaming paradigm was originally developed in Study 2 (see section 4.2.3). The control paradigms were included in the streaming paradigm.

Stimulus type modulation.

Discrimination of spectral (phonemes /ba/ and /da/) and narrowband (tone pairs of 100-100 Hz and 100-300 Hz) frequency contrasts was assessed both in the streaming paradigm and the control one-stream phoneme and tone pair designs. The control paradigms were originally developed for Study 1 (see section 3.2.2).

7.2.3 Stimuli and apparatus.

The EEG paradigms resembled those from Study 2 (section 4.2.3). General information on the phoneme oddball and the long ITI tone pair paradigms can also be found in section 2.4.1. Two control paradigms were used: a phoneme and a tone pair paradigm. The streaming paradigm consisted of phoneme and tone pair streams, which were the two control paradigms plotted in an alternating order.

7.2.4 Procedure.

The full procedure is outlined in section 2.5 in General Methods. Any information specific to Study 5 is detailed here. Three EEG paradigms were conducted during the experimental session. The streaming paradigm was administered first. The control phoneme and tone pair paradigms followed in the counterbalanced order. Each task continued for 6 minutes. Figure 7.2 illustrates the procedural timeline for the study. EEG responses were collected with EGI 128-HydroCel Geodesic Sensor Net (EGI, Eugene, OR) and recorded with EGI Net Station version 4.3.1. Details on the EEG data recording are provided in section 2.5.1.

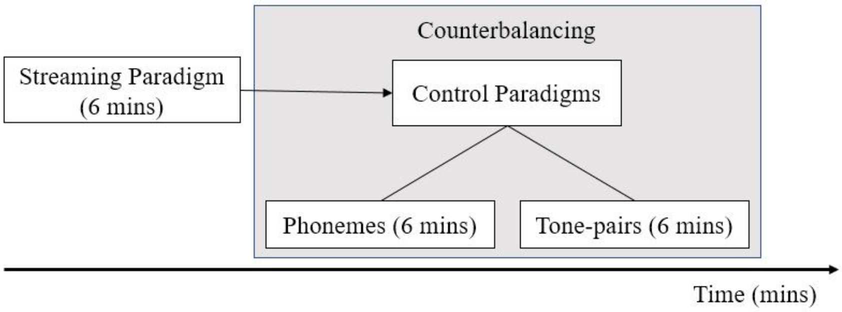

Figure 7.2 Schematic representation of the procedure in Study 5. The streaming paradigm was presented as first. Order of the following phoneme and tone pair paradigms was counterbalanced. An example is presented in the timeline with the duration of each paradigm in brackets.

7.2.5 ERP data processing and analysis.

Processing EEG data.

The full EEG data processing is included in section 2.6.1. In Study 5, it was carried out using Waveform Tools in Net Station 4.3.1. Following artefact rejection, the average percentage of trials for each child accepted for further analysis was 98% (M=68.26; range: 65-70 trials) for /ba/ and /low-high/ deviants and 97% (M=272.84; range: 252-280 trials) /da/ and /low-low/ standards.

Analysis strategy.

Details on the general strategy are found in section 2.6.2. Paired t-tests were performed to establish time windows and clusters with significant MMR to deviance in the phoneme and tone pair paradigms and phoneme and tone pair stream in the streaming paradigm. This was followed by ANOVAs to assess the difference between the onset and mean amplitude of the absolute MMR to the stream and stimulus type manipulations. Figure 7.3 outlines the analysis strategy and specifically manipulations for ANOVA.

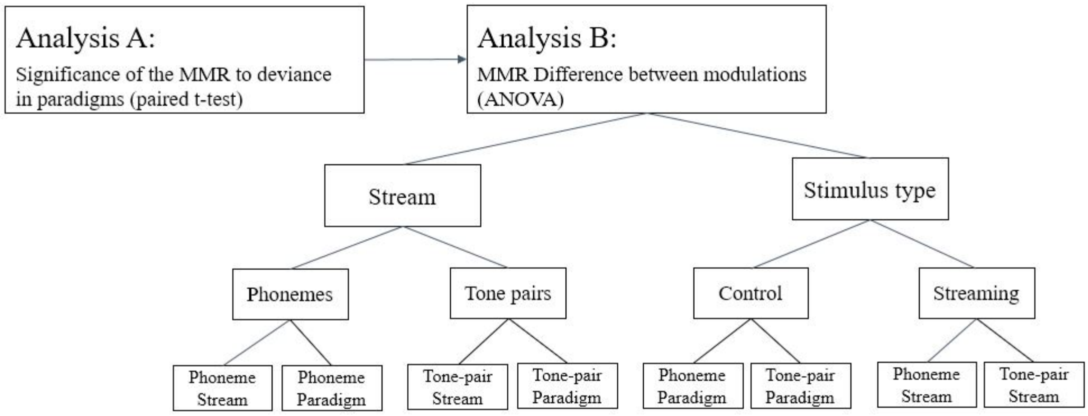

Figure 7.3 Schematic representation of analyses in Study 5. The detailed structure of a paired t-test in Analysis A can be found in Figure 2.10.

7.3 Results

The effect of stream and stimulus modulations on the MMR in children were examined in the current study. The approach used in this investigation resembled the one employed in Study 2 in infants (see section 4.3). The first stage of analysis was to identify the time windows with significant onset and mean MMR amplitude to each of the phoneme and tone pair contrasts in the streaming and control paradigms. Those with probability value $p<0.01$ were considered significant. The stricter approach (as opposed to the standard $p<0.05$) was taken to correct for multiple comparisons and reduce the possibility of Type I error. (see section 2.6.2 for details). The follow-up analyses examined the effect of stream on the linguistic and non-linguistic MMR in children. The final analyses were performed to identify the effect of stimulus within the streaming and control paradigms on the MMR.

To assess these differences, paired t-tests (to establish time windows and clusters with significant MMR) and repeated-measures ANOVAs (on time windows with the onset and absolute MMR deflections) were performed. Age corrected for gestation was included as a covariate and language experience (monolingual versus bilingual) as a between-participant factor in the initial stages of analyses, but they did not affect the modulations and were excluded from the final tests (all $F<3.638$, $p>0.060$, with exception of the stimulus modulation in the control paradigms, section 7.3.3.

7.3.1 Significance of the MMR.

Table 7.1 summarises details on the timing of onset and mean MMR amplitude (as operationalised with 50 ms time windows) in all paradigms. Deviance in the phoneme paradigm evoked only a small MMR amplitude within 400-450 ms in the right frontal cluster, whereas the phoneme stream in the streaming paradigm did not produce a significant MMR. In contrast, tone pairs elicited earlier onset and mean amplitude of the MMR than phonemes (as counted from the onset of the deviant tone in the pair) but timings within both stream modulations were comparative.

Table 7.1

Time Windows with Onset and Mean MMR Amplitude to Deviances in the Streaming and Control Paradigms

	MMR in children (50 ms time windows)	
MMR to deviance in:	Onset	Time of mean MMR amplitude
Phoneme stream in streaming paradigm	Not significant	Not significant
Tone pair stream in streaming paradigm	200-250 (60-110) LF & RF	250-300 (110-160) LF & RF
Phoneme paradigm	400-450 RF	400-450 RF
Tone pair paradigm	200-250 (60-110) LF & RF	250-300 (110-160) LF & RF

Note. Where relevant, numbers in brackets represent time windows after the deviant tone in the tone pair. Abbreviations indicate: LF - left frontal, RT – right frontal, LT – left temporal and RT – right temporal clusters. Paired t-tests the summary is based on are available in Appendix G.

Table 7.2 summarises the MMR mean amplitude results to phonetic and tone pair deviance in the streaming and control paradigms. Tone pair paradigm elicited largest positive MMR amplitude. By contrast, the phoneme paradigm evoked attenuated but negative MMR, whereas significant MMR was not observed to phonetic deviance within the streaming paradigm.

Table 7.2

MMR at the Onset and the Mean Amplitude to Deviances in the Streaming and Control Paradigms

	MMR amplitude in µV (averaged into 50 ms time windows)	
MMR to deviance in:	Onset	Mean MMR amplitude
Phoneme stream in streaming paradigm	Not significant	Not significant
Tone pair stream in streaming paradigm	1.122 LF	2.076 LF
Phoneme paradigm	-1.127 RF	-1.127 RF
Tone pair paradigm	1.510 LF	2.478 LT

Note. The MMR amplitudes to all contrasts were significant at p<0.01. MMR values used in the analyses were absolute, i.e., there were no negative values. Abbreviations indicate: LF - left frontal, RT – right frontal, LT – left temporal and RT – right temporal clusters. Paired t-tests the summary is based on are available in Appendix G.

7.3.2 Stream modulation.

The differential effects of the number of streams in a paradigm on the spatial and temporal distribution of the MMR in children was examined in phonemes and tone pairs.

Stream modulation in phonemes.

MMR to deviance in phonemes. The series of topomaps in Figure 7.4 and 7.5 illustrate the grand average mean MMR difference between ERPs to /ba/ deviant and /da/ standard phonemes in the phoneme paradigm and phoneme stream in the streaming paradigm. No large amplitudes in the MMR were visible to the phoneme paradigm, although some weak negative deflections emerged over the frontal area in the 400-450 ms and for the remainder of the epoch. Phonetic contrast in the streaming paradigm did not elicit a significant MMR, i.e., children did not process consonant deviance when presented as competing with the tonal change in the streaming design.

MMR TO DEVIANCE IN PHONEME STREAM

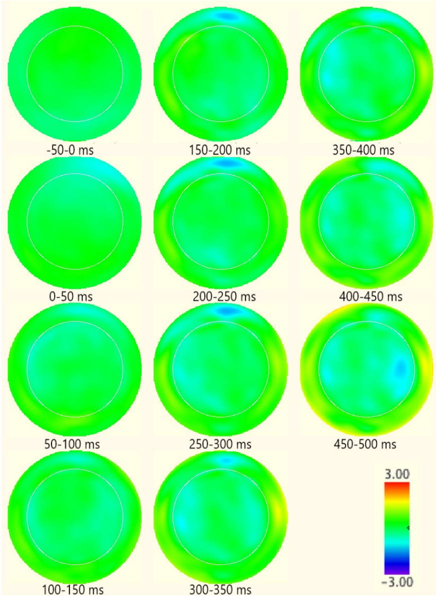

Figure 7.4 Topographic representation of the development of mean MMR amplitude to deviance in the phoneme stream in the streaming paradigm. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. See Table G.1 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

MMR TO DEVIANCE IN PHONEME PARADIGM

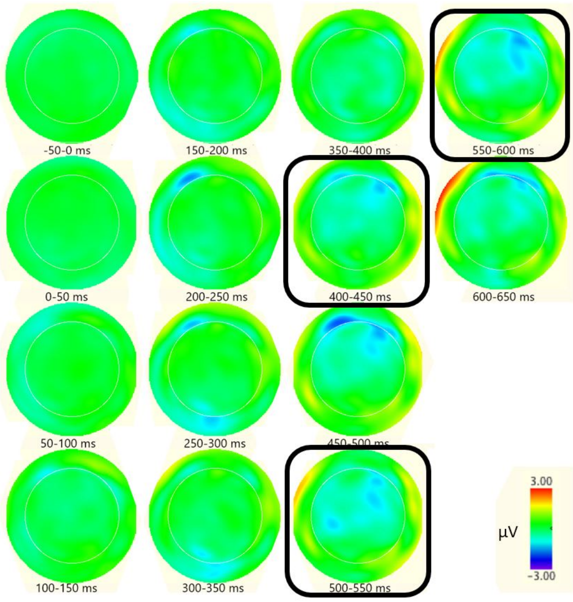

Figure 7.5 Topographic representation of the development of mean MMR amplitude to deviance in the phoneme paradigm. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The encircled time windows indicate significant MMR (p<0.01) in the right temporal cluster (channels 101, 102, 108 and 115). See Table G.3 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

Grand average ERP images of the left and right frontal and temporal clusters confirmed the weak discrimination between deviants and standards in the phoneme, but not in the streaming paradigm. Although the obligatory ERP components were clearly distinguishable in both, only the phoneme paradigm elicited habituation to standard stimuli (Figure 7.7). No such difference between the ERPs to deviants and standards could be observed in the responses to phoneme stream in the streaming paradigm (Figure 7.6).

GRAND AVERAGE ERPS TO PHONEME STREAM

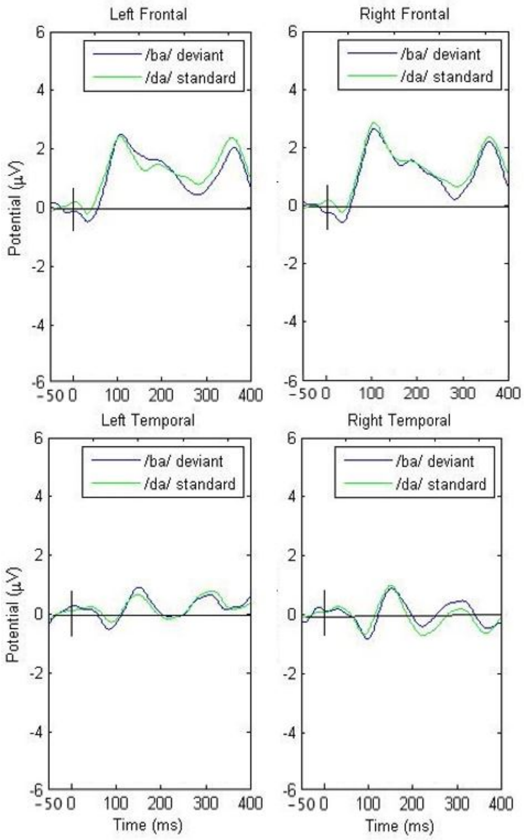

Figure 7.6 Grand-average ERP amplitudes to /ba/ deviant (blue line) and /da/ standard phonemes (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in phonemes stream in the streaming paradigm. Based on paired t-tests between deviants and standards on 50 ms time windows within 100-400 ms post-stimulus-onset, the difference between ERPs to deviants and standards did not reach significance (at p<0.01). See Table G.1 for t-test results and Figure H.1 for distribution of ERPs across the scalp in EGI 128-channel system.

GRAND AVERAGE ERPS TO PHONEME PARADIGM

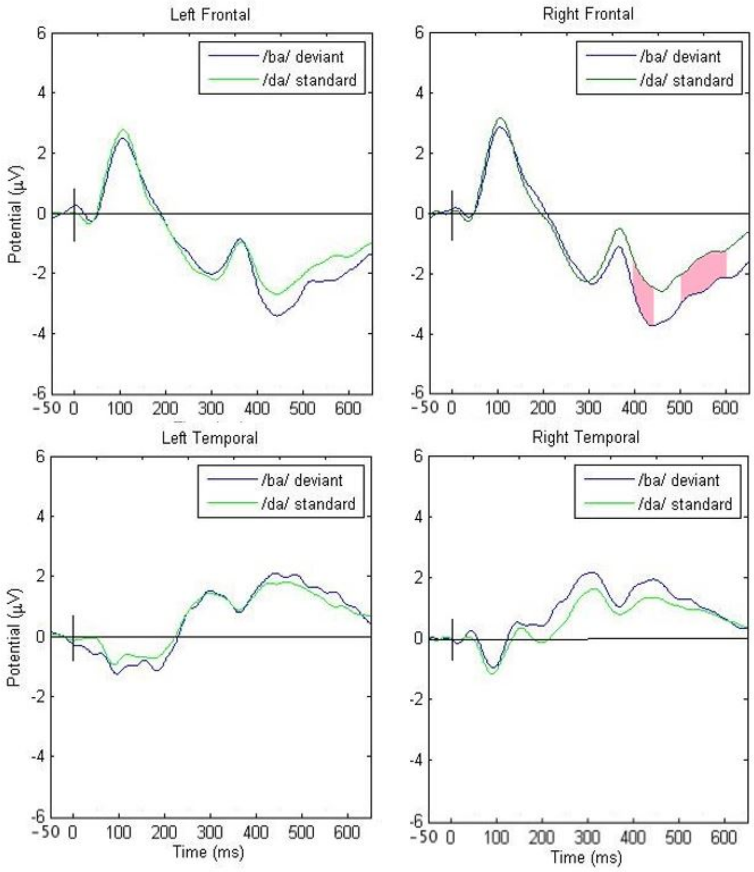

Figure 7.7 Grand-average ERP amplitudes to /ba/ deviant (blue line) and /da/ standard phonemes (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) to deviance in the phoneme paradigm. Significant MMR (based on paired t-tests) is highlighted in red ($p<0.01$). See Table G.3 for t-test results and Figure H.3 for distribution of ERPs across the scalp in EGI 128-channel system.

MMR difference between phonetic contrast in the streaming and control paradigm. Figure 7.8 demonstrates the grand average images MMR waveforms in the left and right frontal and temporal clusters in response to deviance in the phoneme stream within the streaming paradigm and in the phoneme paradigm. The waves in each cluster resemble each other and are close to the baseline. Within the comparison duration, which encompassed the epoch in the phoneme stream, no MMR was observed to either of the contrasts. MMR to deviance in the phoneme paradigm only reached significance within 400-450 ms over the right frontal cluster, which was after the epoch in the phoneme stream ended. No comparison analysis was therefore performed.

MMR WAVEFORMS TO DEVIANCE IN PHONEMES

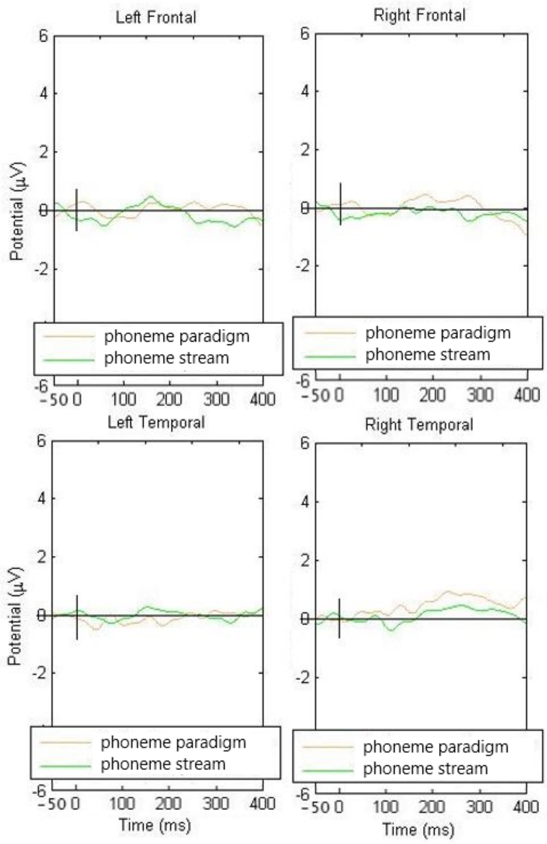

Figure 7.8 Grand average MMR waveforms generated to deviance in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in the phoneme paradigm (orange line) and in phoneme stream in the streaming paradigm (lime green line). See Table G.1 and Table G.3 for mean MMR amplitude values and Figure H.5 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

Stream modulation in tone pairs.

The effect of the number of simultaneous streams on the MMR to deviance in tone pairs was examined in this analysis. The tone pair stream in the streaming paradigm and the control tone pair paradigm were expected to generate a differential effect on the spatial and temporal distribution of the MMR.

MMR to deviance in tone pairs. The series of grand average topomaps (Figures 7.9 and 7.10) illustrate the development of the MMR to deviance in tone pair stream in the streaming paradigm and the tone pair paradigm. Despite much a shorter epoch duration in tone pair stream than in the tone pair paradigm, both figures showed a similar pattern of deflections. The MMR was however more extensive in the tone pair paradigm than in tone pair stream in the streaming paradigm. The MMR emerged frontally as positive deflection within 200-250 ms. This was followed, by negative MMR at the end of the epoch in tone pair stream and up to 450 -500 ms in the tone pair paradigm. Only the first significant MMR deflection was used in analyses.

MMR TO DEVIANCE IN TONE PAIR STREAM

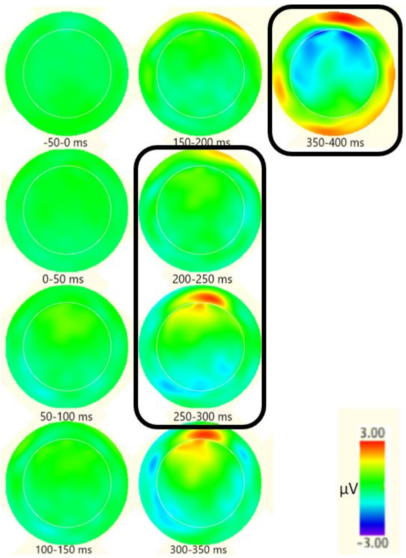

Figure 7.9 Topographic representation of the development of mean MMR amplitude to deviance in tone pair stream in the streaming paradigm. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The encircled time windows indicate significant MMR (p<0.01) bilaterally in the left (channels 19, 20, 23, 24, 27 and 28) and right frontal (3, 4, 117, 118, 123 and 124), and left (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115). See Table G.2 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

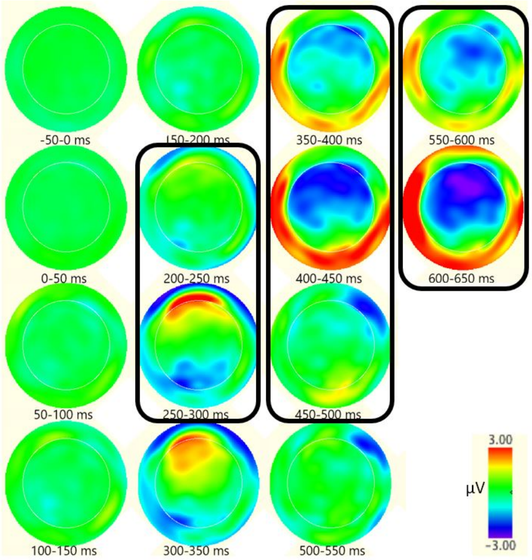

Figure 7.10 Topographic representation of the development of mean MMR amplitude to deviance in the tone pair paradigm. Each topomap demonstrates MMR as distributed across the scalp and averaged into 50 ms time window. The encircled time windows indicate significant MMR (p<0.01) bilaterally in the left (channels 19, 20, 23, 24, 27 and 28) and right frontal (3, 4, 117, 118, 123 and 124), and left (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115). See Table G.4 for t-test results. The scale in the bottom right corner represents the MMR amplitude distribution in microvolts.

The grand average ERPs are recorded in Figure 7.11 and Figure 7.12. Closer inspection revealed large responses with increased effect over the frontal clusters. More intense negative potentials were observed in the tone pair paradigm rather than a tone pair stream in the streaming paradigm.

GRAND AVERAGE ERPS TO TONE PAIR STREAM

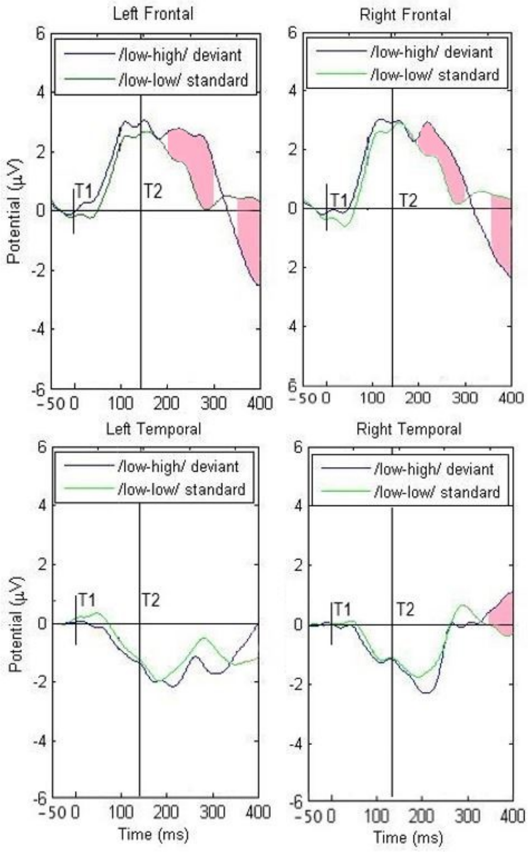

Figure 7.11 Grand average ERP amplitudes to /low-high/ deviant (blue line) and /low-low/ standard tone pairs (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) generated to the deviance in tone pair stream in the streaming paradigm. T1 and T2 indicate the onset of each tone in the pair. Significant mean difference (based on paired t-tests) is highlighted in pink ($p<0.01$). See Table G.2 for t-test results and Figure H.2 for distribution of ERPs across the scalp in EGI 128-channel system.

GRAND AVERAGE ERPS TO TONE PAIR PARADIGM

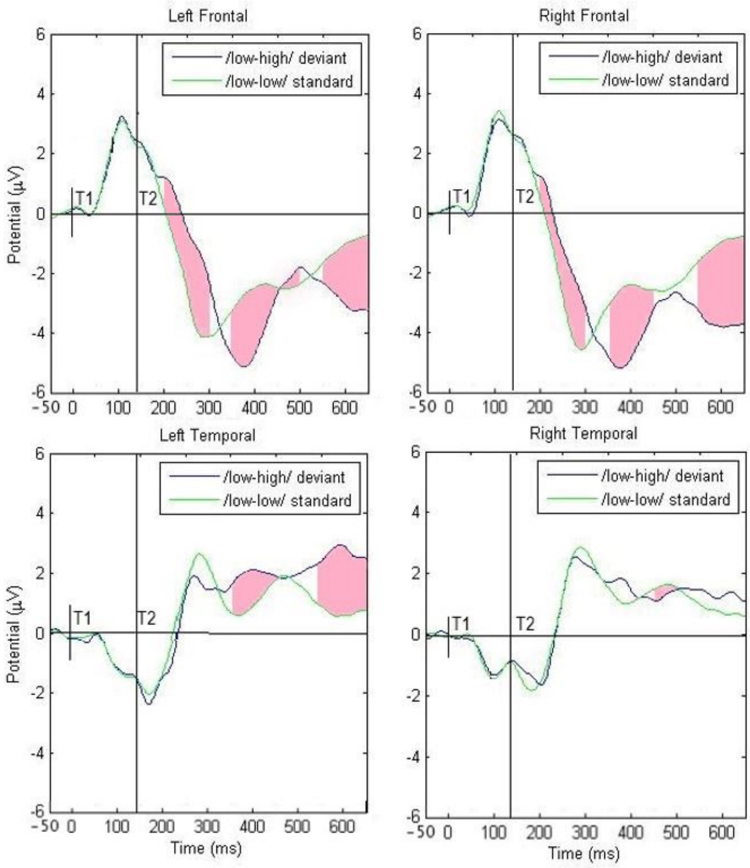

Figure 7.12 Grand average ERP amplitudes to /low-high/ deviant (blue line) and /low-low/ standard tone pairs (green line) in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) generated to the deviance in the tone pair paradigm. T1 and T2 indicate the onset of each tone in the pair. Significant mean difference (based on paired t-tests) is highlighted in pink ($p<0.01$). See Table G.4 for t-test results and Figure H.4 for distribution of ERPs across the scalp in EGI 128-channel system.

MMR difference between tone pair contrasts in the streaming and tone pair paradigm. The grand average images of both MMR waveforms are available in Figure 7.13. Large positive MMR deflections were present to both modulations, and overall, their patterns were similar. This observation was confirmed with three-way repeated-measures ANOVA with factors: stream (tone pair stream in the streaming paradigm versus tone pair paradigm) x hemisphere (left versus right) x time window (200-250 and 250-300 ms) was carried out. The time windows and clusters were selected based on the onset and the first but also the largest mean MMR amplitude in the frontal clusters (at $p<0.01$) in both modulations (see Table 7.1 for a summary of the results).

As expected, the main effect of time was identified, $F_{(1,40)} = 14.497$, $p<0.001$, $\eta^2 = 0.266$, which was likely due to the development of the MMR between the time windows. Importantly, no interactions or other main effects were produced (all $F < 2.153$, $p>0.149$) indicating that the MMR to tone pair was not affected by the stream design.

MMR WAVEFORMS TO TONE PAIRS

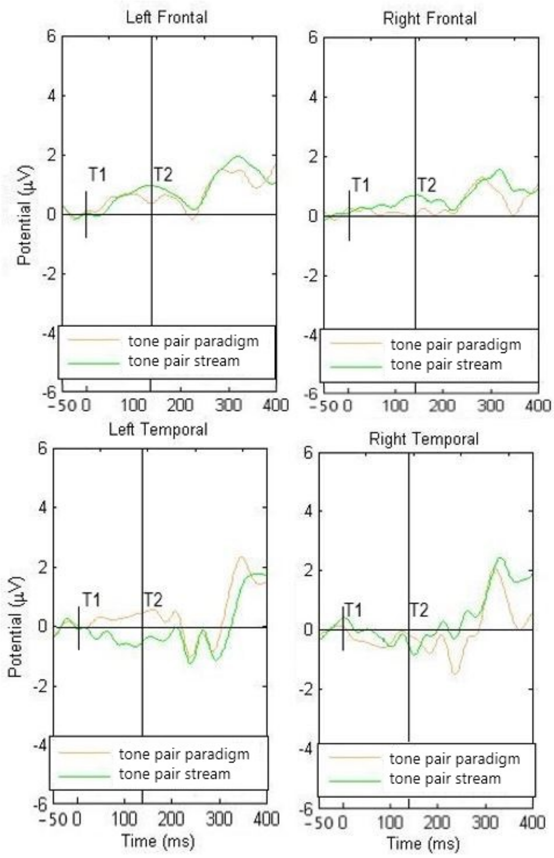

Figure 7.13 Grand average MMR waveforms generated to deviance in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in tone pair stream in the streaming paradigm (lime green line) and in the tone pair paradigm (orange line). T1 and T2 indicate the onset of each tone in the pair. See Table G.2 and Table G.4 for mean MMR amplitude values and Figure H.6 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

7.3.3 Stimulus modulation.

MMR difference between phoneme and tone pair streams in the streaming paradigms.

MMR waveforms to deviance in phonemes and tone pairs in the streaming paradigm were compared in Figure 7.14. Large MMR deflections to tone pairs, particularly in the frontal clusters, were contrasted with poorly developed or indeed absent MMR to phonemes.

MMR WAVEFORMS TO PHONEME AND TONE PAIR STREAMS

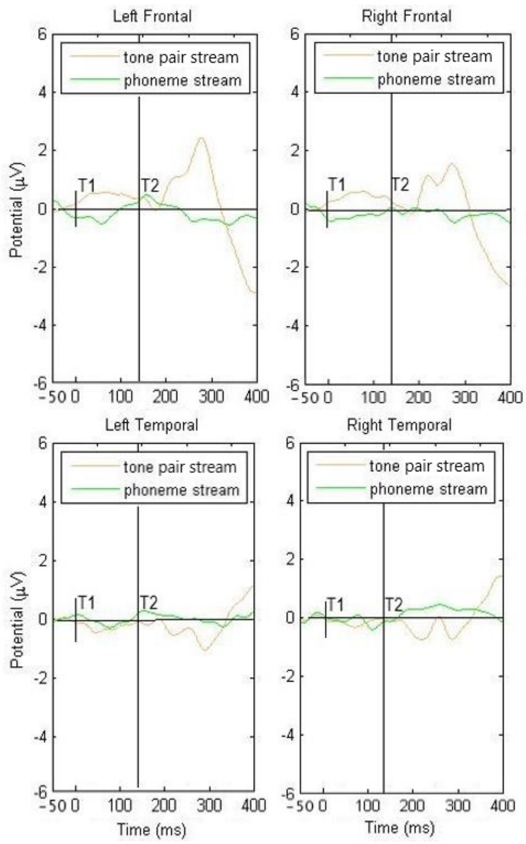

Figure 7.14 Grand average MMR waveforms generated to deviance in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in phoneme (orange line) and tone pair (lime green line) streams in the streaming paradigm. T1 and T2 indicate the onset of each tone in the pair in the tone pair stream. See Table G.1 and Table G.2 for mean MMR amplitude values and Figure H.7 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

Three-way repeated measures ANOVA with factors: stimulus (phonemes versus tone pairs) x hemisphere (left versus right) x time window (200-250 and 250-300 ms) was carried out. The time windows were selected based on the onset and mean MMR amplitude (at $p<0.001$) in the frontal clusters in tone pair stream since no significant MMR was identified in phoneme stream in the streaming paradigm. An interaction between all the factors was identified, $F_{(1,40)}=4.260$, $p=0.046$, $\eta^2=0.096$. Post hoc ANOVAs on each time window confirmed larger MMR to tone pairs (M=2.248, SE=0.265) than phonemes (M=1.537, SE=0.139) within 250-300 ms ($F_{(1,40)}=5.141$, $p=0.029$, $\eta^2=0.114$). Other analyses were not significant, all $F<2.311$, $p>0.135$.

Difference between MMR to deviance in the phoneme and tone pair paradigms.

Figure 7.15 represents MMR waveforms to contrasts in the phoneme and tone pair paradigms. Distinctive MMR deflections to tone pairs were present specifically in the frontal and to a lesser extent in temporal clusters, although some negative deviance was observed in the frontal clusters to phonemes.

Four-way mixed MANOVA with a between-subject factor – language experience (monolingual versus bilingual children) and repeated-measures factors: stimulus (phonemes versus tone pairs) x hemisphere (left versus right) x time window (200-250, 250-300 and 400-450 ms) was performed.

Overall, main effect of stimulus was revealed, $F_{(1,39)}=13.973$, $p=0.001$, $\eta^2=0.264$. Larger MMR was recorded to tone pairs (M=2.438, SE=0.138) than phonemes (M=1.808, SE=0.148). Intriguingly, interaction between language experience and stimulus was identified, $F_{(1,39)}=4.600$, $p=.038$, $\eta^2=0.105$. Post hoc analyses in each language group revealed larger MMR to tone pairs (M=2.278, SE=0.217) than phonemes (M=1.737, SE=0.212) in monolingual participants, $F_{(1,13)}$=15.002, p=0.002, η^2 =0.536, but no difference in bilinguals, $F_{(1,13)}$=1.750, p=0.197, η^2 =0.063 (M=2.148, SD=0.161 to tone pair and M=1.880, SD=0.173 to phoneme contrast). Other effects and interactions were also not significant (all F<3.710, p>0.060).

MMR WAVEFORMS TO PHONEME AND TONE PAIR PARADIGMS

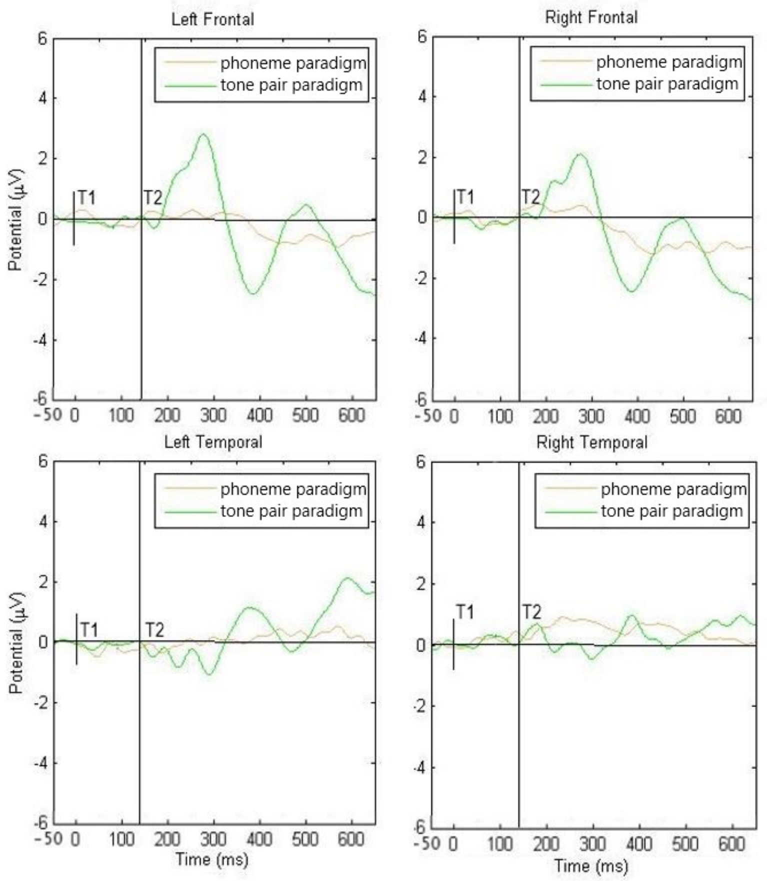

Figure 7.15 Grand average MMR waveforms generated to deviance in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in the phoneme (orange line) and tone pair (lime green line) paradigms. T1 and T2 indicate the onset of each tone in the pair in the tone pair paradigm. See Table G.3 and Table G.4 for mean MMR amplitude values and Figure H.8 for distribution of MMR waveforms across the scalp in EGI 128-channel system.

7.3.4 Summary of the results.

Together these results provide valuable insights into the auditory processing of the acoustic and specifically linguistic stimuli in children. Overall, the stream modulation did not affect MMR to deviances in phonemes and tone pairs within the compared windows. However, despite absence of the MMR within the phoneme comparisons, the phoneme contrast in the control paradigm elicited MMR after the epoch in the streaming paradigm ended. More consistent and larger MMR was elicited to both tone pair deviances, i.e., in the streaming and control paradigms. Stimulus modulation revealed an advantage of the tone pair over phoneme discrimination in monolingual but not bilingual children.

In summary, the results in this chapter indicate that the stream modulation was not influential in processing auditory contrasts. Within the stimulus modulation, the less powerful phonetic discrimination was consequently more vulnerable to competition from the salient tonal MMR in the streaming paradigm. The linguistic MMR however, peaked towards the end of the epoch in the phoneme paradigm, although still attenuated in comparison to MMR to the tone pair paradigm, particularly in monolingual participants. Both contrasts were processed equally in bilinguals.

7.4 Discussion

The current study aimed to systematically examine the difference in MMR to phonetic and tone pair contrasts in the streaming paradigm and the control phoneme and tone pair paradigms in children. Stream modulation did not have a differential effect on the MMR in phonemes or in tone pairs. Indeed, the neural signatures within both stimulus categories were indistinguishable. Hypothesis one, stating that the stream modulation would have a distinctive effect on the MMR was, therefore not supported (H.5.1). Nonetheless, whilst the waveforms to phonetic contrast resembled each other in their absence of the MMR until the end of the epoch in the phoneme stream, MMR to phoneme paradigm reached significance later within 400-450 ms.

By contrast, the stimulus modulation had a differential effect on the MMR difference between phoneme and tone pair streams in the streaming paradigm and the phoneme and tone pair paradigms. The mean MMR component was consistently more spatially and temporally robust to the tonal than phonetic contrast, particularly in the monolingual sample. Hypothesis two was, therefore supported (H.5.2).

7.4.1 Stream modulation and its effect on MMR in children.

The current study revealed no effect of stream modulation on the MMR in children within the duration of the epoch in the streaming paradigm, i.e., up to 400 ms post-stimulus-onset. The finding reflects the results in Study 2 in infants (see Chapter 4. General explanations for this finding, which are associated with both the infants' and children's cohorts are described in section 4.4.1.

Stream modulations in phonemes.

Despite the absence of the MMR early in the epoch, as reflected both in the streaming and the control phoneme paradigm, children processed change in the latter within 400-450 ms and only over the right frontal cluster. Although weak, the MMR was significant. Children were therefore more sensitive to phonetic contrast in an otherwise silent environment, than when it competed with a non-linguistic stream. This accords with previous observations, which showed that the linguistic MMR is generally more pronounced in a single rather than double stream design (Almonte et al., 2005; Baart, Vroomen, Shaw, & Bortfeld, 2014; Deike et al., 2012; Haywood & Roberts, 2010; Moore & Gockel, 2012; Paavilainen, Kaukinen, Koskinen, Kylmälä, & Rehn, 2018; Szycik et al., 2013; Tóth et al., 2016; Venezia et al., 2017) or masked in noise (Koerner, Zhang, Nelson, Wang, & Zou, 2017).

More broadly, speech sounds tend to be processed more efficiently in one rather than two competing contrasts (Day & Wood, 1972; Wood et al., 1971) and speech comprehension is easier against silent background rather than in the multispeaker environment, such as in dichotic listening (Cherry, 1953; Schneider, Li, & Daneman, 2007; Stevens, Sanders, & Neville, 2006) or complex auditory scene (Millward, Hall, Ferguson, & Moore, 2011; Thompson, Woodruff Carr, White-Schwoch, Otto-Meyer, & Kraus, 2017; Weise, Grimm, Müller, & Schröger, 2010).

Another possible explanation for the dissociation between linguistic MMR in streaming and control paradigms, may be attributable to the difference in the duration of epochs. Considering that children's MMR was observed to the phoneme paradigm after the shorter epoch in phoneme stream in the streaming paradigm ended (400 ms after the onset of the stimulus in phoneme stream and 650 ms in phoneme paradigm), it could be claimed that phonetic processing in the streaming design lacked enough time before the next stimulus began to develop and reach significance (Choudhury et al., 2011; Näätänen et al., 2007; Paavilainen, 2013; Sussman et al., 2008; Wang et al., 2005). Section 1.3.6 outlines the effect of trial duration on the MMR.

These speculations are supported by research in adults, which suggests that phonetic contrast in the streaming context, even if participants are instructed to ignore the irrelevant stream, still develops some, although attenuated MMR. This is in particular prevalent in aging adults (Getzmann, Falkenstein, & Wascher, 2015; Getzmann & Näätänen, 2015; Getzmann, Wascher, & Falkenstein, 2015) and may be an indicator of developmental change in MMR and attentional focus across the lifespan (Deoni, Dean, O'Muircheartaigh, Dirks, & Jerskey, 2012; Gomes et al., 2000b; Kushnerenko et al., 2002a; Shafer et al., 2000; Strotseva-Feinschmidt et al., 2015; Todd et al., 2013).

The attenuated MMR to the ignored contrast in streaming may also represent the difference between the early sensory versus later cognitive response. The MMR within 400-450 ms and specifically N4 component in ERP to deviants (Henderson, Baseler, Clarke, Watson, & Snowling, 2011) in the phoneme paradigm may demonstrate cognitive processing of the phonetic contrast (Friederici, 2005; Hahne, Eckstein, & Friederici, 2004). This could be facilitated by the age of the sample, as 4-6-year-old children focus on phonics in learning to read and spell in primary school (Bitz et al., 2007; Jakoby, Goldstein, & Faust, 2011; Jansson-Verkasalo et al., 2004a; Maurer et al., 2003a, 2009; Meng et al., 2005; Partanen et al., 2011; Phillips et al., 2000; Shankarnarayan & Maruthy, 2007; Sussman et al., 2015; Tallal, 1980). No such facilitation took place in the streaming design, as the epoch was presumably only long enough to discriminate the contrast at the basic sensory level (Fischer & Hartnegg, 2004; Nozza, 1987; Ponton, Eggermont, Kwong, & Don, 2000; Presacco, Simon, & Anderson, 2016; Ruggles, Bharadwaj, & Shinn-Cunningham, 2011). This would explain overall immature ERPs and reduced habituation to the standard stimuli in the streaming in comparison to responses to the control paradigm.

Alternatively, since MMR emerged only to the control paradigm and was rather weak and short (although significant), possible attentional interference cannot be ruled out. As children were instructed to watch a silent cartoon but were uninformed either way about the background sounds, discriminating the auditory contrast was not the goal of the task as far as they were concerned. Indeed, paying attention to them could instead hinder following the story on the screen, and the most efficient use of attentional resources in such a complex audio-visual environment would be to ignore the sounds (Gomes et al., 2000, 2007; Phélip et al., 2016; Sussman & Steinschneider, 2009).

In this light not processing the phonetic contrast in the streaming paradigm could be considered an appropriate response (Justen & Herbert, 2018; Näätänen et al., 2007; Sussman et al., 2014) and efficient selective attention to task at hand while ignoring distractors (Gomes et al., 2000b; Snyder & Alain, 2005, 2007; Wetzel & Schröger, 2014). The observed MMR to the phoneme paradigm could, therefore, result from the order of the tasks, with the streaming paradigm always played first, followed by the counterbalanced phoneme and tone pair paradigms. Section 4.4.1 outlines the justification for such design of the EEG session and explains how this may have affected the MMR in infants.

Being exposed to the phonetic and tonal contrasts in the streaming paradigm may have increased neural sensitivity to both contrasts in the control paradigms. However, instead of attenuated habituation, as in infants who processed it at the sensory level (see section 4.3.2 for results on MMR to phonetic contrast in infants), it led to attending and discriminating the contrast at the more cognitive level (Barry et al., 2009; Linnavalli et al., 2018b).

Therefore, although MMR is generally believed to be a preattentive mechanism (Bitz et al., 2007; Čeponiené et al., 2004; Gumenyuk et al., 2003; Molholm, Gomes, & Ritter, 2001), there is support for attentional influence in discriminating linguistic stimuli (Berman & Friedman, 1995; Coch et al., 2005; D'Angiulli, Herdman, Stapells, & Hertzman, 2008; Karns et al., 2015; Stevens, Lauinger, & Neville, 2009; Stevens et al., 2006). Nonetheless, it is important to reiterate that despite the above interpretations, within the comparison windows, the stream modulation did not influence phonetics discrimination.

Stream modulation in tone pairs.

Tone pairs elicited large MMR deflections and generally broad spatial and temporal distribution of the MMR, but there was no difference between MMR to tone pair contrast in the streaming and control tone pair paradigm. Namely, stream modulation did not influence tone pair discrimination. This also accords with the earlier observation in Study 2 in infants (section 4.4.1).

The MMR to deviance in tone pairs in the streaming and tone pair paradigms follows similar pattern as in a publication by Winkler et al. (2003a). In their study, both tone pair modulations elicited MMR. The MMR was more pronounced to the control than streaming design, which also partly reflects the current observation. Although the difference was not significant, the MMR to the tone pair paradigm appeared larger and more widely spread than in response to the tone pair stream.

7.4.2 Stimulus modulation and its effect on MMR in children.

The current study discovered that children appeared to find phoneme contrast more challenging than processing tone pairs. This was the case both for the control phoneme and tone pair paradigms and the streaming paradigm. In contrast, the non-linguistic MMR was consistently more significant than its linguistic counterpart in all samples. The current findings are comparable with those of infants from Studies 1 and 2 (sections 3.3 and 4.3.3).

MMR difference between phoneme and tone pair stream in the streaming paradigm.

The most considerable advantage of tone pairs over phonemes on the MMR was found within the streaming paradigm. Although generally following previous findings in infants in Study 2, the absence of the significant MMR to deviance in phoneme stream likely contributed to this effect. Following the auditory scene theory (section Children appeared to segregate the streams but attended to and processed deviance only in the distinctive narrowband acoustic contrast in tone pairs, while ignoring the perhaps less salient spectral, i.e., less discernible consonant contrast (Snyder & Alain, 2007). The MMR advantage in discriminating non-linguistic over linguistic frequency change was also found in adults (Helenius et al., 1999; Jacobsen et al., 2004b; Kasai et al., 2002; Koelsch, Schröger, & Tervaniemi, 1999; Szycik et al., 2013) although evidence for the opposite effect has also been observed (Čeponiené et al., 2002b; Karns et al., 2015; Sorokin et al., 2010; Vouloumanos et al., 2001).

Furthermore, the current results are partly supported by research in dichotic listening, which suggests that linguistic probes are more likely to elicit negative mismatch, while non-linguistic stimuli tend to evoke positive MMR (Coch et al., 2005; Karns et al., 2015), although in those studies more considerable discrimination was found for linguistic sounds between ages 3-10 years and no difference from 13 years of age onwards.

Whether participants attended to the side from which direction the probes originated was also relevant, with more significant responses to both types of stimuli on the attended side (Sanders et al., 2006; Stevens et al., 2008; Sussman et al., 1998). This is important for interpretation of the current findings, as the children were passively exposed to the sounds. The plausible inference is that phonetic discrimination was influenced by attentional bias, whereas no such effect was present when processing more salient and discerning tone pair contrast.

MMR difference between phoneme and tone pair paradigms.

The MMR pattern of activity was overall more pronounced to change in the tone pair than phoneme paradigm. Indeed, MMR to the phoneme paradigm in the current study was of small spatial and temporal distribution and of the late time window, which contrasted with the large MMR broadly spread over the frontal area of the scalp in the tone pair paradigm. The results reflected those from Study 1 in infants (see section 3.3.4). In support of the current findings, the MMR advantage was found in processing tones versus phonemes in frontal and central channels in 8-11 years old children (Lachmann et al., 2005). Likewise, significant MEG responses to nonspeech than speech stimuli were found in typically developing 6– to 14-year-olds, but no difference was observed in children on the autistic spectrum (Yau et al., 2016).

Importantly, this distinction was present in the monolingual but not in the bilingual children, indicating that language experience may have contributed to this effect. Indeed, it appears that bilinguals processed the deviance both in phonemes and tone pairs which suggests that they were equally focused on the salient acoustic and the less discernible linguistic stimuli. Although this was not analysed further in the current study, it could indicate differences in the direction of the MMR amplitude, as reported by Shafer and colleagues (2012). A vowel contrast generated mismatch negativity in bilingual and positive MMR in monolingual infants (although this effect disappeared in toddlers). As the MMN is associated with more advanced processing of the stimuli (Garrido et al., 2009; Chia Ying Lee & Cheng, 2020; Shafer, Yu, & Datta, 2011), this could be a sign of the increased phonetic sensitivity (Datta et al., 2020; Rinker, Alku, Brosch, & Kiefer, 2010).

As outlined in section 1.2.1, younger infants have the ability to discriminate nuances in linguistic sounds (Pons, Lewkowicz, Soto-Faraco, & Sebastian-Galles, 2009; Ragó et al., 2014; Tsuji & Cristia, 2014), but this perceptual awareness disappears with age. It seems possible that bilingual children maintain this susceptibility for longer. Evidence supporting this interpretation comes from a recent study exploring processing of lexical and nonlexical tones by 5–7-year-old children who were either speakers in English and another atonal language or English-Mandarin bilinguals, reported similar findings. While acoustic stimuli were discriminated by all, only participants familiar with Mandarin, perceived the subtle tonal difference in words (Morett, 2020). Overall, it appears that auditory acuity may be driven by linguistic experience(Cabrera, Bijeljac-Babic, & Bertoncini, 2019; Garcia-Sierra et al., 2011; Sundara, Polka, & Genesee, 2006; Werker et al., 2009), with higher threshold, with bilinguals presumably at an advantage (Floccia et al., 2013; Morton & Harper, 2007; Poulin-Dubois, Blaye, Coutya, & Bialystok, 2011).

7.4.3 Conclusion.

The current study confirms that the number of streams does not generally influence MMR. However, the investigation of stimulus modulation has showed that in the passive auditory paradigm children process the more salient stimuli, i.e., tone pairs, in both the control and streaming design and phonemes only when presented in the control paradigm, but not in the streaming design. An implication of this is the possibility attentional bias may be driving the distinctive processing mechanisms involved in discriminating linguistic versus non-linguistic contrast. Moreover, language exposure seems to be an important factor, particularly in discriminating speech sounds.

The empirical findings in this study provide a new understanding of processing complex auditory scene in children and the importance of attention and task relevance on the auditory processing, while bilingualism may specifically influence speech discrimination. This is the first report revealing the mediating contribution of attentional engagement on speech processing in auditory scene in children.

Chapter 8. Study 6 - Associations between the MMR and language in children

8.1 Introduction

There is a growing body of literature that recognises the importance of the auditory MMR as the neuromarker of early language development. These broad associations between linguistic (Chen et al., 2016; Cheour, Shestakova, et al., 2002; Lovio et al., 2010; Schaadt et al., 2015; Shankarnarayan & Maruthy, 2007; Shestakova, Huotilainen, Čeponiené, & Cheour, 2003; Strotseva-Feinschmidt et al., 2015) and non-linguistic MMR and language proficiency in children (Ahmmed et al., 2008; Bailey & Snowling, 2002b; Čeponiené et al., 2003, 2004; Korpilahti et al., 2001; Sussman et al., 2001, 2015) have been consistently reported. The controversy remains over which stimuli and paradigm design induce the MMR pattern, which is most closely linked to language in children.

8.1.1 Stream modulation and its effect on the relationship between MMR and language ability in children.

The vast majority of studies have examined the relationship between MMR and language development using a single stream paradigm design. Several lines of evidence suggest that significant auditory discrimination is associated with higher language scores in children and adults. (Kujala et al., 2010) compared spatial and temporal distribution of the MMR in a multifeatured paradigm between children with Asperger syndrome and controls aged 8-12 years. They found attenuated MMR to phonetic contrast and lower scores on comprehension of instructions and verbal and semantic fluency in the atypically developing group.

By drawing on the concept, Shankarnarayan and Maruthy (2007) have been able to show longer MMR latency to phonemes and tones and reduced phonological processing in 7-12-year-old children with dyslexia, than with chronologically matched controls. Similar MMR pattern has been reported in 8-12-years-old children with reading difficulties (Sharma et al., 2006) and in 5-year-olds with lower scores on the naming pictures tasks (Jansson-Verkasalo et al., 2004).

In relation to this topic, Helenius et al. (1999) assessed the number and duration of trials required to segregate the sounds into two streams in dyslexic participants and controls. Overall, 20 trials x 200 ms trial duration was required to perceive both streams separately in dyslexic subjects, in comparison to 15 trials x 100 ms in control participants.

In addition, in a study by Bitz and colleagues (2007), 6-7-year-old children with phonological deficits generated smaller MMR to phoneme contrast than matched controls, but there was no group difference for the MMR to the tone block. Others have reported similar reduction in the activity with phonological deficits in children and adults in one stream paradigms (Jansson-Verkasalo, et al., 2004a; Maurer et al., 2003a, 2009; Meng et al., 2005, 2008; Meng, Tian, Jian, & Zhou, 2007; Schulte-Körne, Deimel, Bartling, & Remschmidt, 2001; Shankarnarayan & Maruthy, 2007; Sharma et al., 2006; Sussman et al., 2015).

However, few studies have investigated the association between MMR in streaming and behavioural language ability, and across development (Snyder & Alain, 2007). A systematic understanding of how stream processing contributes to language development is therefore still lacking.

8.1.2 Stimulus modulation and its effect on the relationship between MMR and language ability in children.

MMR to phonetic contrast increases during learning to read, as empirically investigated by Schaadt and colleagues (2014) in initially illiterate adults. An increase in the MMR to phonetic contrast between /da/ and /ga/ was found after one month of training. This corroborates with a study by Jansson-Verkasalo et al. (2004) who found decreased MMR to phoneme duration between Finnish /ta/ and /taa/ and reduced performance on the behavioural picture naming task in 4- and 6-year-old children born preterm, in comparison to the full-term born children. Other accounts support the deduction that larger MMR is associated with more advanced language skills in children (Kraus et al., 1993; Maurer et al., 2003a, 2003b; Meng, Jian, Shu, Tian, & Zhou, 2008; Sussman et al., 2015; Zhang et al., 2012).

These results corroborate the findings of a great deal of the previous work on the tone pair paradigms and their screening properties in identifying children with familial risk of language disorders (Benasich et al., 2002, 2006; Cantiani et al., 2016b, 2019; Carral et al., 2005; Choudhury & Benasich, 2011; Choudhury et al., 2007; Fitch & Tallal, 2003; Gumenyuk et al., 2003; de Haan & Matheson, 2009; Riva et al., 2018).

Contradicting evidence has also been found. Opposite MMR amplitude was identified between responses to phonetic and tonal deviance in 7-16 years old children with language disorders than in typically developing children (Bishop & Hardiman, 2010; Bishop, Hardiman, & Barry, 2010, 2011). Children with lower scores on speech comprehension and production, nonword and sentence repetition presented with positive MMR, whereas typically developing controls produced

MMR negativity, which is thought to be a more advanced neural response (Chen et al., 2016; Volkmer & Schulte-Körne, 2018). Section 1.3.4 provides information on the difference in the direction of the MMR amplitude.

Finally, research shows that although it was found overall to be beneficial, bilingualism may hinder speech perception in a noisy environment. Bidelman and Dexter (2015), assessed ten monolingual speakers of English and ten late sequential bilinguals who learnt English as a second language after the age of six. They were assessed in their ability to distinguish English words, such as “tot' versus “taught” when played among multispeaker speech babble, i.e., ‘the cocktail party effect’. Monolingual participants were more accurate in the behavioural responses, and their MMR amplitude to speech was larger than to pseudowords. In comparison, the bilinguals produced attenuated MMR. Nevertheless, the results only showed the expected disadvantage the late bilinguals had in their second language. If the data were collected in their respective dominant languages or from bilinguals who acquired both languages at birth, the results were likely to be indistinguishable from the monolingual group who were experts in their only language (Centurion & Saunders, 1990).

8.1.3 Rationale for the study.

The relationship between linguistic and non-linguistic MMR and language ability in children was examined in Study 6. The MMR was elicited to auditory contrasts in tone pair stream in the streaming and the control phoneme and tone pair paradigms in Study 5 in children. The mean MMR amplitude in the significant time windows was compared to standardised scores on the NEPSY-II (Korkman et al., 2007a, 2007b, 2007c) language subtests. They included:

comprehension of instructions, oromotor sequences, phonological processing, repetition of nonsense words, speeded naming, and word generation. The tasks within each subtest increased in difficulty, following developmental milestones. Although a comprehensive objective language assessment (Ahmad & Warriner, 2001; Brooks, Sherman, & Strauss, 2010; Davis & Matthews, 2010), it is not free from cultural biases which could affect children's performance on the test (Brooks, Sherman, & Iverson, 2010). Section 1.2.2 outlines the issues related to the behavioural measurement of language in development.

8.1.4 Experimental predictions.

In line with previous research, neural auditory discrimination was expected to be associated to language ability in 4- to 6-year-olds (H.6.1), as operationalised by the MMR to deviance in the phoneme and tone pair paradigms and phoneme and tone pair stream in the streaming paradigm and standardised scores on language subtests in NEPSY-II (Korkman et al., 2007a, 2007b, 2007c).

8.2 Methods

The main methods are presented in Chapter 2. See section 7.2.1 in Study 5 for the demographics of the sample. Any additional information is provided below.

8.2.1 Participants.

Forty-one children from the 2010 - 2011 birth cohort participated in the in Study 5 in Chapter 7. As part of the current study, they also underwent a language assessment. However, not all children were willing to participate in all the language subtests, which is why the participant numbers in Table 8.1 are variable.

8.2.2 Design.

It was a correlational study of a within-subject design. The relationship between MMR to deviance in the streaming and control paradigms from Study 5 and behavioural language ability in children were assessed in the current study. Figure 8.1 demonstrates the manipulation and individual language tasks performed by the children.

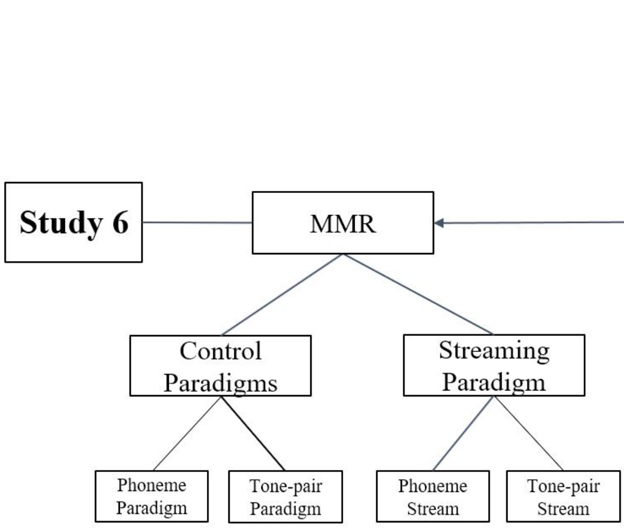

Figure 8.1 Schematic representation of the manipulations in Study 6. The arrow demonstrates the relationship between MMR to deviance in the control paradigms and phoneme and tone pair streams in the stream paradigm and language tests in children.

8.2.3 Stimuli and apparatus.

The tasks used in the study were three EEG auditory paradigms from Study 5 and a behavioural assessment of language.

EEG Paradigms.

General information on the phoneme and the tone pair paradigms is provided in section 2.4.1. The control and streaming paradigms were developed in Study 2 (see section 4.2.3). The two control paradigms were composed of single streams of phoneme or tone pair stimuli each. The streaming paradigm consisted of a phoneme and a tone pair stream, which were combined in the alternating order.

Behavioural language assessment.

The children's language ability was assessed with NEPSY-II assessment (Korkman et al., 2007a, 2007b, 2007c), which involved subtests assessing comprehension of instructions, oromotor sequences, phonological processing, speeded naming, repetition of nonsense words and word generation. Details on the assessment are provided in section 2.5.2.

8.2.4 Procedure.

The general procedure is outlined in section 2.5 Description of the EEG recording can be found in section 2.5.1 and information on NEPSY-II (Korkman et al., 2007a, 2007b, 2007c) language assessment in section 2.5.2. Procedural timeline and counterbalancing the order of all the tasks in Study 6 are outlined in Figure 8.2.

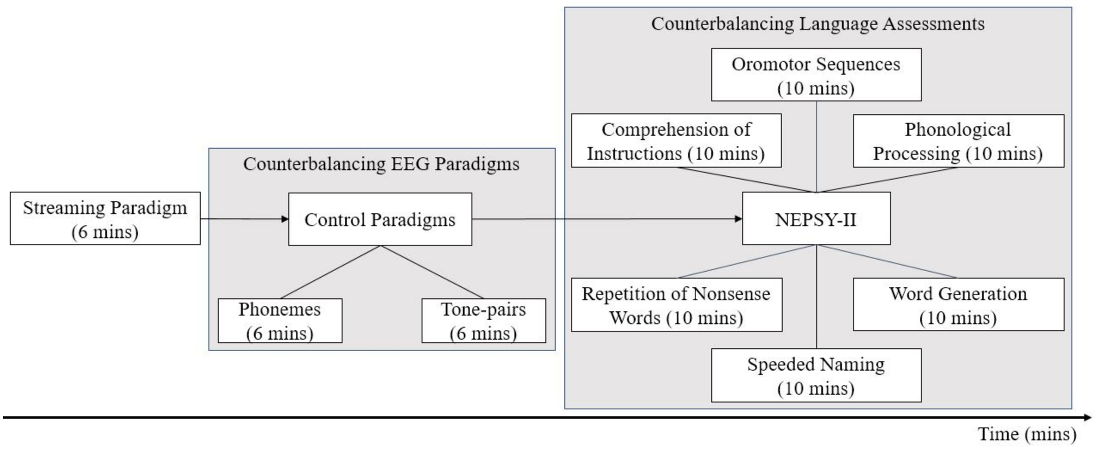

Figure 8.2 Schematic representation of the procedure in Study 6. Within the EEG tasks, the streaming paradigm was presented first. Order of the following phoneme and tone pair paradigms was counterbalanced. The second part of the experimental session involved NEPSY-II subtests, which were also counterbalanced. Approximate duration of each task is provided in brackets.

8.2.5 Data processing and analysis.

EEG data processing.

ERP responses were collected with HGSN 128-channel saline sensor net and recorded with EGI Net Station version 4.3.1 (EGI, Eugene, OR). Data processing was carried out using Waveform Tools in Net Station 4.3.1. The full EEG data processing is included in section 2.6.1 in General Methods and information related specifically to ERP data in Study 5 in section 7.2.5.

Processing scores on NEPSY-II language subtests.

The acquired scores on NEPSY-II language subtests (Korkman, Kirk, Kemp, 2007a, 2007b, 2007c) were standardised using the provided tables to each child's age, which was corrected for gestation. Details on processing the scores can be found in section 2.5.2.

Analysis strategy.

General information on the analysis strategy is provided in section 2.6.2. Figure 8.3 demonstrates the analyses in the current study.

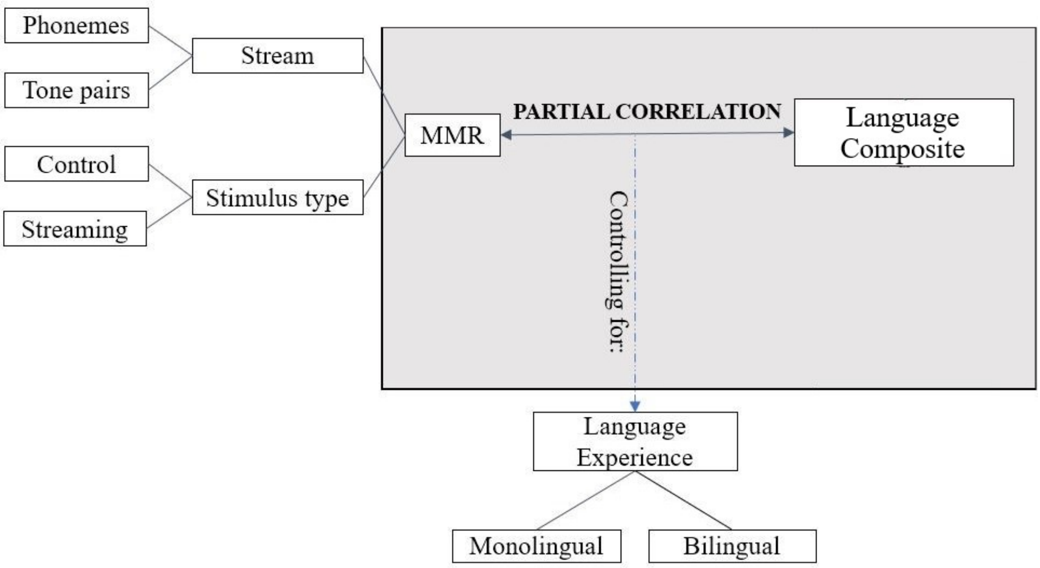

Figure 8.3 Schematic representation of analyses in Study 6. Partial correlations were performed between MMR to EEG modulations and language composite based on the components of NEPSY-II (Korkman et al., 2007c), while controlling for language experience. The detailed structure of a paired t-test used to identify significant MMR can be found in Figure 2.10.

Partial correlations (controlling for language experience) were carried out between clusters and time windows with significant MMR to phoneme and tone pair paradigms and phoneme and tone pair stream in the streaming paradigm and standardised scores on language components in NEPSY-II.

8.3 Results

Study 5 set out to establish the relationship between MMR to deviance in phonemes and tone pairs in the streaming design and phoneme and tone pair paradigms and scores on language subtests on NEPSY-II (Korkman, Kirk, & Kemp, 2007a, 2007b).

8.3.1 Language ability in children.

Language subtests on Neuropsychological Assessment, Second Version (NEPSY-2; Korkman, Kirk, & Kemp, 2007a, 2007b, 2007c) were performed to assess children's language ability. These include comprehension of instructions, repetition of oromotor sequences, phonological processing of words, speeded naming, timed word generation. Language raw scores were standardised using NEPSY-2 (Korkman et al., 2007b, 2007c) standardisation tables that were age-corrected for gestation. Details on the assessments are provided in section 2.5.2.

Table 8.1 provides information on the mean raw and standardised scores. There was no overall indication of any significant differences between monolingual and bilingual participants ($t<1.943$, $p>0.062$), so the data were collapsed across the sample. As indicated by the variable participant numbers, not all children, who participated in the EEG paradigms in Study 5 (section 7.2.1), completed the language tasks. Overall, children performed within the age-expected range.

Table 8.1

Raw and Standardised Scores on NEPSY-II Language Subtests in Children.

	NEPSY-2 scores	Mean	SD	Minimum	Maximum	Scale range	Part. No.
Raw	Comprehension of instructions	20.568	3.686	13	26	0-33	37
	Oromotor sequences	38.944	6.899	25	51	0-70	36
	Phonological processing	25.600	5.842	18	42	0-45	35
	Repetition of nonsense words	24.457	7.237	5	35	0-46	35
	Word generation	19.988	6.068	12	41	-	32
Scaled scores	Comprehension of instructions	12.243	2.842	6	17	1-19	37
	Oromotor sequences (percentile rank)	26-75	-	11-25	75-98	<2 to >75	36
	Oromotor sequences (computed manually)	10.833	2.75162	6	16	1-19	36
	Phonological processing	12.943	2.943	7	19	1-19	35
	Repetition of nonsense words	10.200	3.037	3	17	1-19	35
	Speeded naming	9.875	2.537	5	15	1-19	32
	Word generation	12.875	2.379	8	19	1-19	32
Total Language	Sum of scaled scores	69.821	9.741	52	90	6-114	28
	Composite score	109.679	9.495	92	129	47-153	28

Note. The standardised scores on NEPSY-II language subtests (Korkman et al., 2007a, 2007b, 2007c) in 4- to 6 years-old children. The scores were standardised to age, which was corrected for gestation. See the distribution of the standardised scores in scatterplots in Figure I.1 for comprehension of instructions, Figures I.2 and I.3 for oromotor sequences, Figure I.4 for phonological processing, Figure I.5 for repetition of nonsense words, Figure I.6 for speeded naming, Figure I.7 for word generation and I.8 for language composite.

Partial correlations were performed, between the onset and absolute mean MMR amplitude to deviance in phoneme and tone pair streams in the streaming paradigm and in the phoneme and tone pair paradigms (details on the MMR time windows and clusters are available in Table 7.1) and language subtests on NEPSY-II, while controlling for language experience. No correlations were carried out with phoneme stream in the streaming paradigm, due to absence of significant MMR to this modulation. The partial correlation results are available in Figures 8.2. (for tone pair stream in the streaming paradigm), 8.3 (for the phoneme paradigm) and 8.4 (for the tone pair paradigm). The partial correlations were corrected with Bonferroni adjusted alpha for multiple comparisons and are outlined below.

8.3.2 Associations between MMR and language ability in children.

The simple acoustic contrast, as represented by the tone pair stream in the streaming paradigm was found to have a negative relationship with the language composite scores (see table 8.2 below). The effect was identified over the right frontal electrodes sites during the 200-250 ms time window. Poorer language proficiency indicated increased acoustic discrimination in complex auditory environment.

Table 8.2

Partial Correlation Results Demonstrating Relationship Between MMR to Deviance in Tone Pair Stream in the Streaming Paradigm and Language Composite in Children (Controlling for Language Experience)

Tone Pair Stream			Language Composite	
Bin (ms)	Region	Hemisphere	Pearson	Sig. (2-tailed)
200-250	Frontal	Left	0.100	0.591
		Right	-0.544	0.003*
250-300	Frontal	Left	-0.047	0.815
		Right	-0.371	0.057
350-400	Frontal	Left	0.193	0.335
		Right	0.143	0.476
	Temporal	Right	-0.009	0.964

Note. The language composite scores were computed by summing up the standardised scores on NEPSY-II (Korkman et al., 2007a, 2007b, 2007c) comprehension of instructions, oromotor sequences, phonological processing, repetition of nonsense words, speeded naming and words generation subtests and mapping the total value on a scale ranging 47-153 points and with a median of 100. Time windows were selected based on the significant MMR amplitude to deviance in tone pair stream in the streaming paradigm in children (df=25, N=28) in Study 5. See Table G.2 in Appendix G for details. The correlations were tested against a Bonferroni-adjusted alpha level of 0.007 (0.05/7). The significant correlation is indicated with * and highlighted in grey.

Significant correlations between the phonetic contrast in the phoneme paradigm and language proficiency as well as between the MMR to the tone pair paradigm and behavioural performance were not identified.

Table 8.3

Partial Correlation Results Between MMR to Deviance in the Phoneme Paradigm and Language Composite in Children (Controlling for Language Experience)

Phoneme paradigm			Language Composite	
Bin (ms)	Region	Hemisphere	Pearson	Sig. (2-tailed)
400-450	Frontal	Right	0.027	0.895
500-550	Frontal	Right	-0.310	0.115
550-600	Frontal	Right	-0.140	0.488

Note. The language composite scores were computed by summing up the standardised scores on NEPSY-II (Korkman et al., 2007a, 2007b, 2007c) comprehension of instructions, oromotor sequences, phonological processing, repetition of nonsense words, speeded naming and words generation subtests and mapping the total value on a scale ranging 47-153 points and with a median of 100. Time windows were selected based on the significant MMR amplitude to deviance in the phoneme paradigm in children (df=25, N=28) in Study 5. See Table G.3 in Appendix G for details. The correlations were tested against a Bonferroni-adjusted alpha level correction of 0.016 (0.05/3) and none was significant.

Table 8.4

Partial Correlation Results Between MMR to Deviance in the Tone Pair Paradigm and Language Composite in Children (Controlling for Language Experience)

Tone Pair Paradigm			Language Composite	
Bin (ms)	Region	Hemisphere	Partial R	Sig. (2-tailed)
200-250	Frontal	Left	0.129	0.523
		Right	-0.156	0.437
250-300	Frontal	Left	0.248	0.212
		Right	-0.036	0.860
350-400	Frontal	Left	-0.390	0.044
		Right	-0.477	0.012
	Temporal	Left	-0.224	0.261
400-450	Frontal	Left	-0.323	0.101
		Right	-0.314	0.111
450-500	Temporal	Left	0.090	0.654
		Right	-0.105	0.356
550-600	Frontal	Right	-0.213	0.285
	Temporal	Left	-0.126	0.533
600-650	Frontal	Left	-0.333	0.090
		Right	-0.436	0.023
	Temporal	Left	-0.245	0.217

Note. The language composite scores were computed by summing up the standardised scores on NEPSY-II (Korkman et al., 2007a, 2007b, 2007c) comprehension of instructions, oromotor sequences, phonological processing, repetition of nonsense words, speeded naming and words generation subtests and mapping the total value on a scale ranging 47-153 points and with a median of 100. Time windows were selected based on the significant MMR amplitude to deviance in tone pair stream in the streaming paradigm in children (df=25, N=28) in Study 5. See Table G.4 in Appendix G for details. The correlations were tested against a Bonferroni-adjusted alpha level of 0.003 (0.05/16) and none was significant.

MMR to the tone pair stream associated with language.

Significant partial correlation was identified between language and the MMR to deviance in tone pair stream in the streaming paradigm within 200-250 ms time window (60-110 ms after the second tone in the pair) in the right frontal cluster, $r_{(25)}=-0.544$, $p=0.003$. Figure 8.4 demonstrates this relationship in individual participants. Increased behavioural scores were associated with the decrease in the absolute MMR, which would suggest that lower sensitivity to simple acoustic change in a passive auditory paradigm is linked to increased understanding and following the verbal instructions.

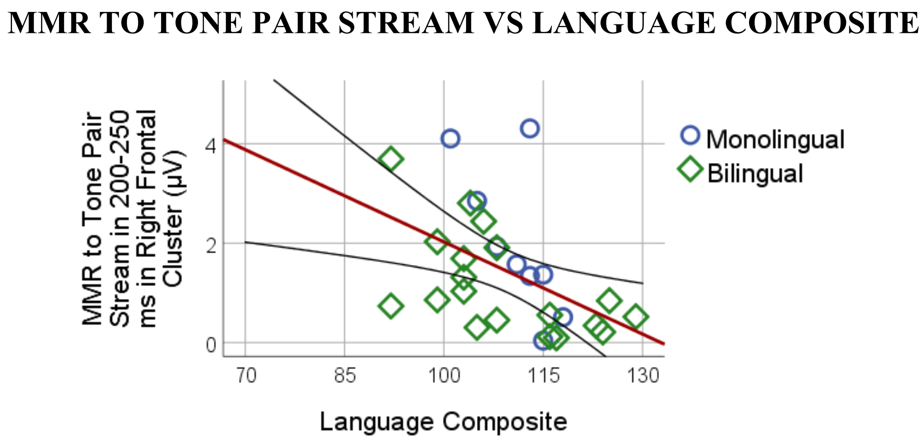

Figure 8.4 Scatterplot illustrating the relationship between the individual language composite scores as part of the NEPSY-II assessment (Korkman et al., 2007a, 2007b, 2007c) and MMR (in microvolts) to deviance in tone pair stream in the tone pair paradigm in the 200-250 ms time window as observed over the right frontal cluster (channels 3, 4, 117, 118, 123 and 124). The shapes indicate children from the monolingual (blue circles) and bilingual families (green diamonds). The red regression line represents the linear fit and the surrounding black lines confidence intervals at 95%.

8.3.3 Summary of the results.

In summary, the results show that discriminating tone pair contrast in streaming design corelated negatively with language in children, Namely, more proficient language was associated with reduced MMR deflections to the simple acoustic contrast. No such relationship was found for the phonetic or tone pair deviance in the single stream paradigms. Overall, these results provide valuable insight into the mechanisms underlying early language development.

8.4 Discussion

The aim of Study 6 was to assess the relationship between MMR to linguistic and non-linguistic contrast and communication skills in 4-6-year-old children. The findings demonstrated that MMR to deviance in tone pair stream in the streaming paradigm was linked to behavioural language performance, which was in accordance with the hypothesis (H.6.1). Nonetheless, these findings appeared somewhat counterintuitive as more advanced language indicated poorer auditory discrimination. This suggested that this relationship was more complex and potentially extended beyond pure linguistic skills (Beres, 2017).

It could be deduced that attentional focus may be contributing to this relationship (Finneran, Francis, & Leonard, 2009; Gomes et al., 2007; Shafer, Ponton, Datta, Morr, & Schwartz, 2007; Courtney Stevens et al., 2008, 2006; Sutcliffe, Bishop, Houghton, & Taylor, 2006). As the children were not instructed to listen to sounds which were played in the background and they were presented with muted cartoons at the same time, the ability to ignore stimuli not related to the activity they were engaged in could be considered an advanced attentional skill (Gomes et al., 2000; Snyder & Alain, 2007). Evidence for the mediating role of attention in this relationship would be difficult to discern based on either the electrophysiological or behavioural performance alone.

8.4.1 Acoustic MMR vs language in children.

During the passive auditory ERP paradigms children were not instructed to actively listen to the sounds. Therefore, the ability to ignore them as irrelevant while watching a silent cartoon could signify a higher level of neural maturation and possibly selective attentional engagement, which indicates developmental changes in attentional focus (Neill, 1979). The neural processing load required in this investigation was proposed to be much higher than in other studies, where one stream per block rather than streaming design was used. This is in agreement with previous studies, which showed decrease in the MMR to the streaming paradigm in comparison to the traditional oddball design (Jansson-Verkasalo et al., 2004; Nie et al., 2014; Shankarnarayan & Maruthy, 2007; Sharma et al., 2006; Sussman et al., 1999, 2001, 2015; Sussman & Steinschneider, 2009).

This finding is consistent with that of Wood and Cowan (1995) who reported interference effect in adults participating in the dichotic listening paradigm. The participants who recognised their name pronounced among the story played in the unattended speaker, exhibited longer response times and larger number of errors to the questions about a story coming from the attended side. This confirms that inability to stream out and ignore irrelevant sounds in the environment may be detrimental to understanding and following the relevant instructions.

There are also similarities between the observation made in relation to the MMR in streaming design and language performance in the current study and those described by Molholm et al. (2001) in 7-9-year-old children. Paradoxically, the MMR increased, but behavioural deviance detection decreased when random frequency changes were added to a sequence with a deviant of shorter duration than the standard stimuli. In other words, neural discrimination to target sounds decreased as children efficiently used their attentional resources to ignore distractors.

More specifically, inhibition and selective attention, which develop alongside each other (Bitan, Cheon, Lu, Burman, & Booth, 2009), may be responsible for the reduced MMR response to environmental sounds, if not goal relevant. It appears that being able to filter out background sounds, signifies more efficient linguistic and attentional adaptation in children (Guerra et al., 2021; Shafer, Ponton, Datta, Morr, & Schwartz, 2007; Strait, Slater, O'Connell, & Kraus, 2015).

It is important to acknowledge the diverse socioeconomic background of the sample as a potential confounding factor in this interpretation (see section 7.2.1). Skoe, Krizman and Kraus (2013) reported attenuated response to auditory deviants in the presence of an audiovisual distractor as well as reduced habituation in 14-year-old adolescents of less educated mothers. Furthermore, Stevens and colleagues (C Stevens et al., 2009, 2015) found deficits in ignoring irrelevant auditory information in 3-8-year-old children from disadvantaged families. While the current sample was fairly diverse, the negative correlations and even more so the absent relationship between phonetic processing and language, as quite surprising, could be driven by the environmental experience.

8.4.2 Conclusion.

In this investigation, the objective was to assess the relationship between linguistic and non-linguistic MMR in the streaming and control design and language ability in children. The findings demonstrated that tone pair discrimination was a key indicator of language proficiency in 4-6-year-old children. Specifically, larger MMR deflections to nonspeech sounds in the complex auditory environment were associated with poorer language skills.

The evidence in this study reveals that the relationship between non-linguistic MMR and language may be driven by the level of attentional focus. Further research is therefore required to highlight the mechanisms underlying the associations between auditory MMR and language proficiency in children. Overall, findings of this investigation provide a new understanding of the sensory and cognitive mechanisms underlying the early auditory and specifically, language development. This discovery is examined in more depth in the final study.

Chapter 9. Study 7 - Comparing the MMR in infants and children and its associations with language in early development

9.1 Introduction

The earlier accounts of this thesis (Studies 2-6) have highlighted both differences and similarities in auditory processing and language ability between infants and children. The purpose of the final study was a systematic synthesis of the findings in a cross-sectional design. The rationale behind this approach was that investigating the early developmental trajectories of the linguistic and non-linguistic MMR and its associations with language outcomes remain a major challenge in neuropsychological and neurolinguistic research.

9.1.1 Changes in the MMR in early development.

Several lines of evidence suggest that infants and younger children do not filter out irrelevant information from the auditory scene, but instead process both the relevant and the irrelevant stimuli (Campbell et al., 2007; Gomes et al., 2000; Hillyard et al., 1973; Karns et al., 2015; Näätänen et al., 1993; Stevens et al., 2015; Strait et al., 2014; Yordanova et al., 2006), potentially at the cost to processing the target stimulus. Some researchers argue this indicates inability to differentiate between the streams in auditory scene (Krishnan, Elhilali, & Shamma, 2014; Neill, 1979; Snyder & Alain, 2007), while others reason the cause is due to the immature selective attention (Gomes et al., 2000, 2007). Both the attentional focus and stream segregation mechanisms are thought to improve with age (Sanders et al., 2006;

Werner, 2007). For instance, the skill of switching or dividing attention does not reach maturity until late adolescence (Posner, 1980).

Another major controversy remains over which type of stimulus is more stable and reliable in eliciting MMR. Although phoneme and tone pairs have been the most popular stimuli employed to examine auditory and specifically speech processing, their contribution (Maurer et al., 2003a, 2009; Volkmer & Schulte-Körne, 2018), as the earlier observations in this thesis suggest, their role may be changing across early childhood. For more details on comparisons between MMR to stimulus modulation, see results in Studies 1, 2 and 5 (sections 3.3.4, 4.3.3 and 7.3.3, respectively).

9.1.2 Relationship between MMR and language in childhood.

Following findings in Studies 3, 4 and 6 (sections 5.3.2, 6.3.2 and 8.3.2), questions have been raised about the role of linguistic and non-linguistic MMR in explaining language outcomes (Friedrich et al., 2004; Partanen, 2013; Schaadt et al., 2015). The debate continues as to which auditory contrast elicits MMR that more closely relates to early speech processing and language development at large (Kostilainen et al., 2018; Shultz & Vouloumanos, 2010).

9.1.3 Rationale for the study.

The aims of Study 7 were twofold. In the first part of the differences in spatial and temporal distribution between the linguistic and non-linguistic MMR (from Studies 2 and 5) between infants and children were examined. Of particular concern were the developmental changes between the early sensory and later more attentional and cognitive auditory processing in response to the stream and stimulus modulations and its relationship with behavioural language proficiency.

The methodological approach taken in the second investigation was of correlational design intending to explore the developmental trajectory of the neural and behavioural signatures of language development. In order to do so, ERP data to deviant and standard stimuli in all the modulations were averaged across infants and children as a single cohort encompassing early development. The MMR was obtained by performing paired t-tests on individual time windows within the left and right frontal and temporal clusters in response to the stream and stimulus modulations. It must be acknowledged that this approach was problematic, due to developmental changes in auditory processing as well as structural and functional maturation of the brain between infancy and primary school age. The advantage of averaging across a wide age range was that only a large MMR component could reach significance in such variable data.

The MMR amplitude correlated with a behavioural language. The latter was created by combining language composite scores on Bailey-III in infants and NEPSY-II in children (Bayely, 2005; Korkman et al., 2007a, 2007b, 2007c). This computation was possible as the standardised scores on both subtests were mapped out on the same scale. They have been associated with neural discrimination of acoustic contrast within each of the age group. The results for correlations are available in section 5.3.2 in Study 3 for infants and section 8.3.2 in Study 5 for the children's cohort. Notwithstanding the exploratory nature of the comparisons in the current study, the potential results offer valuable insights into the early signatures of auditory and explicitly speech processing both of the neurophysiological and behavioural level.

9.1.4 Experimental predictions.

In line with previous literature and corroborating findings in Studies 2 and 5, group differences between the temporal and spatial distribution of the MMR between infants and children were expected (H.7.1). Nonetheless, despite the differences, the MMR was hypothesised to correlate with the composite measure of standardised language ability across both age groups (H.7.2) following on from Studies 3 and 6.

9.2 Methods

General Methods and in particular section 2.2.3 demonstrate distribution of the participants across the studies. Demographic information can be found in sections 4.2.1 for infants and 7.2.1 for children. Details on language ability in infants and children can be found in sections 5.3.1 in Study 3 and 8.3, respectively. Any additional information is provided below.

9.2.1 Participants.

There were 40 infants and 41 children, which summed up to 81 participants (40 males). Forty-two of them were monolingual.

9.2.2 Design.

The design of Study 7 involved cross-sectional research. Experimental between-participants and correlational analyses were performed. Figure 9.1 illustrates their structure and order in the study. The onset and absolute mean amplitude of the MMR from Studies 2 and 5 in infants and children, respectively, were compared in the first modulation. The second manipulation involved an investigation of the relationship between the combined scores on the MMR across both age groups with their language ability.

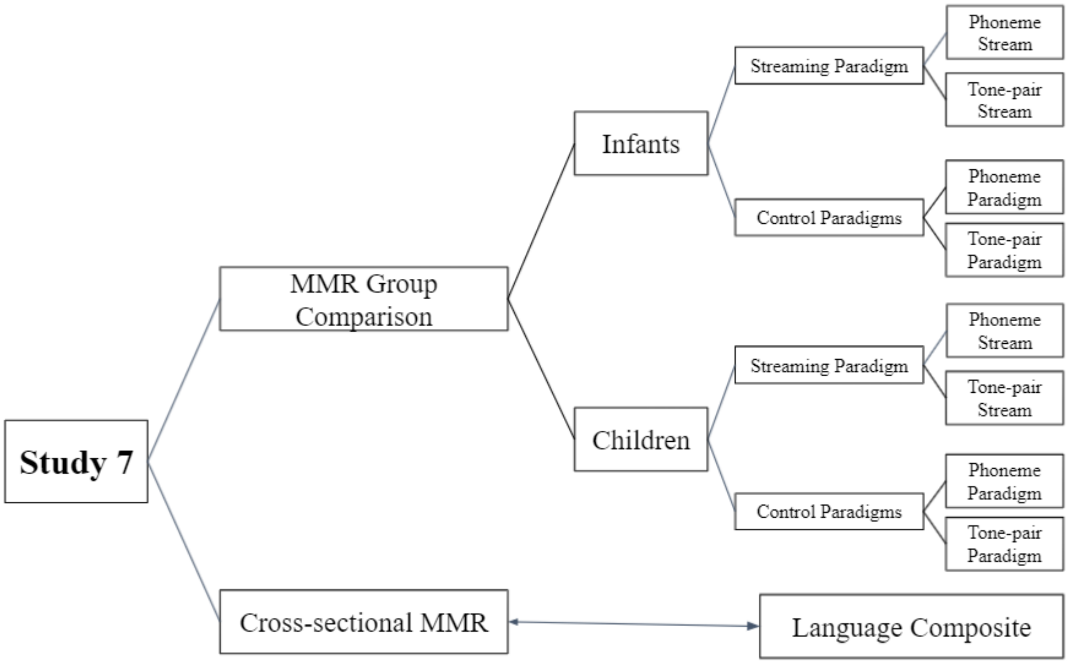

Figure 9.1 Schematic representation of manipulations in Study 7. The first one relates to differences between infants and children in the MMR to deviance in the phoneme and tone pair stream in the streaming paradigm and the control phoneme and tone pair paradigms. The second analysis examines relationship between the MMR to the same modulations but averaged across the infants and children and a composite variable of language across both age groups. The arrow demonstrates the relationship between combined MMR and the language composite.

MMR difference between infants and children.

The experimental investigation of the difference between MMR to deviance in phoneme and tone pair streams in the streaming paradigm and in the control phoneme and tone pair paradigms between infants and children was carried out to explore developmental change in the MMR.

Associations between MMR and receptive language in early development.

The data on the MMR to deviance in phoneme and tone pair streams in the streaming paradigm and in the control phoneme and tone pair paradigms averaged across infants and children were correlated with a compound variable of receptive language computed by combining the standardised scores on receptive communication and comprehension of instructions from infants and children.

9.2.3 Stimuli and apparatus.

EEG paradigms.

The comparison between infants and children involved EEG paradigms, which were carried out in Study 2 in infants and Study 5 in children. The EEG tasks were the control phoneme and tone pair paradigms and the streaming paradigm. Section 2.4.1 provides general information on the blocks, whilst details specific to Studies 2 and 5 can be found in sections 4.2.3 and 7.2.3.

Language Composite.

The language assessment performed in Study 3 (see section 5.2.3) involved Bayley-III (Bayley, 2005) receptive and expressive communication tests in infants. The more complex NEPSY-II (Korkman et al., 2007a, 2007b, 2007c) consisted of comprehension of instructions, oromotor sequences, phonological processing, repetition of nonsense words and word generation subtests. See section 2.4.2 in General Methods for details on the assessments. The language composite variable was created by combining the language composite scores from Bayley-III in infants (section 5.3.1) and NEPSY-II in children (section 7.3.1).

9.2.4 Procedure.

General information on the procedure is presented in section 2.5. In Study 3 in infants and 6 in children, EEG tasks were carried out first, followed by language assessments.

EEG data acquisition.

ERP responses were collected with HGSN 128-channel saline sensor net and recorded with EGI Net Station 5.2.0.2 software in infants in Study 2 (see section 4.2.4 and with EGI Net Station version 4.3.1 in Study 5 (section 7.2.4) in children (section 7.2.4) .

Behavioural language assessments.

Bayley-III (Bayley, 2005) receptive and expressive communication subtests was carried out in infants in Study 3 (see section 5.2.4 NEPSY-II (Korkman et al., 2007a, 2007b, 2007c) comprehension of instructions, oromotor sequences, phonological processing, repetition of nonsense words and word generation subtests and how they were conducted with children in Study 6 (see section 8.2.4).

9.2.5 Data processing and analysis.

ERP data processing.

ERP data were processed in the same way in infants and children (see section 2.6). Information relevant to the specific cohort can be found in section 3.2.5 for Study 2 and section 7.2.5 for Study 5.

Processing language scores.

The acquired scores on Bayley-III receptive and expressive language (Bayley, 2005) were standardised using the provided tables to each participant's age, which was corrected for gestation. The standardised scores were then added up to the sum of scaled scores and then transposed onto the language composite scores using the provided tables.

The raw scores NEPSY-II comprehension of instructions, oromotor sequences, phonological processing, repetition of nonsense words and word generation subtests (Korkman et al., 2007a, 2007b, 2007c) were also added up to the total language score and then mapped out on the language composite spectrum. As the language domain total scale and the language composite were not provided in NEPSY-II (Korkman et al., 2007b), they were developed for this thesis, based on the scales used in Bayley-II manual (Bayley, 2005). Details on processing of the scores can be found in section 2.5.2.

Analysis strategy.

General information on the analysis strategy is outlined in section 2.6.2. All details relevant only to Study 7 are presented below. Analysis A in Figure 9.2 represents the between-subject ANOVA comparison between significant MMR to deviance in phoneme and tone pair paradigms and phoneme and tone pair streams in the streaming paradigm in infants and children.

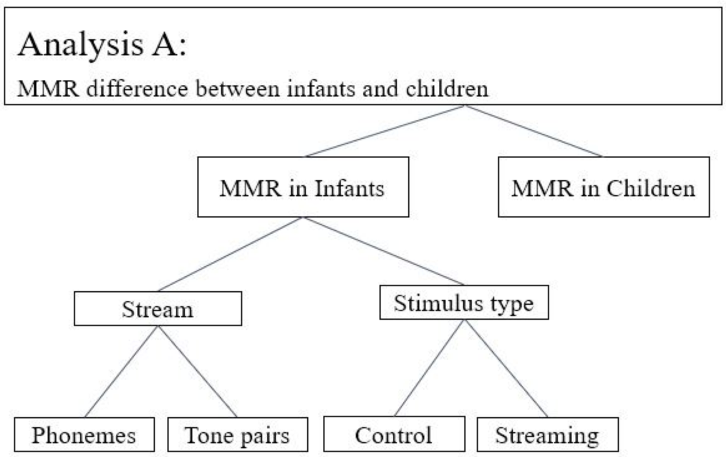

Figure 9.2 Model of comparison analysis between MMR in infants and children in Study 7. Breakdown of the paradigm design demonstrated in the infant sample also applies to children.

The second analysis of Study 7 involved combining the infant and children's data into effectively a single cohort analysis (Figure 9.3). The paired t-tests formed Analysis B. They were carried out on the ERPs to deviants and standards to the phoneme and tone pair paradigms and phoneme and tone pair stream in the streaming paradigm on each the time window, within the left and right frontal and temporal clusters in order to identify significant MMR (at p<0.01). The t-test results are available in Appendix J.

For Analysis C, the combined language composite scores on Bayley-III (Bayley, 2005) in infants and NEPSY-II (Korkman et al., 2007c) in children were used. A scatterplot in Appendix K illustrates the distribution of the scores as a function of participants' age. The relationship between time windows with significant MMR to modulations and language scores across both age groups was assessed with partial correlations, which controlled for language experience and age.

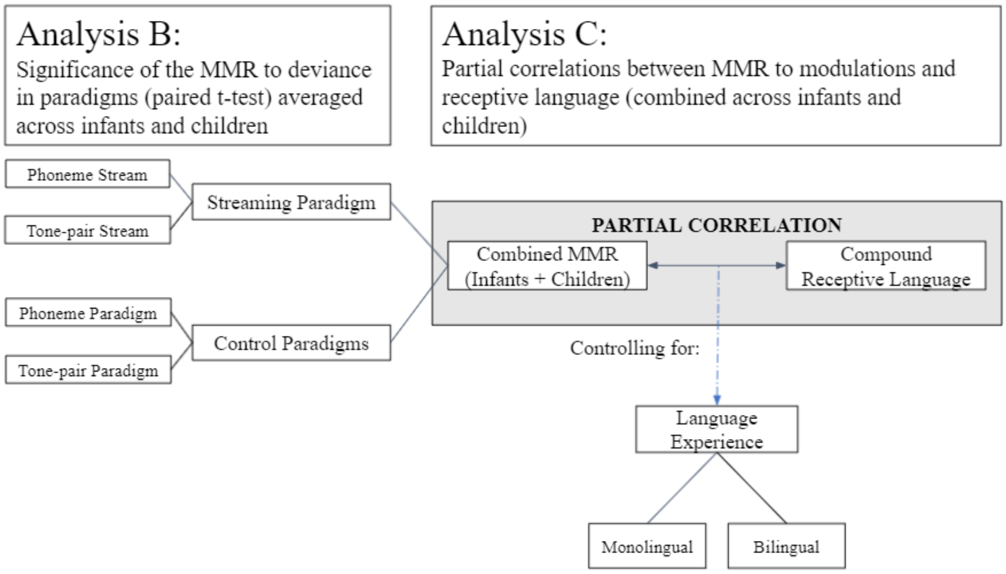

Figure 9.3 Schematic representation of the correlational analyses in Study 7. The MMR responses to the streaming and control paradigms were averaged across infants and children in Analysis B. The detailed structure of a paired t-test used to identify significant MMR can be found in Figure 2.10 and t-test results are available in Appendix J. These were correlated in Analysis C with the language composite variable, which comprised the combined infant and children's data. The partial correlation controlled for participants language experience.

9.3 Results

The MMR produced by infants from Study 2 (section 4.3 in Chapter 4. and children from Study 5 (section 7.3 in Chapter 7) was statistically compared in the final analysis. The time windows and clusters were selected based on the significant onset and mean MMR amplitude in either of the age groups (at p<0.01).

9.3.1 Comparing MMR in infants and children.

The stream and stimulus modulations had differential effects on the MMR in infants and children. Table 9.1 demonstrates the temporal and spatial distribution of the MMR in each paradigm, divided by age group.

Table 9.1

Time Windows with Onset and Mean MMR Amplitude to Deviances in the Streaming and Control Paradigms in Infants and Children

	MMR in Infants (50 ms time windows)		MMR in Children (50 ms time windows)	
MMR to deviance in:	Onset	Time of mean MMR amplitude	Onset	Time of mean MMR amplitude
Phoneme stream in streaming paradigm	250-300 RT	350-400 LT & RT	Not significant	Not significant
Tone pair stream in streaming paradigm	250-300 (110-160) LF & RF	300-350 (160-210) LF, RF & TR	200-250 (60-110) LF & RF	250-300 (110-160) LF & RF
Phoneme paradigm	Not significant	Not significant	400-450 RF	400-450 RF
Tone pair paradigm	300-350 (160-210) RT	500-550 (360-410) LT & RT	200-250 (60-110) LF & RF	250-300 (110-160) LF & RF

Note. Where relevant, numbers in brackets represent time windows after the deviant tone in the tone pair. Abbreviations indicate: LF - left frontal, RT – right frontal, LT – left temporal and RT – right temporal clusters. Paired t-tests, the summary is based on are available in Appendix C for infants and in Appendix G for children.

The most apparent finding is the double dissociation between linguistic MMR in infants and children. Infants, but not children, produced MMR to phonetic contrast within the streaming paradigm. By contrast, deviance in the phoneme paradigm generated short MMR in children and the MMR in infants was absent.

MMR was observed in response to all tone pair contrasts, although it emerged in earlier time windows in children than infants. Table 9.2 Demonstrates mean MMR amplitude to all the modulations in infants and children. Where present, the MMR was larger in infants than children.

Table 9.2

MMR at the Onset and the Mean Amplitude to Deviances in the Streaming and Control Paradigms in Infants and Children

MMR to deviance in:	MMR amplitude in Infants (μV) Onset	MMR amplitude in Infants (μV) Mean MMR amplitude	MMR amplitude in Children (μV) Onset	MMR amplitude in Children (μV) Mean MMR amplitude
Phoneme stream in streaming paradigm	1.939 RT	2.142 LT	Not significant	Not significant
Tone pair stream in streaming paradigm	1.698 LF	2.199 LF	1.122 LF	2.076 LF
Phoneme paradigm	Not significant	Not significant	-1.127 RF	-1.127 RF
Tone pair paradigm	1.823 RT	4.454 RT	1.510 LF	2.478 LT

Note. The MMR amplitudes to all contrasts were significant at p<0.01. MMR values used in the analyses were absolute, i.e., there were no negative values. Abbreviations indicate: LF - left frontal, RT – right frontal, LT – left temporal and RT – right temporal clusters. Paired t-tests the summary is based on are available in Appendix C for infants and in Appendix G for children.

Difference between infants and children on MMR to phonemes.

MMR difference on phoneme contrast in the streaming paradigm. Figure 9.4 presents mean MMR waveforms in both age groups. Positive MMR drifts were visible in all clusters in infants, but no such wave deviations were observed in children. Mixed three-way ANOVA with age group as a between-subject factor (infants and children) and repeated-measures factors: hemisphere (left versus right) x time window (250-300 and 350-400 ms) in temporal clusters (based on the onset and mean MMR amplitude) was performed. It revealed main effect of group, $F_{(1,79)}=24.839$, $p<.001$ $\eta^2=0.239$. with larger MMR in infants (M=2.853, SE=0.203) than children (M=1.403, SE=0.201). Indeed, only infants produced significant MMR (all other $F<3.777$, $p>0.055$).

MMR TO DEVIANCE IN PHONEME STREAM

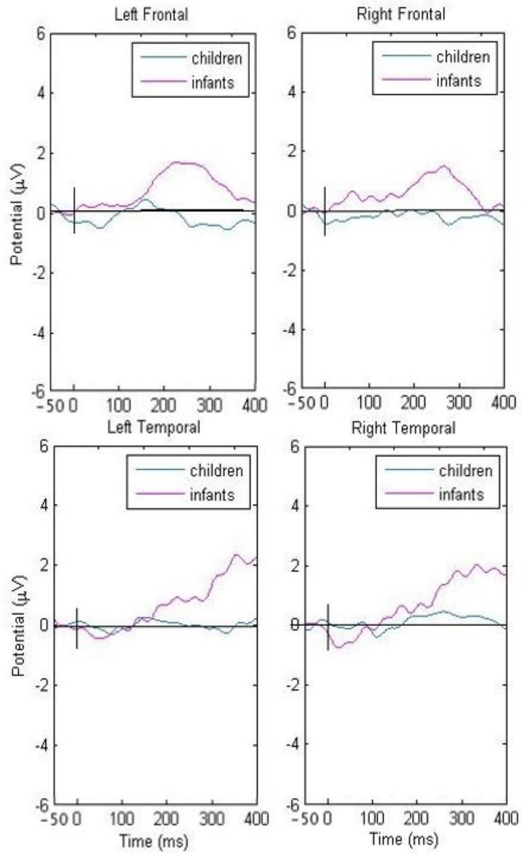

Figure 9.4 Grand-average mean MMR amplitudes to deviance in phoneme stream in the streaming paradigm, as recorded in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in infants (purple line) and children (cyan blue line). See Table C.1 and Table G.1 for mean MMR amplitude in infants and children, respectively.

MMR difference on phoneme contrast in the control paradigm. As seen in Figure 9.5, MMR waveforms in infants and children were close to the baseline and resembled each other. Independent t-test confirmed that there was no significant difference between MMR to deviance in the 550-600 ms time window in the right frontal cluster in the phoneme paradigm between infants and children, $t_{(79)}=0.301$, $p=0.764$, suggesting that both age groups produced similar responses but the MMR in infants was too weak to reach significance.

MMR TO DEVIANCE IN PHONEME PARADIGM

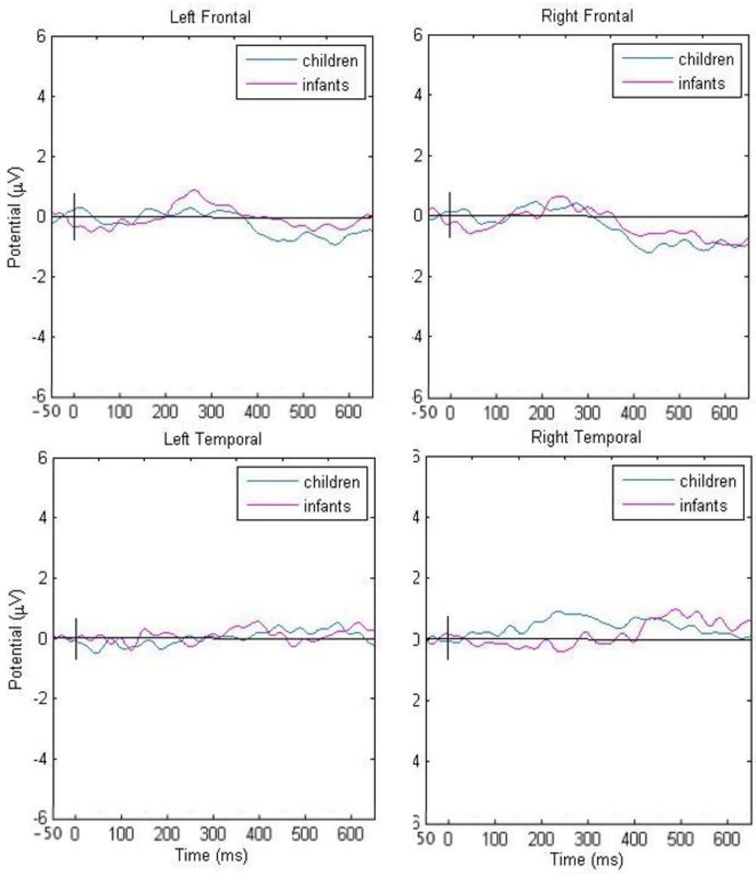

Figure 9.5 Grand-average mean MMR amplitudes to deviance in the phoneme paradigm as recorded in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in infants (purple line) and children (cyan blue line). See Table C.3 and Table G.3 for mean MMR amplitude in infants and children, respectively.

Difference between infants and children on MMR to tone pairs

MMR difference on tone pair contrast in the streaming paradigm. As reflected in Figure 9.6, both age groups elicited distinctive MMR waveforms, although children's MMR appeared larger over the frontal than temporal clusters. Mixed three-way ANOVA with age group as the between-subject factor (infants and children) and repeated-measures factors: region (frontal versus temporal) x hemisphere (left versus right) x time window (200-250, 250-300 and 300-350 ms) was conducted. There was a main effect of group, $F_{(1,79)}$ =11.302, p=0.001, η^2 =0.125. Infants produced larger MMR (M=2.422, SE=0.126) than children

(M=1.826, SE=0.125). Main effect of region was also identified ($F_{(1,79)}$ =6.522, p=.013, η^2=0.076) with larger MMR in the frontal (M=2.314, SE=0.127) than temporal clusters (M=1.934, SE=0.104). Finally, the main effect of time window reflected development of the MMR, $F_{(1,79)}$ =15.535, p<0.001, η^2 =0.164 (all other F<2.769, p>0.068).

MMR TO DEVIANCE IN TONE PAIR STREAM

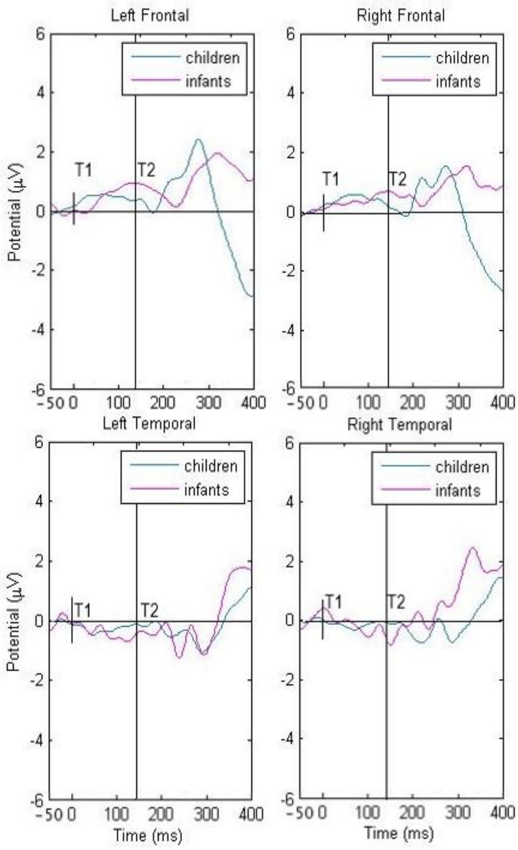

Figure 9.6 Grand-average mean MMR amplitudes to change in tone pair stream in the streaming paradigm, as recorded in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in infants (purple line) and children (cyan blue line). See Table C.2 and Table G.2 for mean MMR amplitude in infants and children, respectively.

MMR difference on tone pair contrast in the control paradigm. MMR waveforms to the modulation are available in Figure 9.7. Infants produced a single but possibly smeared positive MMR across all clusters. By contrast, children's responses presented as two MMR peaks in the frontal clusters, the first as positive deflection, followed by the MMN.

MMR TO DEVIANCE IN TONE PAIR PARADIGM

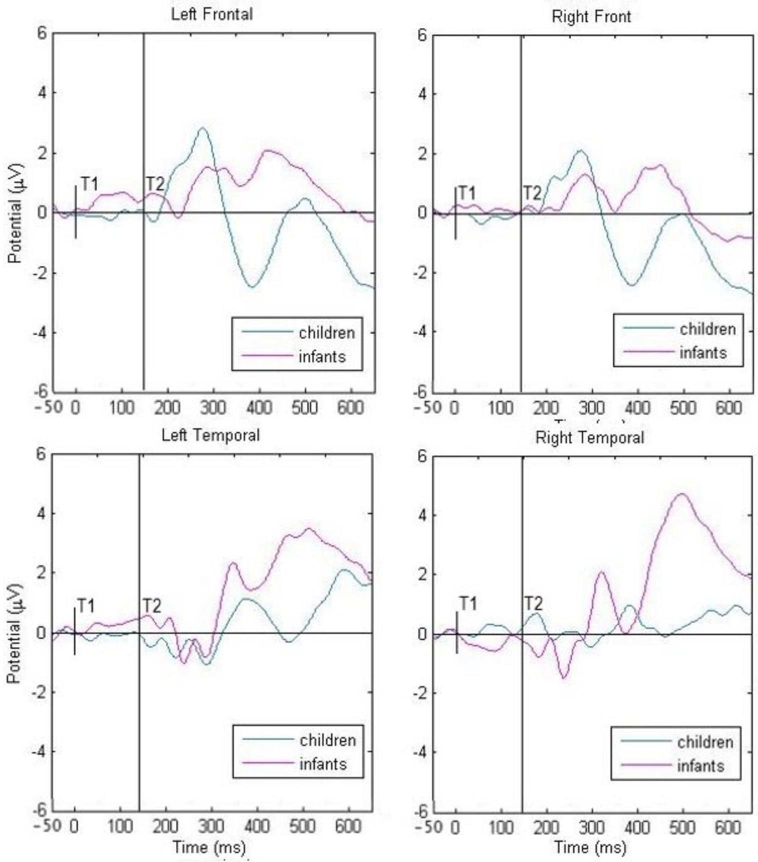

Figure 9.7 Grand-average mean MMR amplitudes to change in the tone pair paradigm, as recorded in the left frontal (channels 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) in infants (purple line) and children (cyan blue line). See Table C.4 and Table G.4 for mean MMR amplitude in infants and children, respectively.

Mixed four-way ANOVA with age group as between-subject factor (infants and children) and within-subject factors: region (frontal and temporal) x hemisphere (left versus right) x time window (200-250, 250-300, 300-350 and 500-550 ms) was conducted. Interactions between group and region ($F_{(1,79)}$ =6.045, p=0.016, η^2 =0.071) and group and time window ($F_{(1,79)}$ =13.101, p<0.001, η^2=0.142) were further explored with post hoc ANOVAs. Infants produced overall larger MMR (M=3.188, SE=0.191) than children (M=1.835, SE=0.189) over temporal clusters ($F_{(1,79)} = 25.398$, $p<0.001$, $\eta^2 = 0.243$) and within 300-350 ms ($F_{(1,79)}=4.991$, $p=0.028$, $\eta^2 = 0.059$; M=3.251, SE=0.291 in infants and M=2.116, SE=0.287 in children) and 500-550 ms ($F_{(1,79)} = 7.711$, $p=.007$, $\eta^2=0.089$; M=2.799, SE=0.258 and M=1.990, SE=0.255 in infants and children, respectively) in the frontal region (all other $F<3.034$, $p>0.084$).

9.3.2 MMR vs language in early development.

In order to explore the associations between the MMR and language development, the MMR to deviance in both streams in the streaming and to control phoneme and tone pair paradigms were averaged across infants and children (see Figure K.1 for distribution of the individual language composite scores as a function of age across infants and children). The combined significance of the MMR was then assessed with paired t-tests on each time window and within each of the clusters (left and right frontal and temporal).

The t-test results are available to view in Appendix J, while correlation tables are provided below (Tables 9.3, 9.4, 9.5 and 9.6). They demonstrate all of the partial correlation results in which the controlled variable was language experience. Bonferroni correction was applied to all the correlation to identify the significant associations. Only the MMR to the tone paradigm significantly correlated with language in early development. Age also contributed to this relationship (as clearly visible in Figures 9.8, 9.9 and 9.10) with reduced deflections in children, but controlling for this variable, along the language experience, removed the significance of the partial correlations (all $r_{(64)}<-0.239$, $p>0.054$). Therefore, age was not included in the final analyses.

Table 9.3

Partial Correlation Results Between MMR to Phoneme Stream in the Streaming Paradigm and Language Composite across Infants and Children (Controlling for Language Experience)

Phoneme Stream in Streaming Paradigm			Language Composite (df=65, N=68)	
Bin (ms)	Region	Hemisphere	Partial correlation	Sig. (2-tailed)
250-300	Temporal	Right	-0.104	0.402
300-350	Temporal	Left	-0.253	0.039
		Right	-0.147	0.235
350-400	Temporal	Left	-0.363	0.003*
		Right	-0.226	0.066

Note. The language composite variable consisted of Bayley-III (Bayley, 2005) language composite scores in infants (N=40) and NEPSY-II (Korkman, 2007a, 2007b, 2007c) language composite scores in children (N=28). They were standardised to participants' age, which was corrected for gestation. Time windows were selected based on the significant MMR to deviance in phoneme stream in the streaming paradigm across infants and children. Paired t-test results are available in Appendix J.1. The correlations were tested against a Bonferroni-adjusted alpha level of 0.01 (0.05/5). Significant correlation is indicated with * and highlighted in grey.

Table 9.4

Partial Correlation Results Demonstrating Relationship Between MMR to Deviance in Tone Pair Stream in the Streaming Paradigm and Language Composite across Infants and Children (Controlling for Language Experience)

Tone Pair Stream in Streaming Paradigm			Language Composite (df=65, N=68)	
Bin (ms)	Region	Hemisphere	Partial correlation	Sig. (2-tailed)
200-250	Frontal	Left	0.004	0.972
		Right	-0.255	0.037
250-300	Frontal	Left	-0.024	0.846
		Right	-0.196	0.112
300-350	Frontal	Left	-0.192	0.120
350-400	Temporal	Left	-0.311	0.011
		Right	-0.146	0.237

Note. The language composite scores in infants (N=40) and NEPSY-II (Korkman, 2007a, 2007b, 2007c) language composite scores in children (N=28). They were standardised to participants' age, which was corrected for gestation. Time windows were selected based on the significant MMR to deviance in phoneme stream in the streaming paradigm across infants and children. Paired t-test results are available in Appendix J.2. The correlations were tested against a Bonferroni-adjusted alpha level of 0.007 (0.05/7) and none was significant.

Table 9.5

Partial Correlation Results Between MMR to Deviance in the Phoneme Paradigm and Language Composite across Infants and Children (Controlling for Language Experience)

Phoneme Paradigm			Language Composite (df=65, N=68)	
Bin (ms)	Region	Hemisphere	Partial R	Sig. (2-tailed)
250-300	Frontal	Left	-0.159	0.199
		Right	0.053	0.670
	Temporal	Right	-0.276	0.024
400-450	Frontal	Right	-0.009	0.944
550-600	Frontal	Right	-0.009	0.944
600-650	Frontal	Right	-0.055	0.658

Note The language composite variable consisted of Bayley-III (Bayley, 2005) language composite scores in children (N=28). They were standardised to participants' age, which was corrected for gestation. Time windows were selected based on the significant MMR to deviance in the phoneme paradigm across infants and children. Paired t-test results are available in Appendix J.3. The correlations were tested against a Bonferroni-adjusted alpha level of 0.008 (0.05/6) and none was significant.

Table 9.6

Partial Correlation Results Between MMR to Deviance in the Tone Pair Paradigm and Language Composite across Infants and Children (Controlling for Language Experience)

Tone Pair Paradigm			Language Composite (df=65, N=68)	
Bin (ms)	Region	Hemisphere	Partial R	Sig. (2-tailed)
250-300	Frontal	Left	0.178	0.150
		Right	0.012	0.921
350-400	Temporal	Left	-0.442	<0.001*
400-450	Temporal	Left	-0.347	0.004*
		Right	-0.280	0.018
450-500	Temporal	Left	-0.336	0.005*
		Right	-0.220	0.074
550-600	Frontal	Right	-0.159	0.200
	Temporal	Left	-0.128	0.301
		Right	-0.277	0.023
600-650	Frontal	Left	-0.015	0.904
		Right	-0.052	0.677
	Temporal	Left	-0.113	0.362
		Right	-0.191	0.122

Note. The language composite variable consisted of Bayley-III (Bayley, 2005) language composite scores in children (N=28). They were standardised to participants' age, which was corrected for gestation. Time windows were selected based on the significant MMR to deviance in the phoneme paradigm across infants and children. Paired t-test results are available in Appendix J.4. The correlations were tested against a Bonferroni-adjusted alpha level of 0.003 (0.05/14). Significant correlation is indicated with * and highlighted in grey.

MMR to phoneme stream associated with language performance.

Partial correlation was identified between the MMR to deviance in phoneme stream in the streaming paradigm within 350-400 ms time window (210-260 ms after the second tone in the pair) in the left temporal cluster and the language composite scores, $r_{(65)}=-0.363$, $p=0.003$. Figure 9.8 demonstrates a negative relationship between these variables. Increased behavioural scores were associated with the decrease in the mean MMR amplitude, which in reverse suggests that poorer sensitivity to linguistic contrast was linked to better behavioural performance.

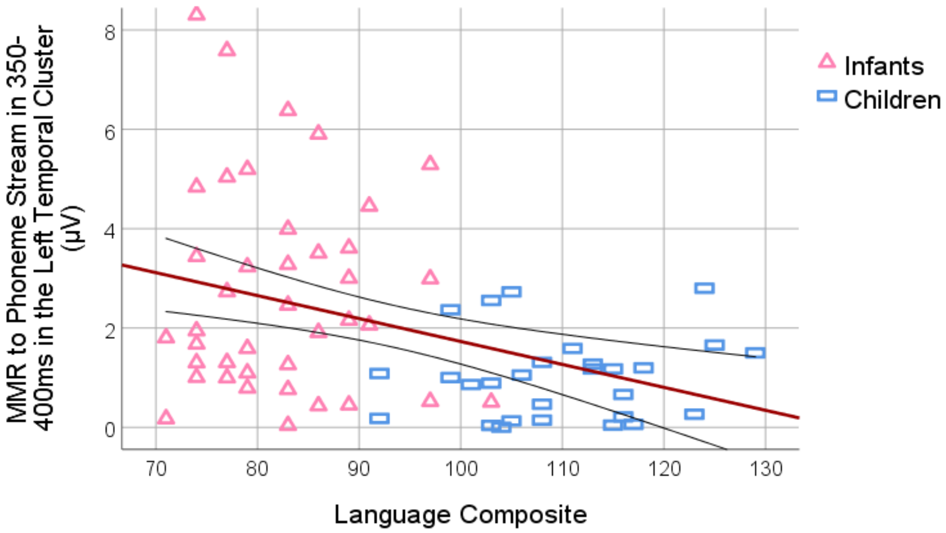

Figure 9.8 Scatterplot illustrating relationship between the individual language composite scores and MMR (in microvolts) to deviance in phoneme stream in the streaming paradigm within the 350-400 ms time window, as observed over the left temporal cluster (channels 39, 45, 46 and 50). The shapes indicate infants (purple triangles) and children (cyan blue rectangles). The red regression line represents the linear fit and the surrounding black lines confidence intervals at 95%.

MMR to tone pair paradigm associated with language performance.

There was a significant negative relationship between language composite scores and MMR to deviance in the tone pair paradigm within 350-400 ms (210-260 ms after the onset of the second tone in the pair) in the left temporal cluster, $r_{(65)}=-0.442$, $p<0.001$. Figure 9.9 represents the distribution of the responses. Ignoring simple acoustic sounds presented in the environment appeared to be beneficial in language ability.

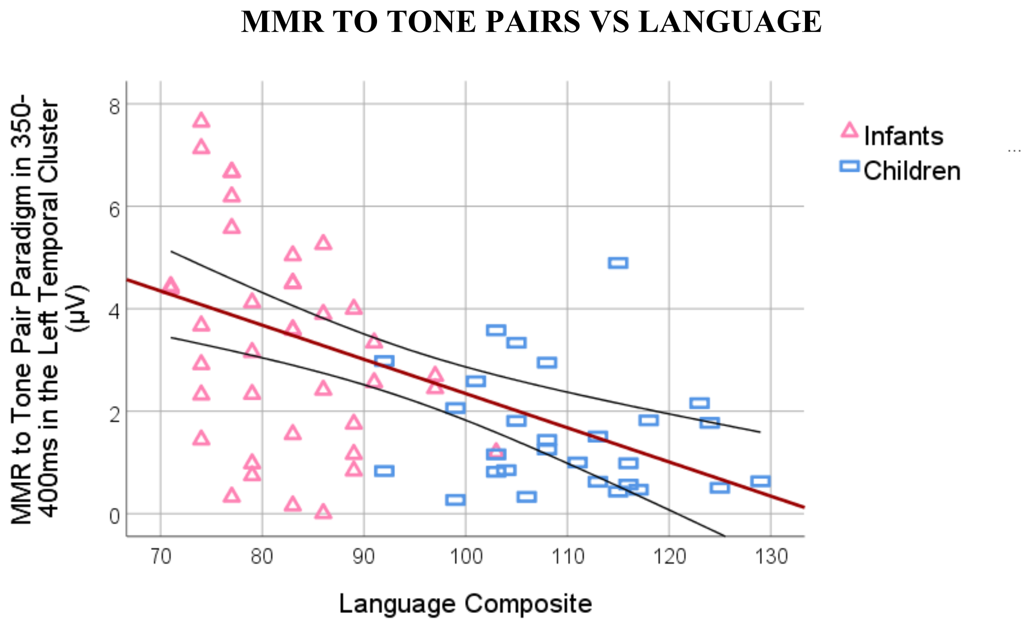

Figure 9.9 Scatterplot illustrating relationship between the individual language composite scores and MMR (in microvolts) to deviance in the tone pair paradigm within 350-400 ms time window as observed over the left temporal cluster (channels 39, 45, 46 and 50). The shapes indicate infants (purple triangles) and children (cyan blue rectangles). The red regression line represents the linear fit and the surrounding black lines confidence intervals at 95%.

9.3.3 Summary of the results.

Together these results provide valuable insights into the early development of the linguistic and non-linguistic MMR. They inform on the overall attenuation of the MMR between infancy and childhood. This is reflected both in the comparative analyses exploring the differences in sound processing between infants and children as well as the subsequent correlational analysis investigating the relationship between MMR to acoustic change and development of language from infancy to primary school age.

Frequency discrimination in tone pairs remained stable in early development, and as it was processed in early time windows, this indicates preattentive processing both in infants and children. Phonetic discrimination was comparable to that of pure acoustic change (although attenuated) in infancy. The MMR appeared was observed early in the epoch, which indicated sensory processing. In contrast, phonetic discrimination in children was observed in the later time window. It could be argued that speech sounds were processed at a more categorical level. This double dissociation in phonetic processing marks changes in the development of auditory attention and speech-specific mechanisms (Gomes et al., 2000; Kinney & Kagan, 1976; Strait et al., 2014; Wemer, 2001).

Despite the differences, the neural and behavioural correlates of auditory processing have been clearly identified. The negative correlation between overall auditory discrimination and behavioural language composite revealed an intriguing picture. Language proficiency correlated with an ability to ignore environmental sounds, if not relevant to the activity at hand, especially while facing complexity of the auditory scene.

9.4 Discussion

In accordance with the predictions (H.7.1), the main findings of Study 7 related to spatial, temporal as well as absolute amplitude differences between the MMR to acoustic change in infants and children. Nonetheless, when the MMR was averaged across infants and children and compared with the total language composite, a significant relationship was found, and thus, hypothesis two was supported (H.7.2). The brief evaluation of the findings is given below (see also Tables 9.1 and 9.2 for summary of the results). More in-depth discussion, summarising findings from Studies 1-7 is provided in Chapter 10.

9.4.1 MMR difference between infants and children.

The first objective of the final study of this thesis was to assess the differences between auditory processing between infants and children. Overall, there was a temporal and intensity reduction in the MMR, with larger deflections but with the later onset time windows in infants than children in all paradigms. This finding is consistent with other studies exploring early development of the MMR (Cheour et al., 1998b; Hövel et al., 2014; Kushnerenko et al., 2002; Linnavalli et al., 2018b; Morr et al., 2002; Muenssinger et al., 2013a; Ponton et al., 2000; Shafer et al., 2000). Researchers propose increased processing speed and functional specialisation as well as neuroanatomical differences, including increased thickness of the scalp (Lamm, Zelazo, & Lewis, 2006) and gradual reduction in movement artefacts (Georgieva, Lester, Yilmaz, Wass, & Leong, 2017) from infancy to primary school age as possible explanations for this phenomenon. Certainly, these are plausible interpretations for the current findings, and they are in agreement with the development of language network in the brain outlined in section 1.2.4.

Dwelling further into data, although not assessed systematically in this study (but see sections 4.4.1 in infant and 7.4.1 in children), the complexity of the auditory scene in processing phonemes appeared not to have a differential effect on infants and children, just as the MMR to tone pairs was not altered by the number of streams. Nonetheless, the MMR in infants and children was influenced by the stimulus type (see sections 4.4.2 and 7.4.2 for details). Tone pairs elicited earlier, more widespread, intense, and overall, more developmentally stable discrimination in both cohorts (Choudhury et al., 2015; Dacewicz, Szymaszek, Nowak, & Szelag, 2018; Näätänen, 2001). MMR to phonemes differed in that the component was less pronounced and changed dramatically between infancy and older childhood (Kushnerenko et al., 2008; Partanen, 2013). These findings are briefly interpreted and evaluated below.

MMR to phonemes.

Phonetic deviance in the streaming paradigm elicited larger mismatch response in infants (section 4.4.1) than children, which also corroborated findings earlier in the thesis in that in fact children did not process the phoneme stream (see section 7.4.1 for details). Even though the effect was not strong enough to reach significant difference between the cohorts, the opposite trend was evident in response to the phoneme paradigm. This double dissociation in the findings of phonetic discrimination between infants and children may be explained by the gradual specialisation of the mechanisms involved in processing speech between infancy and the primary school age (see section 1.2.4).

Based on the development of language network in the brain in section 1.2.4 and its behavioural markers (section 1.2.1), it is conceivable to assume that alertness to all the sounds in the environment may be a crucial learning and survival skill. Rapid processing of sounds tends to focus on the physical or acoustic properties of voice (McGettigan & Scott, 2012; Ramus et al., 1999; Shultz & Vouloumanos, 2010; Telkemeyer et al., 2009).

As children specialise in their native language, and even more so as they begin to learn to read and write (Maurer et al., 2009; Meng et al., 2008, 2005; Sharma et al., 2006), language discrimination engages speech specific pathways in the brain, Therefore, phonological processing potentially requires more time than simple frequency discrimination, as evidenced by the MMR to phonetic contrast, which was recorded later in the epoch in children. This also indicates a more cognitive rather than sensory processing and attentional engagement (Čeponiené et al., 2001; Friedrich & Friederici, 2006; Henderson et al., 2011; Tamura, Mizuba, & Iramina, 2016), both of which are not well established in infancy.

The linguistic neural processing may be thus affected by the development of selective attention (Gomes et al., 2000; Snyder & Alain, 2007; Szymanski et al., 1999) developmental specialisation of the speech-specific mechanisms in early childhood (Čeponiené et al., 2003; Harpaz, Levkovitz, & Lavidor, 2009; Kuhl, Ramirez, Bosseler, Lin, & Imada, 2014; Partanen, 2013; Rocha-Muniz, Befi-Lopes, & Schochat, 2015; Schaadt et al., 2015). This does not explain why infants did not generate MMR in response to phonetic contrast in the phoneme paradigm, but this finding may be confounded by the order of the paradigms in the experimental session. Detailed interpretation of this assumption is provided in section 4.4.2 in Study 2.

MMR to tone pairs.

Overall infants produced larger MMR to the tonal contrast than children both in the streaming and control paradigms. However, MMR waveforms to the tone pair paradigm and tone pair stream in the streaming paradigm differed in pattern between infants and children. The MMR was observed in the earlier time windows in children than infants and was of somewhat different morphology between the two cohorts. Nonetheless, despite the differences in the spatial and temporal distribution of the MMR in infants and children, both age groups produced large and widespread neural signatures to the basic acoustic deviance. It could be speculated that the non-linguistic MMR reflected preattentive mechanisms of discrimination, as confirmed by the previous work in the area of auditory processing (Čeponiené et al., 2002a; Gomes et al., 1995; Gumenyuk et al., 2003; Pekkonen et al., 2002; Schröger, 1997; Winkler et al., 2003).

MMR to streaming.

Of note is the differential treatment of phonetic and acoustic streams by the cohorts. In the streaming condition, infants processed both speech and tone pair contrasts in the paradigm, while children seemed to be preferentially responsive to the tone pair contrast. Given the short trial duration, the paradigm was likely to evoke rapid, sensory response (Yu, Shafer, & Sussman, 2017). The complex auditory scene thus had a differential effect on the attentional engagement in infants and children (Leibold, 2012; Litovsky, 2015; Sussman & Steinschneider, 2009; Thompson, Woodruff Carr, White-Schwoch, Otto-Meyer, & Kraus, 2017). This could be interpreted in terms of saliency of the deviance (Duangudom & Anderson, 2007; Kalinli & Narayanan, 2007; Kaya & Elhilali, 2012).

Children appeared to perceive the simple acoustic contrast as more salient, whereas for infants both subtle phoneme and more distinctive tonal contrasts could be acoustically equal if both types were perceived based on the physical properties of the sounds (Gilley et al., 2017; Musacchia et al., 2013; Werner Olsho, 1984; Ortiz-Mantilla et al., 2016), rather than its speechness (Čeponiené et al., 2001, 2002b, 2003) or speech specific properties. Ultimately, infants streamed out and discriminated phonemes and tone pairs, while children segregated the streams, but processed only the more salient acoustic contrast.

9.4.2 Relationship between MMR and language in childhood.

The second objective of this study was to explore the neural and behavioural correlates of language development. When the data from all participants were combined into the early development cohort, negative relationships were identified between auditory discrimination and language composite. Larger MMR to deviance in phoneme stream in the streaming paradigm and in the tone pair paradigm was associated with poorer language scores. In other words, participants with more advanced language skills, were more likely to ignore the linguistic sounds if presented on the backdrop of the complex auditory scene, while the rhythmical tones fell to the background if children were exposed to them as the lone type of stimulus.

These findings indicate that increased brain reactivity in response to both speech and nonspeech contrasts, when played out as background sounds, could be associated with poorer language performance in early development (Guerra et al., 2021; Shafer et al., 2007), with a potential need for intervention. While it should be acknowledged that the negative correlations were under-powered (Button et al., 2013; Nayak, 2010) and cannot be interpreted beyond nondirectional associations, they may shed light on the development of language-specific mechanisms (Kuhl & Rivera-Gaxiola, 2008). As the infants could not be and the children were not instructed to attend to the sounds presented in the background, the ability to ignore irrelevant environmental noise could indicate and advancement of functional specialisation for language (Kuhl, 2010; Mills, Coffey-Corina, & Neville, 1993; Rosselli, Ardila, Matute, & Vélez-Uribe, 2014; Sperdin & Schaer, 2016). Furthermore, this was supported by the earlier finding in auditory processing in infants and children (section 9.4.1). Namely, the developmental increase in the attentional engagement between findings in Studies 4 in infants and 6 in children could be contributing to this relationship.

It should be noted that despite, as found in the earlier observation (section 9.4.1), MMR in infants was overall larger than in children, language scores were standardised to children's age and language experience was controlled for in the analysis, these associations were still present. This is in line with the initial hypotheses and maturational studies demonstrating general gradual decrease in MMR to tone pairs identified between 12 to 48 months (Bruggemann, Stockill, Lenroot, & Laurens, 2013; Kushnerenko, Čeponiené, Balan, Fellman, & Näätänen, 2002). Overall, these findings highlight the importance of developmental changes in attentional engagement which appear to concord with the progress of auditory and primarily language specialisation.

9.4.3 Conclusion.

It has been conclusively shown that narrowband frequency discrimination is preattentive and generally established in infancy with no significant changes across early childhood, except for small reduction in latency and amplitude. Phonetic processing differs from the simple acoustic sensitivity in several ways. Firstly, it develops throughout childhood, with infants processing phonemes at the sensory level and children engaging attentional focus and sophisticated speech-specific mechanisms.

Secondly, it is somewhat influenced by the complexity of the auditory scene and the relevance of the individual streams towards the goal of the task at hand. Thirdly, infants processed linguistic contrast automatically whereas children did not discriminate phonemes if they were irrelevant to the task and in the presence of more salient acoustic stimuli. However, their attention was drawn towards them if they were the only auditory contrast in the environment, with no interference from other sounds. This reflects changes in auditory attention and phonological processing in early development.

This was supported by the relationship between auditory discrimination and proficiency in language. The ability to inhibit the processing of background sounds was associated with increased speech processing. These findings, as a summary of Studies 1-7, contribute in several ways to our understanding of early auditory processing and language development. These are outlined in the General Discussion.

Chapter 10. General Discussion.

As mentioned in the Literature Review (Chapter 1), the MMR matures in early development (Bruggemann et al., 2013; Cheng et al., 2013, 2015; Cheour et al., 2000; Kushnerenko et al., 2007; Kushnerenko et al., 2013c; Leppänen et al., 2004; Näätänen et al., 2007) due to changes in brain topography (Crone & Ridderinkhof, 2011; de Haan & Johnson, 2016; Eggermont & Moore, 2012; Gao, Alcauter, Smith, Gilmore, & Lin, 2015; Johnson & de Haan, 2001; Paterson et al., 2006; Roth & Dicke, 2005) and cortical activity (Chaudhury et al., 2016; Gomot et al., 2000; He, Hotson, & Trainor, 2007; Lippe, 2009; Mahajan & McArthur, 2012; Picton & Taylor, 2007; Stiles & Jernigan, 2010; Taylor, 2012; Werner, 2010; Wunderlich & Cone-Wesson, 2006).

However, methodological discrepancies between paradigms assessing development of the MMR, involving the type of deviance (Jarkiewicz & Wichniak, 2015; Partanen et al., 2013; Putkinen et al., 2012), length of a trial (Andreou et al., 2011; Elliott, Hammer, Scholl, Carrell, & Wasowicz, 1989; Escera et al., 2000), stimulus (Jacobsen, et al., 2004; Kasai et al., 2002; Lachmann et al., 2005; Szycik et al., 2013) or number of streams in a paradigm (Andreou et al., 2011; Bendixen et al., 2010; Moore & Gockel, 2012; Szycik et al., 2013; Winkler et al., 2003) may contribute to the variability of the findings in the field. The first objective of this thesis was thus to determine the effect of the above design features on the MMR in infants and children.

In addition, several reports have highlighted the link between MMR and language development (Benasich et al., 2006; Cantiani et al., 2016a; Gogate & Bahrick, 1998; Rocha-Muniz et al., 2015; Shafer et al., 2012; Sussman et al., 2015).

Therefore, the second objective was to explore the moderating effect of the paradigm features on this relationship in infants and children.

10.1 Summary

10.1.1 Experimental manipulations.

Across seven studies, an exploratory investigation was carried out to assess MMR generators in infants and children and the relationship between MMR and language development. More explicitly, the effect of modulations including deviance, trial duration, stimulus, and stream on the auditory MMR in infants and children and the associations between MMR obtained in this context and language ability in early development were examined in the thesis.

10.1.2 Experimental results.

In the first instance, the paradigm features which produce large MMR in infants were identified. These included oddball deviance, tone pair stimuli and trial duration between 802 and 932 ms. Subsequently, on the whole, the stream modulation was revealed not to influence processing phonemes or tone pair discrimination. This was followed by an evaluation of the associations between MMR and language proficiency in infants and children and predictions from infancy to 2 years.

Surprisingly, the developmental trajectory of the MMR and its relationship with language were not identified in infants. However, an intriguing pattern was present in older children, which was linked to attentional bias in processing of background sounds. This trend was also present when the data were combined into the early development cohort Overall, the contribution of the paradigm features on the MMR and its relationship with language in early development have been confirmed (Datta, Shafer, Morr, Kurtzberg, & Schwartz, 2010; Guzzetta et al., 2011; Shafer et al., 2012).

Study 1.

Variable evidence between ERP studies exploring auditory processing in infants highlights the need for a systematic approach in order to elicit a more consistent MMR component. Study 1, therefore, set out to establish the differential effects of specific paradigm and stimulus parameters on the auditory MMR in infants. The aim was to identify the design features that reliably elicit significant auditory MMR. The selected modulations included deviance, trial duration and stimulus type.

Thirty-seven infants aged between 5 and 10 months participated in the study. They sat on their parent's lap, watching a silent cartoon while being exposed to sounds in the background. The stimuli were phonemes with the consonant change between /ba/ and /da/ and tone pairs with frequency change of 100-100 and 100-300 Hz between the standard and deviant pairs. Four passive auditory paradigms were employed in the study. The two phoneme paradigms were used to examine the oddball versus roving (sequential) deviance of frequent stimuli intersected with divergent sounds, whereas the tone pair paradigms tested the ITI reduction from 932 to 802 ms. The collected EEG data were analysed by averaging responses to deviants and standards across channels over the frontal and temporal regions (clusters of channels around F3, F4, T3 and T4 on the 10-20 system; Chatrian, Lettich, & Nelson, 1985).

The analysis revealed the advantage of oddball over the roving deviance in generating MMR in phonemes. In contrast, both trial durations produced large MMR and no significant difference between the long, and the short ITI was observed. This indicated the potential for using either the longer or the reduced length of a trial with little cost to the cortical response. Whereas the long ITI has been successfully utilised in research exploring the neural correlates of early language development (Benasich, 2002; Benasich et al., 2006, 2002; Cantiani et al., 2016a; Choudhury & Benasich, 2011), the reduced ITI could prove highly beneficial when testing infants and other vulnerable populations prone to restlessness and tiredness when optimal duration of the paradigm is a priority (Kolesnik et al., 2019; Musacchia et al., 2015).

Based on the results, the optimal paradigm could, therefore, comprise oddball deviance and trials between 802-932 ms duration. Finally, the stimulus modulation between the selected phoneme and tone pair paradigms, revealed the latter as more broadly distributed across the scalp, with earlier onset, longer duration, and larger MMR than to phonemes. In addition, MMR to phonemes presented itself as a negative deflection in the left frontal cluster, whereas large positivity was found for tone pairs bilaterally in the temporal clusters. Phonemes, therefore, evoked a more lateralised, yet attenuated MMR (Friederici, 2005; Ragó et al., 2014), whereas tone pairs were revealed to elicit a more prominent bilateral response (Choudhury & Benasich, 2011). These findings became the foundations for the subsequent studies in infants and children in this thesis.

Study 2.

Study 2 examined the effect of the number of simultaneous streams in a paradigm and stimulus type on the MMR in forty 5-11-month-old infants. The stream and stimulus modulations were hypothesised to have differential effects on the MMR. Design features, which had been established to reliably generate MMR in Study 1, i.e., the oddball deviance and the 932 ms ITI as well as the phoneme and tone pair stimuli were utilised to develop paradigms in Study 2.

The single stream phoneme and tone pair paradigms resembled the phoneme oddball and the long ITI tone pair paradigms from Study 1 and were treated as a control to the streaming paradigm. The latter comprised the phoneme and tone pair streams from the control paradigms but plotted alternately in a sequence: phoneme – tone pair – phoneme – tone pair, and so on. Both the phoneme and tone pair streams in the streaming paradigm retained their individual deviances as in the control phoneme and tone pair paradigms.

MMR to deviance in either of the control paradigms would indicate the ability to discriminate the change. In case of the streaming paradigm, processing deviance in one of the streams signified the ability to segregate them and process one while ignoring the other. In contrast, MMR to changes in both streams was considered the evidence of separating the competing streams and processing, i.e., streaming them individually.

The MMR patterns to phonetic deviance in the streaming and control paradigms were comparable. However, while significant MMR was recorded in response to deviance in the phoneme stream within the streaming paradigm, MMR in the phoneme paradigm did not reach significance. Likewise, MMR to change in tone pairs was not affected by the number of streams in a paradigm, but it differed from the effect of phoneme modulation in that tone pair deviances in the streaming and control paradigms elicited large MMR. This also confirmed the influence of stimulus modulation and it replicated the effect from Study 1, i.e., the tonal change elicited larger MMR than a phonetic contrast.

Study 3.

The objective of Study 3 was to assess the associations between MMR to the streaming and control paradigms and language ability in infants. Participants from Study 2 in addition to the EEG paradigms underwent behavioural language assessment, i.e., they performed tasks from the receptive and expressive communication subtests of Bailey-III (Bayley, 2005). The first test involved listening and responding to acoustics in the environment and in particular to speech, while in the latter infants' vocalisations in response to stimuli were assessed. The auditory MMR produced to deviance in the stream and stimulus modulations in Study 2 were hypothesised to be associated with behavioural language performance. Contrary to expectations, the auditory MMR did not correlate with the language composite scores. Essentially, the link between auditory processing and language was not found in the current sample.

Study 4.

Study 4 set out to evaluate the predictive value of auditory MMR in infancy on language ability at 2 years. A subset of a 2015-2017 birth sample set of infants who had participated in Study 1 or 2 was invited for the second experimental session within two weeks of their second birthday. They were presented with age-appropriate tasks from the receptive and expressive communication subtests of Bailey-III (Bayley, 2005). Their performance was expected to be associated with the

MMR in their infancy. However, such relationship was not identified. More broadly, auditory discrimination in the first year of life, was not linked to language a year later in this study.

Study 5.

The differential influence of the stream and stimulus modulations on the auditory MMR in children were explored in Study 5. Changes in the phoneme and tone pair paradigms and phoneme and tone pair streams in the streaming paradigm were expected to affect the spatial and temporal distribution of the MMR. EEG data from forty-one children aged between 4 and 6 years were analysed.

In accordance with the findings in Study 2 in infants, the number of streams did not generally influence auditory processing. Nevertheless, whilst significant discrimination was recorded in the control phoneme paradigm, the MMR to phonetic contrast did not reach significance in the streaming design. MMR to acoustic deviance was also not affected by the stream modulation. Indeed, both tone pair changes evoked similarly large and robust MMR. Overall, greater MMR was elicited by deviance in tone pairs than in phonemes both in the control and streaming paradigms.

Although the MMR to phonetic contrast in the control paradigm was still present, albeit attenuated in comparison to non-linguistic MMR, a more striking finding was observed within the streaming paradigm. Evidently, the phoneme and tone pair streams were segregated, but phonemes appeared to be ignored in favour of the more salient tone pair contrast, i.e., streaming did not occur (see also segregation of streams in newborns by Winkler et al., 2003). However, considering that MMR to phonetic deviance in the control paradigm developed later than the duration of the epoch in the streaming paradigm and that the patterns of MMR activity to both were alike, it could be also speculated that MMR to deviance in phoneme stream would have required a longer trial to reach significance.

Study 6.

The relationship between auditory MMR to change in phonemes and tone pairs in the control and streaming paradigms in children was assessed within Study 6. In addition to the EEG paradigms, children from Study 5 performed the NEPSY-II (Korkman et al., 2007a, 2007b, 2007c) language subtests. These included: comprehension and following increasingly complex instructions, repetition of oromotor sequences and pseudowords, phonological processing of words (in which children were required to segment words into phonemes and in more advanced tasks should be able to create a new word by changing a segment in the original word), speeded naming, i.e., timed labelling of the features of objects in the pictures and generation of specific lists of words under time pressure. The MMR was expected to be associated with performance on the compiled total language composite.

The results revealed negative correlations between MMR to deviance in tone pair stream the streaming paradigm and the behavioural performance on language. Broadly speaking increased inhibition of background acoustic contrast in the complex auditory environment, if not relevant to the task, i.e., to watching a silent cartoon was associated with higher proficiency in language (see also Guiraud et al., 2012; Jansson-Verkasalo et al., 2004; Sanders et al., 2006).

Study 7.

A study summarising main findings in the infants' and children' cohorts was conducted to identify and compare the difference in electrophysiological activity to sounds and find commonalities regarding language development in early childhood. Firstly, based on the findings in Study 2 in infants and Study 5 in children, group differences between MMR to deviance in phonemes and tone pairs in the streaming and control paradigms were expected. These were investigated in the first comparative analysis of the final study. Overall, MMR to change in all paradigms, except for the control phoneme paradigm where the difference was not significant, had larger deflections in infants than children.

Nevertheless, of note is the weak dissociation observed between phonetic discrimination in infants and children. The younger group processed linguistic contrast along with more salient tonal change, but not when it was presented against a silent background, whereas the older cohort discriminated phonemes in the latter design but ignored them in favour of the tone pair contrast in the streaming paradigm. This opposite trend may reflect changes in processing mechanisms involved in phonetic discrimination between infancy and primary school.

The second, correlational analysis in Study 7, was of exploratory nature. MMR deflections to deviance in the streaming and control conditions were averaged across infants and children into the 'early development cohort' whereas the language composite scores in infants (Bayley, 2005) and children (Korkman et al., 2007a, 2007b, 2007c) were combined into the total language composite variable. A reliable pattern emerged, as the MMR to phonetic contrast in the streaming and the control tone pair paradigms in the early development cohort correlated negatively with scores on the language composite. Overall, more advanced behavioural proficiency than expected for age was associated with the decrease in the MMR amplitude. This result reflected the relationship between auditory discrimination and language in children in study 6, although no such findings were reported in infants in Studies 3 and 4. Consequently, the results highlight the importance of attentional engagement in auditory and specifically language development, in that with age, the efficient selection of the environmental sounds, which is goal-dependent, becomes an important factor in the development of linguistic traits.

10.2 A general overview of the research aims

The overarching purpose of this thesis was to highlight the influence of paradigms features such as deviance, trial duration, stimulus, and number of streams in a paradigm on the auditory MMR in infants and children and develop optimal paradigms which elicit large overall MMR amplitude. The secondary objective was to examine the relationship between MMR and language ability in early development. The individual research aims of the thesis are outlined below.

Research Aim 1.

To determine the optimal paradigm features which evoke large MMR in early development.

Deviance modulation. When deviance type was the only modified feature in the otherwise matched passive phoneme paradigms, oddball deviance produced MMR with earlier onset latency of a more prolonged duration, as well as increased intensity and more widespread activation than the roving change in infants. The oddball change was therefore established as the efficient generator of the auditory MMR.

ITI modulation. Trial duration was reduced from the standard 932 to 802 ms in tone pair paradigms to determine the effect of shorter ITI, than commonly used in infants, on the MMR. However, the 130 ms difference between the paradigms had no differential effect on the MMR. The results instead indicated that reducing the ITI by a small degree did not bear cost in cortical processing of the change, and so shorter paradigms could be used in studying infants.

Stimulus modulation. Overall, the tone pair contrast generated earlier and larger MMR amplitude than phonemes, regardless of the number of streams in the paradigm. This pattern was observed both in infants and children, although on the whole, MMR waveforms in the younger group were larger than in older participants.

Research Aim 2.

To reveal the effect of stream on the MMR in infants and children.

Stream modulation. The differential effects of the number of simultaneous streams in a paradigm on the MMR in infants and children were assessed. Specifically, the difference between MMR to deviance in the phoneme stream within the streaming paradigm and in the control phoneme paradigm was examined. The same analysis was carried out within the tone pair design. Ultimately, differences within the phoneme and separately within the tone pair modulations were not significant in infants or children.

A divergent pattern emerged depending on the stimulus type. In infants, MMR was elicited to phonetic contrast within the streaming paradigm. Despite a similar pattern of activity, MMR to change in the phoneme paradigm did not reach significance. The opposite effect was found in children. Again, the pattern of activity to phonetic contrast was comparable between the manipulations. However, although MMR emerged to deviance in the phoneme paradigm, it appeared within the 400-450 ms time window, which was beyond the epoch duration in the streaming paradigm which may be the reason it was not observed in the latter.

By contrast, tone pair deviance generated characteristic large temporal or frontotemporal bilateral MMR early in the epoch to all the modulations both in children and infants. Within the streaming paradigm therefore, infants appeared to stream out the simultaneous sound sequences independently, while children segregated them but processed only the more salient tone pair contrast, ignoring the less discerning phonemes.

Research Aim 3.

To determine the predictive potential of the auditory MMR in infancy on language ability at 2 years of age.

Association between MMR in infancy and language composite when the infants turned 2 years was not identified and so this aim was not achieved.

Research Aim 4.

To compare MMR between infants and children.

Infants consistently generated larger MMR than children, except for the deviance in the phoneme paradigm, where the difference did not reach significance, despite the similar waveforms. The finding supported previous accounts on the developmental decrease in ERPs.

Research Aim 5.

To assess the relationship between linguistic and non-linguistic MMR and language ability in early development.

A developmental shift between infancy and the primary school age has been discovered. No relationship between language and auditory discrimination was found in infants. Such evidence has however been identified in children. Negative association between MMR in response to deviance in the streaming paradigm and language composite suggests that high responsivity to auditory change may be less beneficial to the development of language functions with age. Children which showed more advanced language skills, were more likely to inhibit processing of background sounds in the complex auditory environment, if not relevant to the task (such as ignoring sounds played from the speakers while following a story in a silent cartoon).

In a similar fashion, when the language scores were collapsed between the age groups into one sample (standardised so age was not supposed to be a factor) and the data plotted against the MMR to the linguistic and non-linguistic contrasts both in the single and two-stream conditions, negative correlations emerged to all. The ability to ignore background sounds in the environment related to better language performance than expected for age. The result supported the relationship between MMR and language in children in the earlier study of the thesis. This overarching finding suggested that auditory MMR could be a neuromarker of language ability in early development, but that this association is complex and needs a more in-depth investigation.

In conclusion, auditory discrimination correlated with language, although this link was stronger in primary school than younger children. Taken together, these relationships revealed hierarchy of linguistic processes as well as a glimpse into the development of attentional focus which may be underlying the convex pattern of the correlations between infancy and primary school.

10.3 Implications

The first objective of the current project was to identify the design features which generate large MMR in infants and determine whether the stimulus type and the number of streams in a paradigm influence MMR in infants and children. The second and final objective was to examine the relationship between MMR and language ability in infants and children.

10.3.1 The influence of paradigm features on the MMR in infants.

Methodological manipulations revealed the advantage of the oddball over roving deviance in generating larger MMR. In contrast, reducing the ITI by 130 ms did not affect the MMR, suggesting that the standard longer as well as the slightly shorter trial duration could be used with little cost to neural processing.

Taken together, the findings highlight the importance of the careful selection of the parameters and rationale for the design of an EEG paradigm (Lange, 2012; Partanen, Vainio, Kujala, & Huotilainen, 2011; Sams, Alho, & Näätänen, 1983). The selected design features may be applied to other studies exploring auditory processing, but they will be of particular interest to child researchers since developmental data is considerably more variable than adult EEG. Poorly selected paradigm features may affect the final averaged responses and generate biases so their contribution should be acknowledged (Luck, 2004; Luck & Gaspelin, 2017).

10.3.2 The effect of stimulus on MMR in infants and children

Tone pair stimuli elicited overall larger and more stable MMR component than phonemes across all paradigms in infants and children. This was evident despite the general trend for the MMR to be reduced in children than in infants. Overall, this finding supports the theory that narrowband tone frequencies are more discernible than spectral sounds, such as phonemes (Hancock, 2004). On a broader scale, it has provided a more in-depth insight into the effect of the linguistic and non-linguistic stimulus on the MMR in infants and children. However, its uniqueness comes from investigating this phenomenon, both separately in the control single stream and complex streaming design.

10.3.3 The effect of streaming on MMR in infants and children.

The difference between MMR generated to deviance in the streaming and control paradigms was investigated in infants and children. While the number of streams did not affect the MMR to deviance in tone pairs across both age groups (De Coensel & Botteldooren, 2008; Micheyl et al., 2007; Snyder et al., 2006), there was a trend in MMR to phonemes. Although the pattern of activity to all phoneme contrasts was comparable in both age groups, infants produced a significant MMR to phonetic contrast in the streaming paradigm, but not in the phoneme paradigm, and the opposite was found in children.

Within the streaming paradigm, this indicates that while both age groups segregated the streams and processed the salient frequency change in tone pairs, as supported by the literature (Smith & Trainor, 2011; Sussman et al., 2001; Sussman & Steinschneider, 2009; Winkler et al., 2003), distinctive attentional processes may have affected phonetic discrimination or the absence thereof in the two age groups.

Considering that epochs in the streaming paradigm were shorter than in the control paradigms (duration of 400 versus 650 m after the stimulus onset), the double dissociation found in discriminating phonemes between infants and children may reflect the different processing mechanisms engaged in generating MMR in infancy and at primary school age. The early MMR elicited in the streaming paradigm in infants may represent sensory processing of the physical properties of sounds (Čeponiené et al., 2002a, 2002b; Cheour, et al., 2002), whereas later MMR in the phoneme paradigm, which emerged beyond the duration of the epoch in the streaming paradigm, could be interpreted as cognitive and possibly speech-specific mechanism (Cunillera et al., 2006; Díaz et al., 2008; Getzmann, et al., 2015; Näätänen et al., 1997).

The dissociation may also indicate differential engagement of selective attention between infants and children (Gomes, Molholm, Christodoulou, et al., 2000). Despite the general belief that MMR is a preattentive neural component (Näätänen et al., 2007), these findings raise questions about the mechanisms involved in processing linguistic and non-linguistic stimuli and the changing role of selective attention in early development (Celsis et al., 1999).

Overall, deviance in tone pairs was found to be a reliable generator of the MMR, while MMR to phonetic change was subjected to differential effect of selective attention between the control and streaming paradigm (Sussman et al., 2003, 2014; Szycik et al., 2013). This double dissociation might reflect changes in attentional focus and linguistic acuity in development between infancy and the primary school age and this work in general is the first systematic investigation of the linguistic and non-linguistic MMR in infants and children

10.3.4 Relationship between MMR and language in childhood.

Relationship between auditory MMR and language composite scores (Bayley, 2005) was not confirmed in infancy or at 2 years of age. On the contrary, negative pattern emerged between the MMR and language associations in children. More proficient behavioural performance (Korkman et al., 2007a, 2007b, 2007c) was linked to selective inhibition of sounds which were not relevant to task at hand.

The final set of analyses explored the relationship between MMR averaged across infants and children and overall language performance. Negative correlations between MMR to tone pair and phonetic deviances in the complex streaming and single stream paradigm and the combined language composite scores indicated that the development of attentional focus could be contributing to this relationship (Sussman et al., 2014). Whilst auditory discrimination does not appear to impact language learning in infants, this changes with age as children inhibit irrelevant sounds in auditory scene and focus on the requirements of the activity they are engaged in (Šimleša & Cepanec, 2015; Vissers, Koolen, Hermans, Scheper, & Knoors, 2015), such as following a story in a silent cartoon instead of listening to sounds in the background.

The differences in the connection between MMR to tone pairs and language proficiency between infants and children evidence the distinctive engagement of selective attention. Indeed, studies report that attention in infants is immature and as a result they process all auditory information from the environment simultaneously, without selection or the need to be awake (Cheour et al., 2002; Cheour-Luhtanen et al., 1995; Dunn, Reissland, & Reid, 2015; Gilley et al., 2017; Kushnerenko et al., 2007; Mai et al., 2014; Martynova et al., 2003; Otte et al., 2013; Zhang, Li, Zheng, Dong, & Tu, 2017).

Raid changes in attentional focus and control may be driven by the gradually increased neuronal transmission, which is the result of wrapping the myelin sheath around the axons (Long, Wan, Roberts, & Corfas, 2018; Moore & Linthicum, 2001; Moore et al., 1995; Pearce, Crowell, Tokioka, & Pacheco, 1989; Warrier et al., 2009; Zatorre, 2001). Therefore, as a moderator between neural processing and behavioural performance, auditory attention could be masking their relationship in infancy (Aslin, Jusczyk, & Pisoni, 1998; Gomes, Molholm, Christodoulou, Ritter, & Cowan, 2000; Vouloumanos & Curtin, 2014).

The mechanism of attentional selection becomes gradually more specialised (Rueda et al., 2004; van de Weijer-Bergsma et al., 2008) and children increasingly focus on the task at hand and learn to ignore distractors (Gomes et al., 2000; Stevens et al., 2009; Turk-Browne et al., 2008; Werner, 2012). Selective auditory attention reaches adult levels by approximately 10 years of age (Leibold, 2012b; Werner, 2007).

10.3.5 Summary.

Overall, these findings corroborate research suggesting that maturation of selective attention underlies differences in MMR between infants and children and to some extent contributes to the relationship between MMR and language proficiency. This work adds to existing knowledge of the MMR by highlighting its associations with the early development of selective attention in the auditory and specifically linguistic context.

10.4 Limitations and future directions

The scope of this thesis was limited to investigating the effects of the paradigm features such as the type of deviance and trial duration on the auditory MMR in infants and exploring the influence of the number of alternating streams in a paradigm and stimulus type on the MMR in infants and children. The final goal of the project was to examine the relationship between MMR and language ability in infants and children. Despite the careful design and stringent implementation of the studies, some extraneous variables may have contributed to the outcomes.

10.4.1 Language experience.

Combining the data from monolingual and bilingual participants could be considered the main weakness of this thesis. Although this provided opportunity to generalise the findings to the more naturalistic and universal environment, the manipulation may have confounded the results (Conboy & Kuhl, 2011; Ferjan

Ramírez, Ramírez, Clarke, Taulu, & Kuhl, 2017; Garcia-Sierra et al., 2011, 2016; Hoff, 2013b; Kuhl, 2010; Shafer et al., 2012; Werker et al., 2009).

However, language experience was accounted for in the analysis. Although it influenced behavioural language scores to some degree in the infant cohort, with monolingual participants scoring on average higher than bilinguals, no such effect was found in children (Hoff, 2013) and variance in the MMR in most of the studies in this thesis (except for a small effect in Study 7) was not explained by exposure to one versus more languages. Nonetheless, the variable may have somewhat contributed to the relationship between MMR and language ability (Cheour et al., 2002; Jost et al., 2015). Whilst exploring this contribution was outside the scope of this thesis, a natural progression of this work would be to analyse the impact of language experience on the MMR and its relationship with English language proficiency in early development or to explore the effect of language experience on the MMR in development.

10.4.2 Age range.

Another critical limitation lies in the wide age range of the samples, in particular in the infant cohort. Although it did not appear to affect the absolute MMR to tone pairs, it may have contributed to the attenuated MMR in the phoneme deviance in EEG paradigms. Considering the rapid maturational changes in the neural activity (Choudhury et al., 2015; Fellman et al., 2004; Guzzetta et al., 2011; Kushnerenko et al., 2013c) and the speed of language development (Kuhl et al., 2006; Luttikhuizen dos Santos et al., 2013; Paterson et al., 2006; Schuele, 1998) in the first year of life, the age range in infant studies tends to be narrow, usually ranging 1-2 months (Cantiani, et al., 2016b; Dehaene-Lambertz & Baillet, 1998;

Friedrich et al., 2004; Gogate & Bahrick, 1998; Guiraud et al., 2012; Minagawa-Kawai, Mori, Naoi, & Kojima, 2007; Weber et al., 2004; Winkler et al., 2003).

In contrast, the infants' ages in the current studies ranged between 5 and 11 months (although see other studies with increased age range: Olsho, Schoon, Sakai, Turpin, & Sperduto, 1982; Shaw et al., 2015; Shultz et al., 2014; Uhler et al., 2018). Narrowing the age range to a month or two could, therefore, reduce variability in the data and ensure large MMR effects. This is particularly important in the second part of the first year, as the direction of the MMR is thought to switch between positive to negative amplitude between 6- to 9-months (Cheng et al., 2013, 2015; Marshall et al., 2009), This is possibly caused by maturation of the grey matter (Deoni et al., 2012) and the development of the fibre pathways between primary auditory cortex and Broca's area (Perani et al., 2011). However, in reality, the ideal MMR signature had to be offset against the time constraints of data collection and availability of participants in the database.

Nevertheless, this limitation was acknowledged in the studies and in order to reduce the effect of the MMR switch, the absolute difference between the ERPs to deviants and standards was used in analyses instead of the direction of the MMR amplitude. Furthermore, behavioural language performance was assessed using the standard scores corrected for gestation rather than raw scores, which would be affected by age. Any correction for gestational age was also included in all initial analyses so as to address its influence on the MMR difference between the manipulations and the relationship between the MMR and language ability although it generally did not affect the performance since it was controlled for at the data processing stage.

In addition, the wider age-ranges of the samples used, than it had been initially planned, provided more naturalistic results, and demonstrated robustness of the MMR to tone pairs while highlighting the differences in MMR to phonemes between paradigms and in infants and children. A more restrictive sampling could however produce more precise and significant findings in the future, which in turn could provide more definitive evidence on the underlying mechanisms associated with the MMR and the relationship between MMR and language in early development.

10.4.3 Cross-sectional design.

The advantage of the longitudinal design is reduced individual variability in the sample (Levin, 2006; Lindell & Whitney, 2001; Mann, 2003). Since a strict timeframe limited the project, the resolution was to resolve to the cross-sectional design, although a successful attempt at exploring the effect of the MMR in infancy on language ability at 2 years was made. If time constraints were not imposed, the developmental trajectories of all infants from 2015-2017 cohort would have been investigated in more detail, not only at 2 years but up to 6 years of age. Although such extended period of data collection was not incorporated within the project timeline, it may serve as the scope for future work (Bailey & Snowling, 2002a; Cantiani et al., 2016b; Choudhury & Benasich, 2011; François et al., 2017). Longitudinal research is, therefore, still needed to examine the predictive value of the MMR in language development.

10.4.4 Sample size.

Another obstacle in developmental research is sampling. While 37-41 participants per sample are generally considered a large enough count for simple child EEG studies, correlations with behavioural scores could have proved more significant, were larger samples employed (Kushnerenko et al., 2008). In particular, the relationship between MMR in infancy and language ability at 2 years would have been more meaningful.

For the research to move forward, a better understanding of the role of selective attention in the MMR and its associations with language ability needs to be developed. This project should be repeated at a larger scale to establish individual differences in the development of the MMR, its relationship with language and the moderating function of the selective attention on this relationship.

10.4.5 Overlapping MMR waveforms in the streaming paradigm.

Due to the short 450 ms epoch duration in the streaming paradigm, there was a possibility for the waveforms from the past or following stimuli to contribute to ERPs to deviants and standards. Given that ERP signal is cumulative, this may have increased the average ERP amplitudes, which in turn would have led to the inflated MMR waveform (Budd et al., 2013; Luck & Gaspelin, 2017).

Incidentally, visual inspection of the MMR waveforms in the grand average images ruled out the effect of the previous stimulus. The ERP waveforms from -50 ms baseline before and up to 100 ms after the stimulus onset was not inflated but close to zero in all the images, indicating a sufficient reset of MMR waveforms before the stimulus (Luck, 2014, pp. 255-258). It is unfortunate that they appeared to display some influence from the following stimulus at the end of the epoch but generally the onset and mean amplitude of the MMR was found before the last 350-400 ms time window in the epoch.

10.4.6 Number of trials in a paradigm.

Paradigm duration and more precisely the number of trials in each paradigm and signal to noise ratio may have influenced the level of habituation to standards and dishabituation to deviants, leading to attenuated MMR (Luck, 2004, pp. 258-263). Admittedly, longer paradigm duration, either with increased number of trials or by reducing the probability of deviants from 20% to 15% in order to increase the dishabituation process (Fisher, Grant, Smith, & Knott, 2011; Sculthorpe & Campbell, 2011) could have contributed to the more significant MMR to deviance in phonemes.

However, considering that participants were exposed to three to four EEG paradigms in a single experimental session and that usable data from all was required to include the participant in analysis, a longer paradigm duration could have affected the quality of data. It could lead to more noisy ERPs (Georgieva et al., 2017) and participant exclusions due to restlessness. Consequently, studies exploring MMR to deviance in phonemes would help to clarify the matter by employing longer paradigms with reduced deviant probability but a larger number of trials.

10.4.7 The amplitude of the MMR.

An alternative way of exploring the EEG data would be to divide the samples by the direction of the MMR amplitude (positive or negative), or by significance or absence of the MMR in individual participants. Research suggests that infants and children who present with positive MMR demonstrate an immature response to the stimulus, whereas negative MMR amplitude or MMN is a sign of more advanced processing (Cheng et al., 2013; Choudhury & Benasich, 2011; Kushnerenko et al., 2013c; Mahajan & McArthur, 2012; Maurer et al., 2003b). The other approach could provide opportunity to explore individual differences in auditory processing, with the focus on typical and atypical development of the MMR in early childhood. Although beyond the scope of this thesis, these concepts could further break down the relationship between MMR and language development and should be considered in future research.

10.5 Future research.

Findings of this thesis highlight the importance of careful paradigm design of EEG studies. Although maturational changes in neural activity tend to be attributed to the variability between developmental studies, the features of the studies such as deviance type, trial duration, number of streams or stimulus type may be contributing to this variability by creating spurious results (Lovio, Näätänen, & Kujala, 2010; Partanen, Vainio, Kujala, & Huotilainen, 2011; Putkinen, Niinikuru, Lipsanen, Tervaniemi, & Huotilainen, 2012; Sams, Alho, & Näätänen, 1983; Schröger & Winkler, 1995). It is crucial that researchers carefully select and calibrate EEG paradigm parameters to ensure the design elicits the relevant components and accurately tests the study hypothesis without influencing or confounding the outcome.

Another avenue to explore is the effect of bilingualism on the MMR in language development. Having only been superficially validated in the current thesis, language experience impacted language development in infants and to some extent its relationship with the MMR. While this did not markedly influence results in children, all the bilinguals were exposed to at least two languages since birth. Sequential bilingualism within migrant families may affect performance on English standardised tests and influence the MMR amplitude, but this phenomenon remains understudied (Jia & Fuse, 2007; Laasonen et al., 2018; Mohades et al., 2012).

Finally, maturational changes in auditory attention appear to have affected the relationship between MMR and language proficiency in the thesis. Despite general assumptions that MMR is preattentive (Alho et al., 1998; Čeponiene et al., 2004; Paavilainen, Kaukinen, Koskinen, Kylmälä, & Rehn, 2018; Schröger, 1997), this was not entirely the case in this thesis. In fact, passive listening or rather the ability to selectively ignore the sounds while engaged in another activity (watching a silent cartoon), attenuated the MMR in children and indeed reduced MMR correlated with the higher-level language in early development. Ultimately, the question arising from the thesis is how the development of selective attention affects the MMR and language in child development.

10.6 General conclusions

The major contribution of this work to the fields of developmental neuroscience, neuropsychology and neurolinguistics is that it investigated the MMR to auditory deviance in infants and children. The main findings involved the differential effects of paradigm features such as the form of deviance, trial duration, type of stimulus and number of simultaneous streams, both on the spatial and temporal distribution of the MMR and its relationship with language ability within and across both age groups.

Namely, auditory processing was detrimental in older children, if the processed sounds were irrelevant to the goal. Instead, the ability to inhibit the background sounds was a more efficient indicator of higher language proficiency in children. None such associations were found in infants. The relationship between MMR and language in early development may therefore reflect changes in attentional engagement.

Findings from this thesis may inform further studies on the auditory and specifically speech processing and language development in infants and children. The phoneme, tone pair and the newly developed streaming paradigm have the potential to be included in the targeted screening programmes to identify infants at risk of language deficits before the neurological patterns are consolidated.

Considerably more work is required to determine the predictive potential of the MMR. The long-term implications of the current findings could lead to the development of clinical EEG assessments identifying infants at risk of impairments in auditory discrimination in order to enrol them into intervention programmes. This approach could have a significant positive impact from reducing the proportion of children presenting with language delay at the time of school entry to influencing policy makers and early years providers. Due to the prevalence of language difficulties in children and adults from disadvantaged backgrounds, ultimately, this work has the potential to contribute significantly to the quality of life of people from diverse socioeconomic backgrounds that will, in turn, offer them and the wider society associated economic benefits.

References

Abrams, R. M., & Gerhardt, K. J. (2000). The acoustic environment and physiological responses of the fetus. *Journal of Perinatology*, *20*(S1), S31–S36. https://doi.org/10.1038/sj.jp.7200445

Adams, K. A., Marchman, V. A., Loi, E. C., Ashland, M. D., Fernald, A., & Feldman, H. M. (2017). Caregiver talk and medical risk as predictors of language outcomes in full term and preterm toddlers. *Child Development, 89*(5), 1674-1690. https://doi.org/10.1111/cdev.12818

Adler, N. E., & Snibbe, A. C. (2003). The role of psychosocial processes in explaining the gradient between socioeconomic status and health. *Current Directions in Psychological Science*, *12*(4), 119–123. https://doi.org/10.1111/1467-8721.01245

Ahmad, S. A., & Warriner, E. M. (2001). Review of the NEPSY: A Developmental Neuropsychological Assessment. *The Clinical Neuropsychologist*, *15*(2), 240–249. https://doi.org/10.1076/clin.15.2.240.1894

Ahmmed, A. U., Clarke, E. M., & Adams, C. (2008). Mismatch negativity and frequency representational width in children with specific language impairment. *Developmental Medicine and Child Neurology*, *50*(12), 938–944. https://doi.org/10.1111/j.1469-8749.2008.03093.x

Akram, S., Presacco, A., Simon, J. Z., Shamma, S. A., & Babadi, B. (2016). Robust decoding of selective auditory attention from MEG in a competing-speaker environment via state-space modeling. *NeuroImage*, *124*, 906–917. https://doi.org/10.1016/j.neuroimage.2015.09.048

Albers, C. A., & Grieve, A. J. (2007). Test review: Bayley, N. (2006). Bayley Scales of Infant and Toddler Development– Third Edition. San Antonio, TX: Harcourt Assessment. *Journal of Psychoeducational Assessment*, *25*(2), 180–190. https://doi.org/10.1177/0734282906297199

Aldridge, H., Born, T. B., Tinson, A., & MacInnes, T. (2015). London's Poverty Profile 2015. *Trust for London: Tackling Poverty & Inequality*. Retrieved from: http://www.londonspovertyprofile.org.uk

Aldridge, H., Bushe, S., Kenway, P., MacInnes, T., & Tinson, A. (2013). London's Poverty Profile 2013. *Trust for London: Tackling Poverty & Inequality* (Issue April). Retrieved from: http://www.londonspovertyprofile.org.uk

Alho, K., Connolly, J. F., Cheour, M., Lehtokoski, A., Huotilainen, M., Virtanen, J., Aulanko, R., & Ilmoniemi, R. J. (1998). Hemispheric lateralization in preattentive processing of speech sounds. *Neuroscience Letters*, *258*(1), 9–12. https://doi.org/10.1016/S0304-3940(98)00836-2

Alho, K., Rinne, T., Herron, T. J., & Woods, D. L. (2014). Stimulus-dependent activations and attention-related modulations in the auditory cortex: A meta-analysis of fMRI studies. *Hearing Research*, *307*, 29–41. https://doi.org/10.1016/j.heares.2013.08.001

Alho, K., Salmi, J., Koistinen, S., Salonen, O., & Rinne, T. (2015). Top-down controlled and bottom-up triggered orienting of auditory attention to pitch activate overlapping brain networks. *Brain Research*, *1626*, 136–145. https://doi.org/10.1016/j.brainres.2014.12.050

Alho, K., Winkler, I., Escera, C., Huotilainen, M., Virtanen, J., Jääskeläinen, I. P., Pekkonen, E., & Ilmoniemi, R. J. (1998). Processing of novel sounds and frequency changes in the human auditory cortex: Magnetoencephalographic recordings. *Psychophysiology*, *35*(2), 211–224. https://doi.org/10.1017/S004857729800211X

Allen, J., Kraus, N., & Bradlow, A. (2000). Neural representation of consciously imperceptible speech sound differences. *Perception and Psychophysics*, *62*(7), 1383–1393. https://doi.org/10.3758/BF03212140

Allison, T., Puce, A., & McCarthy, G. (2002). Category-sensitive excitatory and inhibitory processes in human extrastriate cortex. *Journal of Neurophysiology*, *88*(5), 2864–2868. https://doi.org/10.1152/jn.00202.2002

Almonte, F., Jirsa, V. K., Large, E. W., & Tuller, B. (2005). Integration and segregation in auditory streaming. *Physica D: Nonlinear Phenomena*, *212*(1–2), 137–159. https://doi.org/10.1016/j.physd.2005.09.014

Altmann, C. F., Klein, C., Heinemann, L. V., Wibral, M., Gaese, B. H., & Kaiser, J. (2011). Repetition of complex frequency-modulated sweeps enhances neuromagnetic responses in the human auditory cortex. *Hearing Research*, *282*(1–2), 216–224. https://doi.org/10.1016/j.heares.2011.07.008

Altvater-Mackensen, N., & Grossmann, T. (2018). Modality-independent recruitment of inferior frontal cortex during speech processing in human infants. *Developmental Cognitive Neuroscience*, *34*(October), 130–138. https://doi.org/10.1016/j.dcn.2018.10.002

Anderson, L. A., Christianson, G. B., & Linden, J. F. (2009). Stimulus-specific adaptation occurs in the auditory thalamus. *Journal of Neuroscience*, *29*(22), 7359–7363. https://doi.org/10.1523/JNEUROSCI.0793-09.2009

Anderson, L. A., & Linden, J. F. (2016). Mind the Gap: Two dissociable mechanisms of temporal processing in the auditory system. *Journal of*

Neuroscience, *36*(6), 1977–1995. https://doi.org/10.1523/JNEUROSCI.1652-15.2016

Andreou, L. V., Kashino, M., & Chait, M. (2011). The role of temporal regularity in auditory segregation. *Hearing Research*, *280*(1–2), 228–235. https://doi.org/10.1016/j.heares.2011.06.001

Angelini, E., Campanini, R., Iampieri, E., Lanconelli, N., Masotti, M., Petkov, T., & Roffilli, M. (2009). Repetition suppression and plasticity in the human brain. *NeuroImage*, *48*(1), 269–279. https://doi.org/10.1016/j.neuroimage.2009.06.034.Repetition

Angiulli, A., Herdman, A., Stapells, D., & Hertzman, C. (2008). Children's event-related potentials of auditory selective attention vary with their socioeconomic status. *Neuropsychology*, *22*(3), 293–300. https://doi.org/10.1037/0894-4105.22.3.293

Arora, B., Choudhury, T., Kumar, P., & Mukherjee. (2016). An intelligent way to play music by brain activity using brain computer interface. *Proceedings on 2016 2nd International Conference on Next Generation Computing Technologies, NGCT 2016*, 223–228. https://doi.org/10.1109/NGCT.2016.7877419

Aslin, R. N., Saffran, J. R., & Newport, E. L. (1998). Computation of conditional probability statistics by 8-month-old infants. *Psychological Science*, *9*(4), 321–324. https://doi.org/10.1111/1467-9280.00063

Atherton, L. A., Dupret, D., & Mellor, J. R. (2015). Memory trace replay: The shaping of memory consolidation by neuromodulation. *Trends in Neurosciences*, *38*(9), 560–570. https://doi.org/10.1016/J.TINS.2015.07.004

Ayala, Y. A., & Malmierca, M. S. (2013). Stimulus-specific adaptation and deviance detection in the inferior colliculus. *Frontiers in Neural Circuits*, *6*, 89. https://doi.org/10.3389/fncir.2012.00089

Baart, M., Vroomen, J., Shaw, K., & Bortfeld, H. (2014). Degrading phonetic information affects matching of audiovisual speech in adults, but not in infants. *Cognition*, *130*(1), 31–43. https://doi.org/10.1016/j.cognition.2013.09.006

Bach, S., Brandeis, D., Hofstetter, C., Martin, E., Richardson, U., & Brem, S. (2010). Early emergence of deviant frontal fMRI activity for phonological processes in poor beginning readers. *NeuroImage*, *53*(2), 682–693. https://doi.org/10.1016/j.neuroimage.2010.06.039

Bailey, P. J., & Snowling, M. J. (2002a). Auditory processing and the development of language and literacy. *British Medical Bulletin*, *63*(1), 135–146. https://doi.org/10.1093/bmb/63.1.135

Balaguer-Ballester, E., Bouchachia, A., Jiang, B., & Denham, S. L. (2012). Neurodynamical top-down processing during auditory attention. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *7664 LNCS* (PART 2), 266–273. https://doi.org/10.1007/978-3-642-34481-7_33

Baldeweg, T. (2007). ERP repetition effects and mismatch negativity generation: A predictive coding perspective. *Journal of Psychophysiology, 21*(3–4), 204–213. https://doi.org/10.1027/0269-8803.21.34.204

Baldeweg, T., & Hirsch, S. R. (2015). Mismatch negativity indexes illness-specific impairments of cortical plasticity in schizophrenia: A comparison with bipolar disorder and Alzheimer's disease. *International Journal of Psychophysiology*, *95*(2), 145–155. https://doi.org/10.1016/J.IJPSYCHO.2014.03.008

Baldeweg, T., Klugman, A., Gruzelier, J. H., & Hirsch, S. R. (2002). Impairment in frontal but not temporal components of mismatch negativity in schizophrenia. *International Journal of Psychophysiology, 43*(2), 111–122. https://doi.org/10.1016/S0167-8760(01)00183-0

Baldeweg, T., Klugman, A., Gruzelier, J., & Hirsch, S. R. (2004). Mismatch negativity potentials and cognitive impairment in schizophrenia. *Schizophrenia Research, 69*(2–3), 203–217. https://doi.org/10.1016/j.schres.2003.09.009

Banaschewski, T., & Brandeis, D. (2007). Annotation: What electrical brain activity tells us about brain function that other techniques cannot tell us - a child psychiatric perspective. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *48*(5), 415–435. https://doi.org/10.1111/j.1469-7610.2006.01681.x

Barker, B. A., & Newman, R. S. (2004). Listen to your mother! The role of talker familiarity in infant streaming. *Cognition*, *94*(2), B45-53. https://doi.org/10.1016/j.cognition.2004.06.001

Barnett, W. S., Lamy, C., & Jung, K. (2005). *The Effects of State Prekindergarten Programs on Young Children's School Readiness in Five States*. New Brunswick, NJ: National Institute for Early Education Research. Retrieved from http://www.pewtrusts.org/~/media/legacy/uploadedfiles/wwwpewtrustsorg/reports/pre-k_education/finaloverallmultistatereportpdf.pdf

Barry, J. G., Hardiman, M. J., & Bishop, D. V. M. (2009). Mismatch response to polysyllabic nonwords: A neurophysiological signature of language learning capacity. *PLoS ONE*, *4*(7), e6270. https://doi.org/10.1371/journal.pone.0006270

Basirat, A., Dehaene, S., & Dehaene-Lambertz, G. (2014). A hierarchy of cortical responses to sequence violations in three-month-old infants. *Cognition*, *132*(2), 137–150. https://doi.org/10.1016/j.cognition.2014.03.013

Bayley, N. (2005). Bayley Scales of Infant and Toddler Development. *Pearson*. Psychological Corporation. https://doi.org/10.1002/9780470479216.corpsy0111

Bedford, H., Walton, S., & Ahn, J. (2013). Measures of child development: A review. In *Policy Research Unit in the Health of Children, Young People and Families*. Retrieved from http://www.chimat.org.uk/resource/item.aspx?RID=208040Beeghly, M. (2006). Translational research on early language development: Current challenges and future directions. *Development and Psychopathology*, *18*(3), 737–757. https://doi.org/10.1017/S0954579406060366

Belin, P., Zilbovicius, M., Crozier, S., Thivard, L., Fontaine, and A., Masure, M.-C., & Samson, Y. (1998). Lateralization of speech and auditory temporal processing. *Journal of Cognitive Neuroscience*, *10*(4), 536–540. https://doi.org/10.1162/089892998562834

Bell, M. A., & Cuevas, K. (2012). Using EEG to study cognitive development: Issues and practices. *Journal of Cognition and Development*, *13*(3), 281–294. https://doi.org/10.1080/15248372.2012.691143

Benasich, A. A. (2002). Impaired processing of brief, rapidly presented auditory cues in infants with a family history of autoimmune disorder. *Developmental Neuropsychology*, *22*(1), 351–372. https://doi.org/10.1207/S15326942dn2201_2

Benasich, A. A., Choudhury, N. A., Realpe-Bonilla, T., & Roesler, C. P. (2014). Plasticity in developing brain: Active auditory exposure impacts prelinguistic acoustic mapping. *Journal of Neuroscience*, *34*(40), 13349–13363. https://doi.org/10.1523/JNEUROSCI.0972-14.2014

Benasich, A. A., Choudhury, N., Friedman, J. T., Realpe-Bonilla, T., Chojnowska, C., & Gou, Z. (2006). The infant as a prelinguistic model for language learning impairments: Predicting from event-related potentials to behavior. *Neuropsychologia*, *44*(3), 396–411. https://doi.org/10.1016/j.neuropsychologia.2005.06.004

Benasich, A. A., Choudhury, N., Peters, S., & Ortiz-Mantilla, S. (2016). Early screening and intervention of infants at high risk for developmental language disorders: The role of nonlinguistic rapid auditory processing. *Perspectives on Language and Literacy*, *42*(1), 24–29.

Benasich, A. A., & Tallal, P. (1996). Auditory temporal processing thresholds, habituation, and recognition memory over the 1st year. *Infant Behavior and Development*, *19*(3), 339–357. https://doi.org/10.1016/S0163-6383(96)90033-8

Benasich, A. A., & Tallal, P. (2002). Infant discrimination of rapid auditory cues predicts later language impairment. *Behavioural Brain Research*, *136*(1), 31–49. https://doi.org/10.1016/S0166-4328(02)00098-0

Benasich, A. A., Thomas, J. J., Choudhury, N., & Leppänen, P. H. T. T. (2002). The importance of rapid auditory processing abilities to early language development: Evidence from converging methodologies. *Developmental Psychobiology*, *40*(3), 278–292. https://doi.org/10.1002/dev.10032

Benavides-Varela, S., Hochmann, J.-R., Macagno, F., Nespor, M., & Mehler, J. (2012). Newborn's brain activity signals the origin of word memories. *Proceedings of the National Academy of Sciences*, *109*(44), 17908–17913. https://doi.org/10.1073/pnas.1205413109

Bendixen, A., Denham, S. L., Gyimesi, K., & Winkler, I. (2010). Regular patterns stabilize auditory streams. *The Journal of the Acoustical Society of America*, *128*(6), 3658–3666. https://doi.org/10.1121/1.3500695

Bent, T., Bradlow, A. R., & Wright, B. A. (2006). The influence of linguistic experience on the cognitive processing of pitch in speech and nonspeech sounds. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(1), 97–103. https://doi.org/10.1037/0096-1523.32.1.97

Beres, A. M. (2017). Time is of the essence: A review of electroencephalography (EEG) and event-related brain potentials (ERPs) in language research. *Applied Psychophysiology Biofeedback, 42*(4), 247–255. https://doi.org/10.1007/s10484-017-9371-3

Bergmann, C., Bosch, L. Ten, Fikkert, P., & Boves, L. (2015). Modelling the noise-robustness of infant's word representations: The impact of previous experience. *PLoS ONE*, *10*(7), e0132245. https://doi.org/10.1371/journal.pone.0132245

Berman, S., & Friedman, D. (1995). The development of selective attention as reflected by event-related brain potentials. *Journal of Experimental Child Psychology*, *59*(1), 1–31. https://doi.org/10.1006/jecp.1995.1001

Bidelman, G. M., & Dexter, L. (2015). Bilinguals at the "cocktail party": Dissociable neural activity in auditory-linguistic brain regions reveals neurobiological basis for nonnative listeners' speech-in-noise recognition deficits. *Brain and Language*, *143*, 32–41. https://doi.org/10.1016/j.bandl.2015.02.002

Binder, J. R. (2000). Human temporal lobe activation by speech and nonspeech sounds. *Cerebral Cortex*, *10*(5), 512–528. https://doi.org/10.1093/cercor/10.5.512

Bishop, D. V. M., & Hardiman, M. J. (2010). Measurement of mismatch negativity in individuals: A study using single-trial analysis. *Psychophysiology*, *47*(4), 697–705. https://doi.org/10.1111/j.1469-8986.2009.00970.x

Bishop, D. V. M., Hardiman, M. J., & Barry, J. G. (2010). Lower-frequency event-related desynchronization: A signature of late mismatch responses to sounds, which is reduced or absent in children with specific language impairment. *Journal of Neuroscience*, *30*(46), 15578–15584. https://doi.org/10.1523/JNEUROSCI.2217-10.2010

Bishop, D. V. M., Hardiman, M. J., & Barry, J. G. (2011). Is auditory discrimination mature by middle childhood? A study using time-frequency analysis of mismatch responses from 7 years to adulthood. *Developmental Science*, *14*(2), 402–416. https://doi.org/10.1111/j.1467-7687.2010.00990.x

Bishop, D. V. M., Snowling, M. J., Thompson, P. A., & Greenhalgh, T. (2017). Phase 2 of CATALISE: A multinational and multidisciplinary Delphi consensus study of problems with language development: Terminology. *Journal of Child Psychology and Psychiatry*, *58*(10), 1068–1080. https://doi.org/10.1111/jcpp.12721

Bitan, T., Cheon, J., Lu, D., Burman, D. D., & Booth, J. R. (2009). Developmental increase in top–down and bottom–up processing in a phonological task: An effective connectivity, fMRI Study. *Journal of Cognitive Neuroscience*, *21*(6), 1135–1145. https://doi.org/10.1162/jocn.2009.21065

Bitz, U., Gust, K., Spitzer, M., & Kiefer, M. (2007). Phonological deficit in school children is reflected in the mismatch negativity. *NeuroReport*, *18*(9), 911–915. https://doi.org/10.1097/WNR.0b013e32810f2e25

Botting, N., Gaynor, M., Tucker, K., & Orchard-Lisle, G. (2016). The importance of natural change in planning school-based intervention for children with Developmental Language Impairment (DLI). *Child Language Teaching and Therapy*, *32*(2), 159–177. https://doi.org/10.1177/0265659015595444

Bradley, R. H., & Corwyn, R. F. (2002). Socioeconomic status and child development. *Annual Review of Psychology*, *53*(1), 371–399. https://doi.org/10.1146/annurev.psych.53.100901.135233

Brauer, J., Anwander, A., & Friederici, A. D. (2011). Neuroanatomical prerequisites for language functions in the maturing brain. *Cerebral Cortex*, *21*(2), 459–466. https://doi.org/10.1093/cercor/bhq108

Brechmann, A., Baumgart, F., & Scheich, H. (2002). Sound-level-dependent representation of frequency modulations in human auditory cortex: A low-noise fMRI Study. *Journal of Neurophysiology*, *87*(1), 423–433. https://doi.org/10.1152/jn.00187.2001

Bregman, A. S. (1978). Auditory streaming is cumulative. *Journal of Experimental Psychology: Human Perception and Performance*, *4*(3), 380–387. https://doi.org/10.1037/0096-1523.4.3.380

Bregman, A. S. (2009). Auditory Scene Analysis. In N.J. Smelzer & P.B. Bates (Eds.). *Encyclopedia of Neuroscience* (Vol. 3, pp. 729–736). Amsterdam: Pergamon. Elsevier. https://doi.org/10.1016/B978-008045046-9.00246-1

Bregman, A. S. (2015). Progress in understanding auditory scene analysis. *Music Perception: An Interdisciplinary Journal*, *33*(1), 12–19. https://doi.org/10.1525/mp.2015.33.1.12

Bregman, A. S., & Campbell, J. (1971). Primary auditory stream segregation and perception of order in rapid sequences of tones. *Journal of Experimental Psychology*, *89*(2), 244–249. https://doi.org/10.1037/h0031163

Bregman, A. S., & Rudnicky, A. I. (1975). Auditory segregation: Stream or streams? *Journal of Experimental Psychology: Human Perception and Performance*, *1*(3), 263–267. https://doi.org/10.1037//0096-1523.1.3.263

Bressler, S., Masud, S., Bharadwaj, H., & Shinn-Cunningham, B. (2014). Bottom-up influences of voice continuity in focusing selective auditory attention. *Psychological Research*, *78*(3), 349–360. https://doi.org/10.1007/s00426-014-0555-7

Bridwell, D. A., Cavanagh, J. F., Collins, A. G. E., Nunez, M. D., Srinivasan, R., Stober, S., & Calhoun, V. D. (2018). Moving beyond ERP components: A selective review of approaches to integrate EEG and behavior. *Frontiers in Human Neuroscience*, *12*(March), 1–17. https://doi.org/10.3389/fnhum.2018.00106

Broca, P. (1865). Sur le siège de la faculté du langage articulé. *Bulletins de La Société d'anthropologie de Paris*, *6*(1), 377–393. https://doi.org/10.3406/bmsap.1865.9495

Brooks, B. L., Sherman, E. M. S., & Iverson, G. L. (2010). Healthy children get low scores too: prevalence of low scores on the NEPSY-II in preschoolers, children, and adolescents. *Archives of Clinical Neuropsychology*, *25*(3), 182–190. https://doi.org/10.1093/arclin/acq005

Brooks, B. L., Sherman, E. M. S., & Strauss, E. (2010). Test review: NEPSY-II: A Developmental neuropsychological assessment, second edition. *Child Neuropsychology*, *16*(1), 80–101. https://doi.org/10.1080/09297040903146966

Bruggemann, J. M., Stockill, H. V., Lenroot, R. K., & Laurens, K. R. (2013). Mismatch negativity (MMN) and sensory auditory processing in children aged 9-12 years presenting with putative antecedents of schizophrenia. *International Journal of Psychophysiology*, *89*(3), 374–380. https://doi.org/10.1016/j.ijpsycho.2013.05.008

Budd, M.-J., Paulmann, S., Barry, C., & Clahsen, H. (2013). Brain potentials during language production in children and adults: An ERP study of the English past tense. *Brain and Language*, *127*(3), 345–355. https://doi.org/10.1016/J.BANDL.2012.12.010

Budd, T. W., Nakamura, T., Fulham, W. R., Todd, J., Schall, U., Hunter, M., Hodgson, D. M., & Michie, P. T. (2013). Repetition suppression of the rat auditory evoked potential at brief stimulus intervals. *Brain Research*, *1498*, 59–68. https://doi.org/10.1016/j.brainres.2012.12.033

Burton, M. W., LoCasto, P. C., Krebs-Noble, D., & Gullapalli, R. P. (2005). A systematic investigation of the functional neuroanatomy of auditory and visual phonological processing. *NeuroImage*, *26*(3), 647–661. https://doi.org/10.1016/j.neuroimage.2005.02.024

Burton, M. W., Small, S. L., & Blumstein, S. E. (2000). The role of segmentation in phonological processing: An fMRI investigation. *Journal of Cognitive Neuroscience*, *12*(4), 679–690. https://doi.org/10.1162/089892900562309

Button, K. S., Ioannidis, J. P. A., Mokrysz, C., Nosek, B. A., Flint, J., Robinson, E. S. J., & Munafò, M. R. (2013). Power failure: Why small sample size undermines the reliability of neuroscience. *Nature Reviews Neuroscience*, *14*(5), 365–376. https://doi.org/10.1038/nrn3475

Byers-Heinlein, K., & Lew-Williams, C. (2013). Bilingualism in the early years: what the science says. *LEARNing Landscapes*, *7*(1), 95–112.

Cacciaglia, R., Escera, C., Slabu, L., Grimm, S., Sanjuán, A., Ventura-Campos, N., & Ávila, C. (2015). Involvement of the human midbrain and thalamus in auditory deviance detection. *Neuropsychologia*, *68*, 51–58. https://doi.org/10.1016/j.neuropsychologia.2015.01.001

Calderwood, P. E. (1999). Emily's song: a case study of egocentric speech. *Early Childhood Education Journal*, *27*(1), 21–27. https://doi.org/10.1023/A:1026015406206

Campbell, T., Winkler, I., & Kujala, T. (2007). N1 and the mismatch negativity are spatiotemporally distinct ERP components: Disruption of immediate memory by auditory distraction can be related to N1. *Psychophysiology*, *44*(4), 530–540. https://doi.org/10.1111/j.1469-8986.2007.00529.x

Cantiani, C., Choudhury, N. A., Yu, Y. H., Shafer, V. L., Schwartz, R. G., & Benasich, A. A. (2016a). From sensory perception to lexical-semantic processing: An ERP study in non-verbal children with autism. *PLoS ONE*, *11*(8), e0161637. https://doi.org/10.1371/journal.pone.0161637

Cantiani, C., Ortiz-Mantilla, S., Riva, V., Piazza, C., Bettoni, R., Musacchia, G., Molteni, M., Marino, C., & Benasich, A. A. (2019). Reduced left-lateralized pattern of event-related EEG oscillations in infants at familial risk for language and learning impairment. *NeuroImage: Clinical*, *22*, 101778. https://doi.org/10.1016/j.nicl.2019.101778

Cantiani, C., Riva, V., Piazza, C., Bettoni, R., Molteni, M., Choudhury, N., Marino, C., & Benasich, A. A. (2016b). Auditory discrimination predicts linguistic outcome in Italian infants with and without familial risk for language learning impairment. *Developmental Cognitive Neuroscience*, *20*, 23–34. https://doi.org/10.1016/j.dcn.2016.03.002

Carbajal, G. V., & Malmierca, M. S. (2018). The neuronal basis of predictive coding along the auditory pathway: From the subcortical roots to cortical deviance detection. *Trends in Hearing*, *22*(8), 233121651878482. https://doi.org/10.1177/2331216518784822

Carlin, M. A., & Elhilali, M. (2015). Modeling attention-driven plasticity in auditory cortical receptive fields. *Frontiers in Computational Neuroscience*, *9*, 106. https://doi.org/10.3389/fncom.2015.00106

Carlyon, R. P. (2004). How the brain separates sounds. *Trends in Cognitive Sciences*, *8*(10), 465–471. https://doi.org/10.1016/j.tics.2004.08.008

Carral, V., Huotilainen, M., Ruusuvirta, T., Fellman, V., Näätänen, R., & Escera, C. (2005). A kind of auditory “primitive intelligence” already present at birth. *European Journal of Neuroscience*, *21*(11), 3201–3204. https://doi.org/10.1111/j.1460-9568.2005.04144.x

Carson, D. K., Klee, T., Perry, C. K., Muskina, G., & Donaghy, T. (1998). Comparisons of children with delayed and normal language at 24 months of age on measures of behavioral difficulties, social and cognitive development. *Infant Mental Health Journal*, *19*(1), 59–75. https://doi.org/10.1002/(SICI)1097-0355(199821)19:1<59::AID-IMHJ4>3.0.CO;2-V

Casey, B. J., & de Haan, M. (2002). Introduction: New methods in developmental science. *Developmental Science*, *5*(3), 265–267. https://doi.org/10.1111/1467-7687.00365

Castro-Camacho, W., Peñaloza-López, Y., Pérez-Ruiz, S. J., García-Pedroza, F., Padilla-Ortiz, A. L., Poblano, A., Villarruel-Rivas, C., Romero-Díaz, A., & Careaga-Olvera, A. (2015). Localización sonora y discriminación de palabras en ambientes reverberantes en niños con dislexia del desarrollo. *Arquivos de Neuro-Psiquiatria*, *73*(4), 314–320. https://doi.org/10.1590/0004-282X20150005

Cattani, A., Abbot-Smith, K., Farag, R., Krott, A., Arreckx, F., Dennis, I., & Floccia, C. (2014). How much exposure to English is necessary for a bilingual toddler to perform like a monolingual peer in language tests? *International Journal of Language and Communication Disorders*, *49*(6), 649–671. https://doi.org/10.1111/1460-6984.12082

Celsis, P., Boulanouar, K., Doyon, B., Ranjeva, J. P., Berry, I., Nespoulous, J. L., & Chollet, F. (1999). Differential fMRI responses in the left posterior superior temporal gyrus and left supramarginal gyrus to habituation and change detection in syllables and tones. *NeuroImage*, *9*(1), 135–144. https://doi.org/10.1006/nimg.1998.0389

Centurion, H., & Saunders, G. (1990). Bilingual children: from birth to teens. *The Modern Language Journal*, *74*(3), 388. https://doi.org/10.2307/327639

Čeponiené, R., Cheour, M., & Näätänen, R. (1998). Interstimulus interval and auditory event-related potentials in children: Evidence for multiple generators. *Electroencephalography and Clinical Neurophysiology - Evoked Potentials*, *108*(4), 345–354. https://doi.org/10.1016/S0168-5597(97)00081-6

Čeponiené, R., Kushnerenko, E., Fellman, V., Renlund, M., Suominen, K., & Näätänen, R. (2002). Event-related potential features indexing central auditory discrimination by newborns. *Cognitive Brain Research*, *13*(1), 101–113. https://doi.org/10.1016/S0926-6410(01)00093-3

Čeponiené, R., Lepisto, T., Shestakova, A., Vanhala, R., Alku, P., Näätänen, R., & Yaguchi, K. (2003). Speech-sound-selective auditory impairment in children with autism: They can perceive but do not attend. *Proceedings of the National Academy of Sciences*, *100*(9), 5567–5572. https://doi.org/10.1073/pnas.0835631100

Čeponiené, R., Lepistö, T., Soininen, M., Aronen, E., Alku, P., & Näätänen, R. (2004). Event-related potentials associated with sound discrimination versus novelty detection in children. *Psychophysiology*, *41*(1), 130–141. https://doi.org/10.1111/j.1469-8986.2003.00138.x

Čeponiené, R., Service, E., Kurjenluoma, S., Cheour, M., & Näätänen, R. (1999). Children's performance on pseudoword repetition depends on auditory trace quality: Evidence from event-related potentials. *Developmental Psychology*, *35*(3), 709–720. https://doi.org/10.1037/0012-1649.35.3.709

Čeponiené, R., Shestakova, A., Balan, P., Alku, P., Yiaguchi, K., & Näätänen, R. (2001). Children's auditory event-related potentials index sound complexity and "speechness." *International Journal of Neuroscience*, *109*(3–4), 245–260. https://doi.org/10.3109/00207450108986536

Čeponiené, R., Torki, M., Alku, P., Koyama, A., & Townsend, J. (2008). Event-related potentials reflect spectral differences in speech and non-speech stimuli in children and adults. *Clinical Neurophysiology*, *119*(7), 1560–1577. https://doi.org/10.1016/j.clinph.2008.03.005

Čeponiené, R., Yaguchi, K., Shestakova, A., Alku, P., Suominen, K., & Näätänen, R. (2002). Sound complexity and "speechness" effects on preattentive auditory discrimination in children. *International Journal of Psychophysiology*, *43*(3), 199–211. https://doi.org/10.1016/S0167-8760(01)00172-6

Chall, J. S., & Jacobs, V. A. (1983). Writing and reading in the elementary grades: Developmental trends among low SES children. *Language Arts*, *60*(5), 617–626. https://doi.org/10.2307/41961511

Chandrasekaran, B., Krishnan, A., & Gandour, J. T. (2007). Mismatch negativity to pitch contours is influenced by language experience. *Brain Research*, *1128*(1), 148–156. https://doi.org/10.1016/j.brainres.2006.10.064

Chapman, R. M., & Bragdon, H. R. (1964). Evoked responses to numerical and non-numerical visual stimuli while problem solving. *Nature*, *203*(4950), 1155–1157. https://doi.org/10.1038/2031155a0

Chatrian, G. E., Lettich, E., & Nelson, P. L. (1985). Ten percent electrode system for topographic studies of spontaneous and evoked EEG activities. *American Journal of EEG Technology*, *25*(2), 83–92. https://doi.org/10.1080/00029238.1985.11080163

Chaudhury, S., Sharma, V., Kumar, V., Nag, T. C., & Wadhwa, S. (2016). Activity-dependent synaptic plasticity modulates the critical phase of brain development. *Brain and Development*, *38*(4), 355–363. https://doi.org/10.1016/j.braindev.2015.10.008

Chen, Y., Tsao, F.-M., & Liu, H.-M. (2016). Developmental changes in brain response to speech perception in late-talking children: A longitudinal MMR study. *Developmental Cognitive Neuroscience*, *19*, 190–199. https://doi.org/10.1016/j.dcn.2016.03.007

Cheng, Y. Y., Wu, H. C., Tzeng, Y. L., Yang, M. T., Zhao, L. L., & Lee, C. Y. (2013). The development of mismatch responses to mandarin lexical tones in early infancy. *Developmental Neuropsychology*, *38*(5), 281–300. https://doi.org/10.1080/87565641.2013.799672

Cheng, Y. Y., Wu, H. C., Tzeng, Y. L., Yang, M. T., Zhao, L. L., & Lee, C. Y. (2015). Feature-specific transition from positive mismatch response to mismatch negativity in early infancy: Mismatch responses to vowels and initial consonants. *International Journal of Psychophysiology*, *96*(2), 84–94. https://doi.org/10.1016/j.ijpsycho.2015.03.007

Cheour, M., Alho, K., Čeponiené, R., Reinikainen, K., Sainio, K., Pohjavuori, M., Aaltonen, O., & Näätänen, R. (1998a). Maturation of mismatch negativity in infants. *International Journal of Psychophysiology*, *29*(2), 217–226. https://doi.org/10.1016/S0167-8760(98)00017-8

Cheour, M., Alho, K., Sainio, K., Reinikainen, K., Renlund, M., Aaltonen, O., Eerola, O., & Näätänen, R. (1997). The mismatch negativity to changes in speech sounds at the age of three months. *Developmental Neuropsychology*, *13*(2), 167–174. https://doi.org/10.1080/87565649709540676

Cheour, M., Čeponiené, R., Hukki, J., Haapanen, M. L., Näätänen, R., & Alho, K. (1999). Brain dysfunction in neonates with cleft palate revealed by the mismatch negativity. *Clinical Neurophysiology*, *110*(2), 324–328. https://doi.org/10.1016/S1388-2457(98)00005-4

Cheour, M., Čeponiené, R., Lehtokoski, A., Luuk, A., Allik, J., Alho, K., & Näätänen, R. (1998b). Development of language-specific phoneme representations in the infant brain. *Nature Neuroscience*, *1*(5), 351–353. https://doi.org/10.1038/1561

Cheour, M., Ćeponiené, R., Leppänen, P., Alho, K., Kujala, T., Renlund, M., Fellman, V., & Näätänen, R. (2002). The auditory sensory memory trace decays rapidly in newborns. *Scandinavian Journal of Psychology*, *43*(1), 33–39. https://doi.org/10.1111/1467-9450.00266

Cheour, M., Imada, T., Taulu, S., Ahonen, A., Salonen, J., & Kuhl, P. (2004). Magnetoencephalography is feasible for infant assessment of auditory discrimination. *Experimental Neurology*, *190*(SUPPL. 1), 44–51. https://doi.org/10.1016/j.expneurol.2004.06.030

Cheour, M., Kushnerenko, E., Čeponiené, R., Fellman, V., & Näätänen, R. (2002). Electric brain responses obtained from newborn infants to changes in duration in complex harmonic tones. *Developmental Neuropsychology*, *22*(2), 471–479. https://doi.org/10.1207/S15326942DN2202_3

Cheour, M., Leppänen, P. H. T., & Kraus, N. (2000). Mismatch negativity (MMN) as a tool for investigating auditory discrimination and sensory memory in infants and children. *Clinical Neurophysiology*, *111*(1), 4–16. https://doi.org/10.1016/S1388-2457(99)00191-1

Cheour, M., Shestakova, A., Alku, P., Čeponiené, R., & Näätänen, R. (2002). Mismatch negativity shows that 3-6-year-old children can learn to discriminate non-native speech sounds within two months. *Neuroscience Letters*, *325*(3), 187–190. https://doi.org/10.1016/S0304-3940(02)00269-0

Cheour-Luhtanen, M., Alho, K., Kujala, T., Sainio, K., Reinikainen, K., Renlund, M., Aaltonen, O., Eerola, O., & Näätänen, R. (1995). Mismatch negativity indicates vowel discrimination in newborns. *Hearing Research*, *82*(1), 53–58. https://doi.org/10.1016/0378-5955(94)00164-L

Cheour-Luhtanen, M., Alho, K., Sainio, K., Rinne, T., Reinikainen, K., Pohjavuori, M., Renlund, M., Aaltonen, O., Eerola, O., & Näätänen, R. (1996). The ontogenetically earliest discriminative response of the human brain. *Psychophysiology*, *33*(4), 478–481. https://doi.org/10.1111/j.1469-8986.1996.tb01074.x

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with 2 ears. *Journal of the Acoustical Society of America*, *25*(5), 975–979. https://doi.org/10.1121/1.1907229

Chonchaiya, W., Tardif, T., Mai, X., Xu, L., Li, M., Kaciroti, N., Kileny, P. R., Shao, J., & Lozoff, B. (2013). Developmental trends in auditory processing can provide early predictions of language acquisition in young infants. *Developmental Science*, *16*(2), 159–172. https://doi.org/10.1111/desc.12012

Choudhury, N. A., Parascando, J. A., & Benasich, A. A. (2015). Effects of presentation rate and attention on auditory discrimination: A comparison of long-latency auditory evoked potentials in school-aged children and adults. *PLoS ONE*, *10*(9), e0138160. https://doi.org/10.1371/journal.pone.0138160

Choudhury, N., & Benasich, A. A. (2003). A family aggregation study: The influence of family history and other risk factors on language development. *Journal of Speech, Language, and Hearing Research*, *46*(2), 261–272. https://doi.org/10.1044/1092-4388(2003/021)

Choudhury, N., & Benasich, A. A. (2011). Maturation of auditory evoked potentials from 6 to 48 months: Prediction to 3 and 4 year language and cognitive abilities. *Clinical Neurophysiology*, *122*(2), 320–338. https://doi.org/10.1016/j.clinph.2010.05.035

Choudhury, N., Leppänen, P. H. T., Leevers, H. J., & Benasich, A. A. (2007). Infant information processing and family history of specific language impairment: Converging evidence for RAP deficits from two paradigms. *Developmental Science*, *10*(2), 213–236. https://doi.org/10.1111/j.1467-7687.2007.00546.x

Clearfield, M. W., & Jedd, K. E. (2013). The effects of socio-economic status on infant attention. *Infant and Child Development*, *22*(1), 53–67. https://doi.org/10.1002/icd.1770

Coch, D., Sanders, L. D., & Neville, H. J. (2005). An event-related potential study of selective auditory attention in children and adults. *Journal of Cognitive Neuroscience*, *17*(4), 605–622. https://doi.org/10.1162/0898929053467631

Coensel, B. De, & Botteldooren, D. (2010). A model of saliency-based auditory attention to environmental sound. *20th International Congress on Acoustics, ICA 2010*, *August*, 1–8.

Collisson, B. A., Graham, S. A., Preston, J. L., Rose, M. S., McDonald, S., & Tough, S. (2016). Risk and protective factors for late talking: An epidemiologic investigation. *Journal of Pediatrics*, *172*, 168-174e1. https://doi.org/10.1016/j.jpeds.2016.02.020

Colmar, S. H. (2014). A parent-based book-reading intervention for disadvantaged children with language difficulties. *Child Language Teaching and Therapy*, *30*(1), 79–90. https://doi.org/10.1177/0265659013507296

Colombo, J., Shaddy, D. J., Richman, W. A., Maikranz, J. M., & Blaga, O. M. (2004). The developmental course of habituation in infancy and preschool outcome. *Infancy*, *5*(1), 1–38. https://doi.org/10.1207/s15327078in0501_1

Conboy, B. T., & Kuhl, P. K. (2011). Impact of second-language experience in infancy: Brain measures of first- and second-language speech perception. *Developmental Science*, *14*(2), 242–248. https://doi.org/10.1111/j.1467-7687.2010.00973.x

Conboy, B. T., Rivera-Gaxiola, M., Silva-Pereyra, J., & Kuhl, P. K. (2014). Chapter 2. Event-related potential studies of early language processing at the phoneme, word, and sentence levels. In A.D. Friederici & G. Thierry (Eds.). *Early Language Development: Bridging Brain and Behaviour, Trends in Language*

Acquisition Research Series (Issue October, pp. 23–64). John Benjamins. https://doi.org/10.1075/tilar.5.04con

Cooke, M. (1993). *Modelling Auditory Processing and Organisation*. Cambridge University Press.

Cooper, R. J., Atkinson, R. J., Clark, R. A., & Michie, P. T. (2013). Event-related potentials reveal modelling of auditory repetition in the brain. *International Journal of Psychophysiology*, *88*(1), 74–81.

Cowan, N. (1984). On short and long auditory stores. *Psychological Bulletin*, *96*(2), 341–370. https://doi.org/10.1037/0033-2909.96.2.341

Cowan, N., Winkler, I., Teder, W., & Näätänen, R. (1993). Memory prerequisites of mismatch negativity in the auditory event-related potential (ERP). *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*(4), 909–921. https://doi.org/10.1037/0278-7393.19.4.909

Crestani, C. A. M., Clendon, S. A., & Hemsley, B. (2010). Words needed for sharing a story: Implications for vocabulary selection in augmentative and alternative communication. *Journal of Intellectual and Developmental Disability*, *35*(4), 268–278. https://doi.org/10.3109/13668250.2010.513966

Crone, E. A., & Ridderinkhof, R. K. (2011). The developing brain: From theory to neuroimaging and back. *Developmental Cognitive Neuroscience*, *1*(2), 101–109. https://doi.org/10.1016/j.dcn.2010.12.001

Cunillera, T., Toro, J. M., Sebastián-Gallés, N., & Rodríguez-Fornells, A. (2006). The effects of stress and statistical cues on continuous speech segmentation: An event-related brain potential study. *Brain Research*, *1123*(1), 168–178. https://doi.org/10.1016/j.brainres.2006.09.046

Cusack, R. (2005). The intraparietal sulcus and perceptual organization. *Journal of Cognitive Neuroscience*, *17*(4), 641–651. https://doi.org/10.1162/0898929053467541

D'Astolfo, L., & Rief, W. (2017). Learning about expectation violation from prediction error paradigms: A meta-analysis on brain processes following a prediction error. *Frontiers in Psychology*, *8*(JUL). https://doi.org/10.3389/fpsyg.2017.01253

Datta, H., Shafer, V. L., Morr, M. L., Kurtzberg, D., & Schwartz, R. G. (2010). Electrophysiological indices of discrimination of long-duration, phonetically similar vowels in children with typical and atypical language development. *Journal of Speech, Language, and Hearing Research*, *53*(3), 757–777. https://doi.org/10.1044/1092-4388(2009/08-0123)

Davis, J. L., & Matthews, R. N. (2010). NEPSY-II review. *Journal of Psychoeducational Assessment 28*(2), 175–182. https://doi.org/10.1177/0734282909346716

Davis, P. A. (1939). Effects of acoustic stimuli on the waking human brain. *Journal of Neurophysiology*, *2*(6), 494–499. https://doi.org/10.1152/jn.1939.2.6.494

Dawes, P., & Bishop, D. V. M. (2008). Maturation of visual and auditory temporal processing in school-aged children. *Journal of Speech, Language, and Hearing Research*, *51*(4), 1002–1015. https://doi.org/10.1044/1092-4388(2008/073)

Day, R. S., & Wood, C. C. (1972). Interactions between linguistic and non-linguistic processing. *Journal of the Acoustical Society of America*, *51*, 79.

De Coensel, B., & Botteldooren, D. (2008). Modeling auditory attention focusing in multisource environments. *The Journal of the Acoustical Society of America*, *123*(5), 3394–3394. https://doi.org/10.1121/1.2934070 de Haan, M. (2013). *Introduction to infant EEG and event-related potentials*. In Infant EEG and Event-Related Potentials. Psychology Press. https://doi.org/10.4324/9780203759660 https://doi.org/10.4324/9780203759660

de Haan, M., & Johnson, M. H. (2016). Typical and Atypical Human Functional Brain Development. *Developmental Psychopathology*, 1–22. https://doi.org/10.1002/9781119125556.devpsy216

de Haan, M. de, & Matheson, A. (2009). The development and neural bases of processing emotion in faces and voices. In M. de Haan, M. R. Gunnar (Eds.). *Handbook of Developmental Social Neuroscience.* (pp. 107–121). London: The Guildford Press.

de Haan, M., & Thomas, K. M. (2002). Applications of ERP and fMRI techniques to developmental science. *Developmental Science*, *5*(3), 335–343. https://doi.org/10.1111/1467-7687.00373

Deanda, S., Arias-Trejo, N., Poulin-Dubois, D., Zesiger, P., & Friend, M. (2016). Minimal second language exposure, SES, and early word comprehension: New evidence from a direct assessment. *Bilingualism*, *19*(1), 162–180. https://doi.org/10.1017/S1366728914000820

Debener, S., Kranczioch, C., Herrmann, C. S., & Engel, A. K. (2002). Auditory novelty oddball allows reliable distinction of top-down and bottom-up processes of attention. *International Journal of Psychophysiology*, *46*(1), 77–84. https://doi.org/10.1016/S0167-8760(02)00072-7

Dehaene-Lambertz, G. (1997). Electrophysiological correlates of categorical phoneme perception in adults. *NeuroReport*, *8*(4), 919–924. https://doi.org/10.1097/00001756-199703030-00021

Dehaene-Lambertz, G., & Baillet, S. (1998). A phonological representation in the infant brain. *NeuroReport*, *9*(8), 1885–1888. https://doi.org/10.1097/00001756-199806010-00040

Dehaene-Lambertz, G., & Gliga, T. (2004). Common neural basis for phoneme processing in infants and adults. *Journal of Cognitive Neuroscience*, *16*(8), 1375–1387. https://doi.org/10.1162/0898929042304714

Dehaene-Lambertz, G., Montavont, A., Jobert, A., Allirol, L., Dubois, J., Hertz-Pannier, L., & Dehaene, S. (2010). Language or music, mother or Mozart? Structural and environmental influences on infants' language networks. *Brain and Language*, *114*(2), 53–65. https://doi.org/10.1016/j.bandl.2009.09.003

Deike, S., Deliano, M., & Brechmann, A. (2016). Probing neural mechanisms underlying auditory stream segregation in humans by transcranial direct current stimulation (tDCS). *Neuropsychologia*, *91*, 262–267. https://doi.org/10.1016/j.neuropsychologia.2016.08.017

Deike, S., Heil, P., Böckmann-Barthel, M., & Brechmann, A. (2012). The build-up of auditory stream segregation: A different perspective. *Frontiers in Psychology*, *3*(OCT), 461. https://doi.org/10.3389/fpsyg.2012.00461

Deike, S., Scheich, H., & Brechmann, A. (2010). Active stream segregation specifically involves the left human auditory cortex. *Hearing Research*, *265*(1–2), 30–37. https://doi.org/10.1016/j.heares.2010.03.005

Delle Luche, C., Durrant, S., Poltrock, S., & Floccia, C. (2015). A methodological investigation of the Intermodal Preferential Looking paradigm: Methods of analyses, picture selection and data rejection criteria. *Infant Behavior and Development*, *40*, 151–172. https://doi.org/10.1016/j.infbeh.2015.05.005

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Delorme, A., Mullen, T., Kothe, C., Akalin Acar, Z., Bigdely-Shamlo, N., Vankov, A., & Makeig, S. (2011). EEGLAB, SIFT, NFT, BCILAB, and ERICA: New tools for advanced EEG processing. *Computational Intelligence and Neuroscience*, *2011*, 130714. https://doi.org/10.1155/2011/130714

Delorme, A., Sejnowski, T., & Makeig, S. (2007). Enhanced detection of artifacts in EEG data using higher-order statistics and independent component analysis. *NeuroImage*, *34*(4), 1443–1449. https://doi.org/10.1016/j.neuroimage.2006.11.004

Demany, L. (1982). Auditory stream segregation in infancy. *Infant Behavior and Development*, *5*(2–4), 261–276. https://doi.org/10.1016/S0163-6383(82)80036-2

Denham, S. L., & Winkler, I. (2006). The role of predictive models in the formation of auditory streams. *Journal of Physiology Paris*, *100*(1–3), 154–170. https://doi.org/10.1016/j.jphysparis.2006.09.012

Denman, D., Speyer, R., Munro, N., Pearce, W. M., Chen, Y. W., & Cordier, R. (2017). Psychometric properties of language assessments for children aged 4-12 years: A systematic review. *Frontiers in Psychology*, *8*(SEP). https://doi.org/10.3389/fpsyg.2017.01515

Deoni, S. C. L., Dean, D. C., O'Muircheartaigh, J., Dirks, H., & Jerskey, B. A. (2012). Investigating white matter development in infancy and early childhood using myelin water faction and relaxation time mapping. *NeuroImage*, *63*(3), 1038–1053. https://doi.org/10.1016/j.neuroimage.2012.07.037

Desmarais, C., Sylvestre, A., Meyer, F., Bairati, I., & Rouleau, N. (2008). Systematic review of the literature on characteristics of late-talking toddlers. *International Journal of Language and Communication Disorders*, *43*(4), 361–389. https://doi.org/10.1080/13682820701546854

Díaz, B., Baus, C., Escera, C., Costa, A., & Sebastián-Gallés, N. (2008). Brain potentials to native phoneme discrimination reveal the origin of individual differences in learning the sounds of a second language. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(42), 16083–16088. https://doi.org/10.1073/pnas.0805022105

Dien, J. (1998). Issues in the application of the average reference: Review, critiques, and recommendations. *Behavior Research Methods, Instruments, and Computers*, *30*(1), 34–43. https://doi.org/10.3758/BF03209414

Dockrell, J. E., & Marshall, C. R. (2015). Measurement Issues: Assessing language skills in young children. *Child and Adolescent Mental Health*, *20*(2), 116–125. https://doi.org/10.1111/camh.12072

Doesburg, S. M., Tingling, K., MacDonald, M. J., & Pang, E. W. (2016). Development of network synchronization predicts language abilities. *Journal of Cognitive Neuroscience*, *28*(1), 55–68. https://doi.org/10.1162/jocn_a_00879

Dollaghan, C. A., Campbell, T. F., Paradise, J. L., Feldman, H. M., Janosky, J. E., Pitcairn, D. N., & Kurs-Lasky, M. (1999). Maternal education and measures of early speech and language. *Journal of Speech Language and Hearing Research*, *42*(6), 1432. https://doi.org/10.1044/jslhr.4206.1432

Doost, H. T. N., Moradi, A. R., Taghavi, M. R., Yule, W., & Dalgleish, T. (1999). The development of a corpus of emotional words produced by children and adolescents. *Personality and Individual Differences*, *27*(3), 433–451. https://doi.org/10.1016/S0191-8869(98)00253-0

Downes, M., Kirkham, F. J., Telfer, P. T., & de Haan, M. (2018). Altered neurophysiological processing of auditory attention in preschool children with sickle cell disease. *Journal of Pediatric Psychology*, *43*(8), 856-869. https://doi.org/10.1093/jpepsy/jsx115

Draganova, R., Eswaran, H., Murphy, P., Huotilainen, M., Lowery, C., & Preissl, H. (2005). Sound frequency change detection in fetuses and newborns, a magnetoencephalographic study. *NeuroImage*, *28*(2), 354–361. https://doi.org/10.1016/j.neuroimage.2005.06.011

Draganova, R., Schollbach, A., Schleger, F., Braendle, J., Brucker, S., Abele, H., Kagan, K. O., Wallwiener, D., Fritsche, A., Eswaran, H., & Preissl, H. (2018). Fetal auditory evoked responses to onset of amplitude modulated sounds. a fetal magnetoencephalography (fMEG) study. *Hearing Research*, *363*, 70–77. https://doi.org/10.1016/j.heares.2018.03.005

Dronkers, N. F. F., & Baldo, J. V. V. (2001). Neural basis of speech production. In *International Encyclopedia of the Social & Behavioral Sciences, 200*(6), 14875–14879. Elsevier. https://doi.org/10.1016/B0-08-043076-7/03491-4

Dronkers, N. F., Plaisant, O., Iba-Zizen, M. T., & Cabanis, E. A. (2007). Paul Broca's historic cases: high resolution MR imaging of the brains of Leborgne and Lelong. *Brain*, *130*(5), 1432–1441. https://doi.org/10.1093/brain/awm042

D'Souza, D., D'Souza, H., & Karmiloff-Smith, A. (2017). Precursors to language development in typically & atypically developing infants & toddlers: The importance of embracing complexity. *Journal of Child Language*, *44*(3), 591–627. https://doi.org/10.1017/S030500091700006X

du Bois-Reymond, E. (1848). Untersuchungen über thierische Elektricität. *Annalen Der Physik*, *151*(11), 463–464. https://doi.org/10.1002/andp.18481511120

Duangudom, V., & Anderson, D. V. (2007). Using auditory saliency to understand complex auditory scenes. *European Signal Processing Conference*, *Eusipco*, 1206–1210.

Duff, F. J., Nation, K., Plunkett, K., & Bishop, D. (2015). Early prediction of language and literacy problems: is 18 months too early? *PeerJ*, *3*, e1098. https://doi.org/10.7717/peerj.1098

Dunn, K., Reissland, N., & Reid, V. M. (2015). The functional foetal brain: A systematic preview of methodological factors in reporting foetal visual and auditory capacity. *Developmental Cognitive Neuroscience*, *13*, 43–52. https://doi.org/10.1016/j.dcn.2015.04.002

Dürschmid, S., Edwards, E., Reichert, C., Dewar, C., Hinrichs, H., Heinze, H. J., Kirsch, H. E., Dalal, S. S., Deouell, L. Y., & Knight, R. T. (2016). Hierarchy of prediction errors for auditory events in human temporal and frontal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(24), 6755–6760. https://doi.org/10.1073/pnas.1525030113

Dykstra, A. R., & Gutschalk, A. (2015). Does the mismatch negativity operate on a consciously accessible memory trace? *Science Advances*, *1*(10), e1500677. https://doi.org/10.1126/sciadv.1500677

Eggermont, J., & Moore, J. (2012). Morphological and functional development of the auditory nervous system. In *Human Auditory Development SE – 3*, *42*(61–105). Springer, New York, NY. https://doi.org/10.1007/978-1-4614-1421-6_3

El Karoui, I., King, J. R., Sitt, J., Meyniel, F., Van Gaal, S., Hasboun, D., Adam, C., Navarro, V., Baulac, M., Dehaene, S., Cohen, L., & Naccache, L. (2015). Event-related potential, time-frequency, and functional connectivity facets of local and global auditory novelty processing: An intracranial study in humans. *Cerebral Cortex*, *25*(11), 4203–4212. https://doi.org/10.1093/cercor/bhu143

Eling, P., & Whitaker, H. (2009). Chapter 36 History of aphasia. From brain to language. In *Handbook of Clinical Neurology* (3rd ed., Vol. 95, Issue C). Elsevier B.V. https://doi.org/10.1016/S0072-9752(08)02136-2

Elliott, L. L., Hammer, M. A., Scholl, M. E., Carrell, T. D., & Wasowicz, J. M. (1989). Discrimination of rising and falling simulated single-formant frequency transitions: practice and transition duration effects. *Journal of Acoustical Society of America*, *86*(3), 945–953. https://doi.org/10.1121/1.398729

Escera, C., & Corral, M. J. (2007). Role of mismatch negativity and novelty-P3 in involuntary auditory attention. *Journal of Psychophysiology*, *21*(3–4), 251–264. https://doi.org/10.1027/0269-8803.21.34.251

Escera, C., Yago, E., & Alho, K. (2002). Electrical responses reveal the temporal dynamics of brain events during involuntary attention switching. *European Journal of Neuroscience*, *14*(5), 877–883. https://doi.org/10.1046/j.0953-816X.2001.01707.x

Escera, C., Yago, E., Polo, M. D., & Grau, C. (2000). The individual replicability of mismatch negativity at short and long inter-stimulus intervals. *Clinical Neurophysiology*, *111*(3), 546–551. https://doi.org/10.1016/S1388-2457(99)00274-6

Espy, K. A., & Cwik, M. F. (2004). The development of a Trial Making Test in young children: The TRAILS-P. *Clinical Neuropsychologist*, *18*(3), 411–422. https://doi.org/10.1080/138540409052416

Eulitz, C., & Hannemann, R. (2010). On the matching of top-down knowledge with sensory input in the perception of ambiguous speech. *BMC Neuroscience*, *11*(June 2010). https://doi.org/10.1186/1471-2202-11-67

Farah, M. J., Shera, D. M., Savage, J. H., Betancourt, L., Giannetta, J. M., Brodsky, N. L., Malmud, E. K., & Hurt, H. (2006). Childhood poverty: Specific associations with neurocognitive development. *Brain Research*, *1110*(1), 166–174. https://doi.org/10.1016/j.brainres.2006.06.072

Fellman, V., & Huotilainen, M. (2006). Cortical auditory event-related potentials in newborn infants. *Seminars in Fetal and Neonatal Medicine*, *11*(6), 452–458. https://doi.org/10.1016/j.siny.2006.07.004

Fellman, V., Kushnerenko, E., Mikkola, K., Čeponiené, R., Leipälä, J., & Näätänen, R. (2004). Atypical auditory event-related potentials in preterm infants during the first year of life: A possible sign of cognitive dysfunction? *Pediatric Research*, *56*(2), 291–297. https://doi.org/10.1203/01.PDR.0000132750.97066.B9

Fenson, L., Pethick, S., Renda, C., Cox, J. L., Dale, P. S., & Reznick, J. S. (2000). Short-form versions of the MacArthur Communicative Development Inventories. *Applied Psycholinguistics*, *21*(01). https://doi.org/10.1017/S0142716400001053

Ferjan Ramírez, N., Ramírez, R. R., Clarke, M., Taulu, S., & Kuhl, P. K. (2017). Speech discrimination in 11-month-old bilingual and monolingual infants: A magnetoencephalography study. *Developmental Science*, *20*(1), e12427. https://doi.org/10.1111/desc.12427

Fernald, A. (1985). Four-month-old infants prefer to listen to motherese. *Infant Behavior and Development*, *8*(2), 181–195. https://doi.org/10.1016/S0163-6383(85)80005-9

Fernald, A., & Marchman, V. A. (2012). Individual differences in lexical processing at 18 months predict vocabulary growth in typically developing and late-talking toddlers. *Child Development*, *83*(1), 203–222. https://doi.org/10.1111/j.1467-8624.2011.01692.x

Finkelstein, G. W. (2013). *Emil du Bois-Reymond: Neuroscience, Self and Society in Nineteenth Century Germany*. The MIT Press, 272–273. https://doi.org/10.1055/s-0029-1208698

Finneran, D. A., Francis, A. L., & Leonard, L. B. (2009). sustained attention in children with specific language impairment (SLI). *Journal of Speech, Language, and Hearing Research*, *52*(4), 915–929. https://doi.org/10.1044/1092-4388(2009/07-0053)

Fischer, B., & Hartnegg, K. (2004). On the development of low-level auditory discrimination and deficits in dyslexia. *Dyslexia*, *10*(2), 105–118. https://doi.org/10.1002/dys.268

Fish, M., & Pinkerman, B. (2003). Language skills in low-SES rural Appalachian children: Normative development and individual differences, infancy to preschool. *Journal of Applied Developmental Psychology*, *23*(5), 539–565. https://doi.org/10.1016/S0193-3973(02)00141-7

Fisher, D. J., Grant, B., Smith, D. M., & Knott, V. J. (2011). Effects of deviant probability on the “optimal” multi-feature mismatch negativity (MMN) paradigm. *International Journal of Psychophysiology*, *79*(2), 311–315. https://doi.org/10.1016/j.ijpsycho.2010.11.006

Fishman, Y. I., Arezzo, J. C., & Steinschneider, M. (2004). Auditory stream segregation in monkey auditory cortex: Effects of frequency separation, presentation rate, and tone duration. *The Journal of the Acoustical Society of America*, *116*(3), 1656–1670. https://doi.org/10.1121/1.1778903

Fitch, R. H., & Tallal, P. (2003). Neural mechanisms of language-based learning impairments: Insights from human populations and animal models. *Behavioral and Cognitive Neuroscience Reviews*, *2*(3), 155–178. https://doi.org/10.1177/1534582303258736

Fiveash, A., Thompson, W. F., Badcock, N. A., & McArthur, G. (2018). Syntactic processing in music and language: Effects of interrupting auditory streams with alternating timbres. *International Journal of Psychophysiology*, *129*, 31–40. https://doi.org/10.1016/j.ijpsycho.2018.05.003

Flinker, A., Korzeniewska, A., Shestyuk, A. Y., Franaszczuk, P. J., Dronkers, N. F., Knight, R. T., & Crone, N. E. (2015). Redefining the role of Broca's area in speech. *Proceedings of the National Academy of Sciences*, *112*(9), 2871–2875. https://doi.org/10.1073/pnas.1414491112

Floccia, C., Keren-Portnoy, T., DePaolis, R., Duffy, H., Delle Luche, C., Durrant, S., White, L., Goslin, J., & Vihman, M. (2016). British English infants segment words only with exaggerated infant-directed speech stimuli. *Cognition*, *148*, 1–9. https://doi.org/10.1016/j.cognition.2015.12.004

Floccia, C., Sambrook, T. D., Delle Luche, C., Kwok, R., Goslin, J., White, L., Cattani, A., Sullivan, E., Abbot-Smith, K., Krott, A., Mills, D., Rowland, C., Gervain, J., & Plunkett, K. (2018). Vocabulary of 2-year-olds learning English and an additional language: Norms and effects of linguistic distance. (2018). *Monographs of the Society for Research in Child Development, 83*(1), 43–60.

Forssman, L. (2012). *Attention and the early development of cognitive control. Infant's and toddlers' performance on the A-not-B task*. (Unpublished Doctoral dissertation, Uppsala University, Sweden) Retrieved from Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Social Sciences. http://uu.diva-portal.org/smash/get/diva2:476696/FULLTEXT01.pdf

François, C., Teixidó, M., Takerkart, S., Agut, T., Bosch, L., & Rodriguez-Fornells, A. (2017). Enhanced Neonatal Brain Responses to Sung Streams Predict Vocabulary Outcomes by Age 18 Months. *Scientific Reports*, *7*(1), 12451. https://doi.org/10.1038/s41598-017-12798-2

Friederici, A. D. (2005). Neurophysiological markers of early language acquisition: From syllables to sentences. *Trends in Cognitive Sciences*, *9*(10), 481–488. https://doi.org/10.1016/j.tics.2005.08.008

Friederici, A. D., Friedrich, M., & Weber, C. (2002). Neural manifestation of cognitive and precognitive mismatch detection in early infancy. *NeuroReport*, *13*(10), 1251–1254. https://doi.org/10.1097/00001756-200207190-00006

Friedrich, M., & Friederici, A. D. (2006). Early N400 development and later language acquisition. *Psychophysiology*, *43*(1), 1–12. https://doi.org/10.1111/j.1469-8986.2006.00381.x

Friedrich, M., Weber, C., & Friederici, A. D. (2004). Electrophysiological evidence for delayed mismatch response in infants at-risk for specific language impairment. *Psychophysiology*, *41*(5), 772–782. https://doi.org/10.1111/j.1469-8986.2004.00202.x

Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1456), 815–836. https://doi.org/10.1098/rstb.2005.1622

Fujii, M., Maesawa, S., Ishiai, S., Iwami, K., Futamura, M., & Saito, K. (2016). Neural basis of language: An overview of an evolving model. *Neurologia Medico-Chirurgica, 56*(7), 379–386. https://doi.org/10.2176/nmc.ra.2016-0014

Galaburda, A., LeMay, M., Kemper, T., & Geschwind, N. (1978). Right-left asymmetrics in the brain. *Science*, *199*(4331), 852–856. https://doi.org/10.1126/science.341314

Gall, F. J. (1835). *On the Function of the Brain and Each of Its Parts: With Observations on the Possibility of Determining the Instincts, Propensities and Talents, or the Moral*. In Boston: Marsh, Capen and Lyon.

Gandour, J. T., & Harshman, R. A. (1978). Crosslanguage differences in tone perception: A multidimensional scaling investigation. *Language and Speech*, *21*(1), 1–33. https://doi.org/10.1177/002383097802100101

Gao, W., Alcauter, S., Smith, J. K., Gilmore, J. H., & Lin, W. (2015). Development of human brain cortical network architecture during infancy. *Brain Structure and Function*, *220*(2), 1173–1186. https://doi.org/10.1007/s00429-014-0710-3

Garagnani, M., & Pulvermüller, F. (2011). From sounds to words: A neurocomputational model of adaptation, inhibition and memory processes in auditory change detection. *NeuroImage*, *54*(1), 170–181. https://doi.org/10.1016/j.neuroimage.2010.08.031

Garcia-Sierra, A., Ramírez-Esparza, N., & Kuhl, P. K. (2016). Relationships between quantity of language input and brain responses in bilingual and monolingual infants. *International Journal of Psychophysiology*, *110*, 1–17. https://doi.org/10.1016/j.ijpsycho.2016.10.004

Garcia-Sierra, A., Rivera-Gaxiola, M., Percaccio, C. R., Conboy, B. T., Romo, H., Klarman, L., Ortiz, S., & Kuhl, P. K. (2011). Bilingual language learning: An ERP study relating early brain responses to speech, language input, and later word production. *Journal of Phonetics*, *39*(4), 546–557. https://doi.org/10.1016/j.wocn.2011.07.002

Garrido, M. I. (2008). *Causal Modelling of Evoked Brain Responses*. (Unpublished Doctoral Thesis, University College London, United Kingdom). Retrieved from http://discovery.ucl.ac.uk/65543/

Garrido, M. I., Friston, K. J., Kiebel, S. J., Stephan, K. E., Baldeweg, T., & Kilner, J. M. (2008). The functional anatomy of the MMN: A DCM study of the roving paradigm. *NeuroImage*, *42*(2), 936–944. https://doi.org/10.1016/j.neuroimage.2008.05.018

Garrido, M. I., Kilner, J. M., Stephan, K. E., & Friston, K. J. (2009). The mismatch negativity: A review of underlying mechanisms. *Clinical Neurophysiology*, *120*(3), 453–463. https://doi.org/10.1016/j.clinph.2008.11.029

Garrido, M. I., Teng, C. L. J., Taylor, J. A., Rowe, E. G., & Mattingley, J. B. (2016). Surprise responses in the human brain demonstrate statistical learning under high concurrent cognitive demand. *Npj Science of Learning*, *1*(1), 16006. https://doi.org/10.1038/npjscilearn.2016.6

Gazzaniga, M. S. (2000). Cerebral specialization and interhemispheric communication: does the corpus callosum enable the human condition? *Brain*, *123*(7), 1293–1326. https://doi.org/10.1093/brain/123.7.1293

Geodesics. (2003). *Net station waveform tools technical manual.* Electrical Geodesics, Inc. Eugene, OR.

George, D., & Mallery, P. (2016). *IBM SPSS statistics 23 step by step: A simple guide and reference.* Routledge.

Georgieva, S., Lester, S., Yilmaz, M., Wass, S., & Leong, V. (2018). Topographical and spectral signatures of infant and adult movement artifacts in naturalistic EEG. *BioRxiv*, 206029. https://doi.org/10.1101/206029

Gerber, S. E. (1985). Stimulus, response, and state variables in the testing of neonates. *Ear and Hearing*, *6*(1), 15–19. https://doi.org/10.1097/00003446-198501000-00005

Gervain, J. (2018). The role of prenatal experience in language development. *Current Opinion in Behavioral Sciences*, *21*, 62–67. https://doi.org/10.1016/j.cobeha.2018.02.004

Gervain, J., Macagno, F., Cogoi, S., Pena, M., Mehler, J., Peña, M., & Mehler, J. (2008). The neonate brain detects speech structure. *Proceedings of the National Academy of Sciences*, *105*(37), 14222–14227. https://doi.org/10.1073/pnas.0806530105

Gervain, J., & Mehler, J. (2010). Speech perception and language acquisition in the first year of life. *Annual Review of Psychology*, *61*(1), 191–218. https://doi.org/10.1146/annurev.psych.093008.100408

Geschwind, N. (1965). Disconnexion syndromes in animal and man. *Brain*, *88*, 237–294. https://doi.org/10.1007/978-94-010-2093-0_8

Getzmann, S., Falkenstein, M., & Wascher, E. (2015). ERP correlates of auditory goal-directed behavior of younger and older adults in a dynamic speech perception task. *Behavioural Brain Research*, *278*, 435–445. https://doi.org/10.1016/j.bbr.2014.10.026

Getzmann, S., & Näätänen, R. (2015). The mismatch negativity as a measure of auditory stream segregation in a simulated "cocktail-party" scenario: Effect of age. *Neurobiology of Aging*, *36*(11), 3029–3037. https://doi.org/10.1016/j.neurobiolaging.2015.07.017

Getzmann, S., Wascher, E., & Falkenstein, M. (2015). What does successful speech-in-noise perception in aging depend on? Electrophysiological correlates of high and low performance in older adults. *Neuropsychologia*, *70*, 43–57. https://doi.org/10.1016/j.neuropsychologia.2015.02.009

Giard, M. H., Perrin, F., Pernier, J., & Bouchet, P. (1990). Brain generators implicated in the processing of auditory stimulus deviance: a topographic event-related potential study. *Psychophysiology*, *27*(6), 627–640.

Gillen, J. (2000). Listening to Young Children Talking on the Telephone: A reassessment of Vygotsky's notion of 'egocentric speech.' *Contemporary Issues in Early Childhood*, *1*(2), 171–184. https://doi.org/10.2304/ciec.2000.1.2.5

Gilley, P. M., Uhler, K., Watson, K., & Yoshinaga-Itano, C. (2017). Spectral-temporal EEG dynamics of speech discrimination processing in infants during sleep. *BMC Neuroscience*, *18*(1), 34. https://doi.org/10.1186/s12868-017-0353-4

Ginsborg, J. (2006). The Effects of Socio-economic Status on Children's Language Acquisition and Use. In J. Clegg & J. Ginsborg (Eds.). *Language and Social Disadvantage: Theory into Practice* (pp. 9–27). Chichester, England: John Wiley & Sons, Ltd

Girolametto, L., Wiigs, M., Smyth, R., Weitzman, E., & Pearce, P. S. (2001). Children with a history of expressive vocabulary delay: Outcomes at 5 years of age. *American Journal of Speech-Language Pathology*, *10*(4), 358–369. https://doi.org/10.1044/1058-0360(2001/030)

Godfrey, J. J., Syrdal-Lasky, A. K., Millay, K. K., & Knox, C. M. (1981). Performance of dyslexic children on speech perception tests. *Journal of Experimental Child Psychology*, *32*(3), 401–424. https://doi.org/10.1016/0022-0965(81)90105-3

Gogate, L. J., & Bahrick, L. E. (1998). Intersensory redundancy facilitates learning of arbitrary relations between vowel sounds and objects in seven-month-old infants. *Journal of Experimental Child Psychology*, *69*(2), 133–149. https://doi.org/10.1006/jecp.1998.2438

Golinkoff, R. M., Ma, W., Song, L., & Hirsh-Pasek, K. (2013). Twenty-five years using the intermodal preferential looking paradigm to study language acquisition: What have we learned? *Perspectives on Psychological Science*, *8*(3), 316–339. https://doi.org/10.1177/1745691613484936

Golob, E. J., Venable, K. B., Anderson, M. T., Benzell, J. A., & Scheuerman, J. (2017). Modelling auditory spatial attention with constraints. *CEUR Workshop Proceedings*, *1895*, 59–72.

Gomes, H., Molholm, S., Christodoulou, C., Ritter, W., & Cowan, N. (2000). The development of auditory attention in children. *Frontiers in Bioscience*, *5*, d108-120. https://doi.org/10.1093/toxsci/kfs057

Gomes, H., Molholm, S., Ritter, W., Kurtzberg, D., Cowan, N., & Vaughan, H. G. (2000). Mismatch negativity in children and adults, and effects of an attended task. *Psychophysiology*, *37*(6), 807–816. https://doi.org/10.1017/S0048577200990632

Gomes, H., Ritter, W., & Vaughan, H. G. (1995). The nature of preattentive storage in the auditory system. *Journal of Cognitive Neuroscience*, *7*(1), 81–94. https://doi.org/10.1162/jocn.1995.7.1.81

Gomes, H., Wolfson, V., & Halperin, J. M. (2007). Is there a selective relationship between language functioning and auditory attention in children? *Journal of Clinical and Experimental Neuropsychology*, *29*(6), 660–668. https://doi.org/10.1080/13803390600920455

Gomez, D. M., Berent, I., Benavides-Varela, S., Bion, R. A. H., Cattarossi, L., Nespor, M., & Mehler, J. (2014). Language universals at birth. *Proceedings of the National Academy of Sciences*, *111*(16), 5837–5841. https://doi.org/10.1073/pnas.1318261111

Gomez, R. L., & Gerken, L. (1999). Artificial grammar learning by 1-year-olds leads to specific and abstract knowledge. *Cognition*, *70*(2), 109–135. https://doi.org/10.1016/S0010-0277(99)00003-7

Gomot, M., Bruneau, N., Laurent, J. P., Barthélémy, C., & Saliba, E. (2007). Left temporal impairment of auditory information processing in prematurely born 9-year-old children: An electrophysiological study. *International Journal of Psychophysiology*, *64*(2), 123–129. https://doi.org/10.1016/j.ijpsycho.2007.01.003

Gomot, M., Giard, M. H., Roux, S., Barthelemy, C., & Bruneau, N. (2000). Maturation of frontal and temporal components of mismatch negativity (MMN) in children. *NeuroReport*, *11*(14), 3109–3112. https://doi.org/10.1097/00001756-200009280-00014

Goswami, U., Wang, H.-L. S., Cruz, A., Fosker, T., Mead, N., & Huss, M. (2011). Language-universal Sensory Deficits in Developmental Dyslexia: English, Spanish, and Chinese. *Journal of Cognitive Neuroscience*, *23*(2), 325–337. https://doi.org/10.1162/jocn.2010.21453

Gou, Z., Choudhury, N., & Benasich, A. A. (2011). Resting frontal gamma power at 16, 24 and 36 months predicts individual differences in language and cognition at 4 and 5 years. *Behavioural Brain Research*, *220*(2), 263–270. https://doi.org/10.1016/j.bbr.2011.01.048

Gozzo, Y., Vohr, B., Lacadie, C., Hampson, M., Katz, K. H., Maller-Kesselman, J., Schneider, K. C., Peterson, B. S., Rajeevan, N., Makuch, R. W., Constable, R. T., & Ment, L. R. (2009). Alterations in neural connectivity in preterm children at school age. *NeuroImage*, *48*(2), 458–463. https://doi.org/10.1016/j.neuroimage.2009.06.046

Gratier, M., & Devouche, E. (2017). The development of infant participation in communication. In F., Manuela, K., Pierre, W., Bjorn (Eds.). *Early Vocal Contact and Preterm Infant Brain Development: Bridging the Gaps Between Research and Practice* (pp. 55–69). Springer International Publishing. https://doi.org/10.1007/978-3-319-65077-7_4

Green, J. R., & Wilson, E. M. (2006). Spontaneous facial motility in infancy: A 3D kinematic analysis. *Developmental Psychobiology*, *48*(1), 16–28. https://doi.org/10.1002/dev.20112

Grimwade, J. C., Walker, D. W., Bartlett, M., Gordon, S., & Wood, C. (1971). Human fetal heart rate change and movement in response to sound and vibration. *American Journal of Obstetrics and Gynecology*, *109*(1), 86–90. https://doi.org/10.1016/0002-9378(71)90839-8

Gross, M. M., Begleiter, H., Tobin, M., & Kissin, B. (1965). Auditory evoked response comparison during counting clicks and reading. *Electroencephalography and Clinical Neurophysiology*, *18*(5), 451–454. https://doi.org/10.1016/0013-4694(65)90125-2

Grossmann, T., Oberecker, R., Koch, S. P., & Friederici, A. D. (2010). The Developmental origins of voice processing in the human brain. *Neuron*, *65*(6), 852–858. https://doi.org/10.1016/j.neuron.2010.03.001

Guiraud, J. A., Kushnerenko, E., Tomalski, P., Davies, K., Ribeiro, H., & Johnson, M. H. (2011). Differential habituation to repeated sounds in infants at high risk for autism. *NeuroReport*, *22*(16), 845–849. https://doi.org/10.1097/WNR.0b013e32834c0bec

Guiraud, J. A., Tomalski, P., Kushnerenko, E., Ribeiro, H., Davies, K., Charman, T., Elsabbagh, M., Johnson, M. H., & BASIS Team. (2012). Atypical audiovisual speech integration in infants at risk for autism. *PloS One*, *7*(5), 3–8. https://doi.org/10.1371/journal.pone.0036428

Gumenyuk, V., Korzyukov, O., Alho, K., Winkler, I., Paavilainen, P., & Näätänen, R. (2003). Electric brain responses indicate preattentive processing of abstract acoustic regularities in children. *NeuroReport*, *14*(11), 1411–1415. https://doi.org/10.1097/00001756-200308060-00001

Guthrie, D., & Buchwald, J. S. (1991). Significance testing of difference potentials. *Psychophysiology*, *28*(2), 240–244. https://doi.org/10.1111/j.1469-8986.1991.tb00417.x

Gutschalk, A., & Dykstra, A. R. (2014). Functional imaging of auditory scene analysis. *Hearing Research*, *307*, 98–110. https://doi.org/10.1016/j.heares.2013.08.003

Gutschalk, A., Micheyl, C., Melcher, J. R., Rupp, A., Scherg, M., & Oxenham, A. J. (2005). Neuromagnetic correlates of streaming in human auditory cortex. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *25*(22), 5382–5388. https://doi.org/10.1523/JNEUROSCI.0347-05.2005

Guttorm, T. K., Leppänen, P. H. T., Hämäläinen, J. A., Eklund, K. M., & Lyytinen, H. J. (2010). Newborn event-related potentials predict poorer pre-reading skills in children at risk for dyslexia. *Journal of Learning Disabilities*, *43*(5), 391–401. https://doi.org/10.1177/0022219409345005

Guttorm, T. K., Leppänen, P. H. T., Poikkeus, A. M., Eklund, K. M., Lyytinen, P., & Lyytinen, H. (2005). Brain event-related potentials (ERPs) measured at birth predict later language development in children with and without familial risk for dyslexia. *Cortex*, *41*(3), 291–303. https://doi.org/10.1016/S0010-9452(08)70267-3

Guttorm, T. K., Leppänen, P. H. T., Richardson, U., & Lyytinen, H. (2001). Event-related potentials and consonant differentiation in newborns with familial risk for dyslexia. *Journal of Learning Disabilities*, *34*(6), 534–544. https://doi.org/10.1177/002221940103400606

Guttorm, T. K., Leppänen, P. H. T., Tolvanen, A., & Lyytinen, H. (2003). Event-related potentials in newborns with and without familial risk for dyslexia: Principal component analysis reveals differences between the groups. *Journal of Neural Transmission*, *110*(9), 1059–1074. https://doi.org/10.1007/s00702-003-0014-x

Guzzetta, F. (2014). Behavioral assessment of language brain processing in the first year of life. *European Journal of Paediatric Neurology*, *18*(5), 551–557. https://doi.org/10.1016/j.ejpn.2014.04.015

Guzzetta, F., Conti, G., & Mercuri, E. (2011). Auditory processing in infancy: Do early abnormalities predict disorders of language and cognitive development? *Developmental Medicine and Child Neurology, 53*(12), 1085–1090. https://doi.org/10.1111/j.1469-8749.2011.04084.x

Hack, M. (2005). Poor predictive validity of the Bayley Scales of Infant Development for cognitive function of extremely low birth weight children at school age. *Pediatrics*, *116*(2), 333–341. https://doi.org/10.1542/peds.2005-0173

Hackett, T. A. (2011). Information flow in the auditory cortical network. *Hearing Research*, *271*(1–2), 133–146. https://doi.org/10.1016/j.heares.2010.01.011

Hackett, T. A., Stepniewska, I., & Kaas, J. H. (1999). Prefrontal connections of the parabelt auditory cortex in macaque monkeys. *Brain Research*, *817*(1–2), 45–58. https://doi.org/10.1016/S0006-8993(98)01182-2

Hackman, D. A., Gallop, R., Evans, G. W., & Farah, M. J. (2015). Socioeconomic status and executive function: Developmental trajectories and mediation. *Developmental Science*, *18*(5), 686–702. https://doi.org/10.1111/desc.12246

Háden, G. P., Honing, H., Török, M., & Winkler, I. (2015a). Detecting the temporal structure of sound sequences in newborn infants. *International Journal of Psychophysiology*, *96*(1), 23–28. https://doi.org/10.1016/j.ijpsycho.2015.02.024

Háden, G. P., Németh, R., Török, M., & Winkler, I. (2015b). Predictive processing of pitch trends in newborn infants. *Brain Research*, *1626*, 14–20. https://doi.org/10.1016/j.brainres.2015.02.048

Háden, G. P., Németh, R., Török, M., & Winkler, I. (2016). Mismatch response (MMR) in neonates: Beyond refractoriness. *Biological Psychology*, *117*, 26–31. https://doi.org/10.1016/j.biopsycho.2016.02.004

Haenschel, C., Vernon, D. J., Dwivedi, P., Gruzelier, J. H., & Baldeweg, T. (2005). Event-related brain potential correlates of human auditory sensory memory-trace formation. *Journal of Neuroscience*, *25*(45), 10494–10501. https://doi.org/10.1523/JNEUROSCI.1227-05.2005

Hahne, A., Eckstein, K., & Friederici, A. D. (2004). Brain signatures of syntactic and semantic processes during children's language development. *Journal of Cognitive Neuroscience*, *16*(7), 1302–1318. https://doi.org/10.1162/0898929041920504

Haider, M., Spong, P., & Lindsley, D. B. (1964). Attention, vigilance, and cortical evoked-potentials in humans. *Science*, *145*(3628), 180–182. https://doi.org/10.1126/science.145.3628.180

Halgren, E., Baudena, P., Clarke, J. M., Heit, G., Liégeois, C., Chauvel, P., & Musolino, A. (1995). Intracerebral potentials to rare target and distractor auditory and visual stimuli. I. Superior temporal plane and parietal lobe. *Electroencephalography and Clinical Neurophysiology*, *94*(3), 191–220. https://doi.org/10.1016/0013-4694(94)00259-N

Hall, D. A., Barrett, D. J. K., Akeroyd, M. a, & Summerfield, a Q. (2005). Cortical representations of temporal structure in sound. *Journal of Neurophysiology*, *94*(5), 3181–3191. https://doi.org/10.1152/jn.00271.2005

Hall, D. A., Hart, H. C., & Johnsrude, I. S. (2003). Relationships between human auditory cortical structure and function. *Audiology and Neuro-Otology*, *8*(1), 1–18). https://doi.org/10.1159/000067894

Hallez, H., Vanrumste, B., Grech, R., Muscat, J., De Clercq, W., Vergult, A., D'Asseler, Y., Camilleri, K. P., Fabri, S. G., Van Huffel, S., & Lemahieu, I. (2007). Review on solving the forward problem in EEG source analysis.

Journal of NeuroEngineering and Rehabilitation, *4*(1), 46. https://doi.org/10.1186/1743-0003-4-46

Halliday, L. F., Barry, J. G., Hardiman, M. J., & Bishop, D. V. (2014). Late, not early mismatch responses to changes in frequency are reduced or deviant in children with dyslexia: an event-related potential study. *Journal of Neurodevelopmental Disorders*, *6*(1), 21. https://doi.org/10.1186/1866-1955-6-21

Halliday, L. F., Taylor, J. L., Edmondson-Jones, A. M., & Moore, D. R. (2008). Frequency discrimination learning in children. *The Journal of the Acoustical Society of America*, *123*(6), 4393–4402. https://doi.org/10.1121/1.2890749

Halliday, L. F., Taylor, J. L., Millward, K. E., & Moore, D. R. (2012). Lack of Generalization of Auditory Learning in Typically Developing Children. *Journal of Speech Language and Hearing Research*, *55*(1), 168. https://doi.org/10.1044/1092-4388(2011/09-0213)

Hämäläinen, J. A., Ortiz-Mantilla, S., & Benasich, A. A. (2011). Source localization of event-related potentials to pitch change mapped onto age-appropriate MRIs at 6months of age. *NeuroImage*, *54*(3), 1910–1918. https://doi.org/10.1016/j.neuroimage.2010.10.016

Hamilton, A., Plunkett, K., & Schafer, G. (2000). Infant vocabulary development assessed with a British communicative development inventory. *Journal of Child Language*, *27*(3), 689–705. https://doi.org/10.1017/S0305000900004414

Hancock, K. E. (2004). A physiologically based model of interaural time difference discrimination. *Journal of Neuroscience*, *24*(32), 7110–7117. https://doi.org/10.1523/JNEUROSCI.0762-04.2004

Handy, T. C. (2005). Event-Related Potentials: A Methods Handbook. MIT Press. https://doi.org/10.1212/01.wnl.0000217365.45426.9a

Harms, L., Fulham, W. R., Todd, J., Budd, T. W., Hunter, M., Meehan, C., Penttonen, M., Schall, U., Zavitsanou, K., Hodgson, D. M., & Michie, P. T. (2014). Mismatch negativity (MMN) in freely-moving rats with several experimental controls. *PLoS ONE*, *9*(10), e110892. https://doi.org/10.1371/journal.pone.0110892

Harold, M. P., & Barlow, S. M. (2013). Effects of environmental stimulation on infant vocalizations and orofacial dynamics at the onset of canonical babbling. *Infant Behavior and Development*, *36*(1), 84–93. https://doi.org/10.1016/j.infbeh.2012.10.001

Harpaz, Y., Levkovitz, Y., & Lavidor, M. (2009). Lexical ambiguity resolution in Wernicke's area and its right homologue. *Cortex*, *45*(9), 1097–1103. https://doi.org/10.1016/j.cortex.2009.01.002

Hartmann, W. M., & Johnson, D. (1991). Stream segregation and peripheral channeling. *Music Perception: An Interdisciplinary Journal*, *9*(2), 155–183. https://doi.org/10.2307/40285527

Haywood, N. R., & Roberts, B. (2010). Build-up of the tendency to segregate auditory streams: Resetting effects evoked by a single deviant tone. *The Journal of the Acoustical Society of America*, *128*(5), 3019–3031. https://doi.org/10.1121/1.3488675

He, C., Hotson, L., & Trainor, L. J. (2007). Mismatch responses to pitch changes in early infancy. *Journal of Cognitive Neuroscience*, *19*(5), 878–892. https://doi.org/10.1162/jocn.2007.19.5.878

He, C., Hotson, L., & Trainor, L. J. (2009). Development of infant mismatch responses to auditory pattern changes between 2 and 4 months old. *European Journal of Neuroscience*, *29*(4), 861–867. https://doi.org/10.1111/j.1460-9568.2009.06625.x

He, P., Wilson, G., Russell, C., & Gerschutz, M. (2007). Removal of ocular artifacts from the EEG: a comparison between time-domain regression method and adaptive filtering method using simulated data. *Medical & Biological Engineering & Computing*, *45*(5), 495–503. https://doi.org/10.1007/s11517-007-0179-9

Heim, S., Keil, A., Choudhury, N., Thomas Friedman, J., & Benasich, A. A. (2013). Early gamma oscillations during rapid auditory processing in children with a language-learning impairment: Changes in neural mass activity after training. *Neuropsychologia*, *51*(5), 990–1001. https://doi.org/10.1016/j.neuropsychologia.2013.01.011

Helenius, P., Uutela, K., & Hari, R. (1999). Auditory stream segregation in dyslexic adults. *Brain*, *122*(5), 907–913. https://doi.org/10.1093/brain/122.5.907

Henderson, L. M., Baseler, H. A., Clarke, P. J., Watson, S., & Snowling, M. J. (2011). The N400 effect in children: Relationships with comprehension, vocabulary and decoding. *Brain and Language*, *117*(2), 88–99. https://doi.org/10.1016/J.BANDL.2010.12.003

Hepper, P. G., Scott, D., & Shahidullah, S. (1993). Newborn and fetal response to maternal voice. *Journal of Reproductive and Infant Psychology*, *11*(3), 147–153. https://doi.org/10.1080/02646839308403210

Herholz, S. C., Lappe, C., & Pantev, C. (2009). Looking for a pattern: an MEG study on the abstract mismatch negativity in musicians and nonmusicians. *BMC Neuroscience*, *10*, 42. https://doi.org/10.1186/1471-2202-10-42

Hickok, G. (2013). The functional neuroanatomy of language. *Handbook of Clinical Neurophysiology*, *10*(3), 61–70. https://doi.org/10.1016/B978-0-7020-5310-8.00003-X

Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. (1973). Electrical Signs of Selective Attention in the Human Brain. *Science*, *182*(4108), 177–180. https://doi.org/10.1126/science.182.4108.177

Hirasawa, K., Kurihara, M., & Konishi, Y. (2002). The relationship between mismatch negativity and arousal level. Can mismatch negativity be an index for evaluating the arousal level in infants? *Sleep Medicine*, *3*(SUPPL. 2), S45-8. https://doi.org/10.1016/S1389-9457(02)00164-8

Hochmann, J. R., Benavides-Varela, S., Nespor, M., & Mehler, J. (2011). Consonants and vowels: Different roles in early language acquisition. *Developmental Science*, *14*(6), 1445–1458. https://doi.org/10.1111/j.1467-7687.2011.01089.x

Hoehl, S., & Wahl, S. (2012). Recording infant ERP data for cognitive research. *Developmental Neuropsychology*, *37*(3), 187–209. https://doi.org/10.1080/87565641.2011.627958

Hoff, E. (2013). Interpreting the early language trajectories of children from low-SES and language minority homes: Implications for closing achievement gaps. *Developmental Psychology*, *49*(1), 4–14. https://doi.org/10.1037/a0027238

Hollich, G., Newman, R. S., & Jusczyk, P. W. (2005). Infants' use of synchronized visual information to separate streams of speech. *Child Development*, *76*(3), 598–613. https://doi.org/10.1111/j.1467-8624.2005.00866.x

Holt, L. L., & Lotto, A. J. (2007). Determinants of auditory cue weighting and selective attention. *The Journal of the Acoustical Society of America*, *122*(5), 2970. https://doi.org/10.1121/1.2942596

Hoonhorst, I., Deltenre, P., Markessis, E., Collet, G., Pablos Martin, X., & Colin, C. (2012). Evidence for a dual versus single origin of the MMNs evoked by cued versus cueless deviants. *Clinical Neurophysiology*, *123*(8), 1479–1480. https://doi.org/10.1016/j.clinph.2011.12.015

Horowitz, F. D. (1974). Visual attention, auditory stimulation, and language discrimination in young infants. *Monographs of the Society for Research in Child Development*, *39*(5–6), 1–140. https://doi.org/10.2307/1165968

Horváth, J., Czigler, I., Sussman, E., & Winkler, I. (2001). Simultaneously active preattentive representations of local and global rules for sound sequences in the human brain. *Cognitive Brain Research*, *12*(1), 131–144. https://doi.org/10.1016/S0926-6410(01)00038-6

Hövel, H., Partanen, E., Huotilainen, M., Lindgren, M., Rosén, I., & Fellman, V. (2014). Auditory event-related potentials at preschool age in children born very preterm. *Clinical Neurophysiology*, *125*(3), 449–456. https://doi.org/10.1016/j.clinph.2013.07.026

Hu, S., Stead, M., & Worrell, G. A. (2007). Automatic identification and removal of scalp reference signal for intracranial EEGs based on independent component analysis. *IEEE Transactions on Biomedical Engineering*, *54*(9), 1560–1572. https://doi.org/10.1109/TBME.2007.892929

Hua, Z., & Dodd, B. (2000). The phonological acquisition of Putonghua (Modern standard Chinese). *Journal of Child Language*, *27*(1), 3–42. https://doi.org/10.1017/S030500099900402X

Huttenlocher, P. R. (2002). Neural Plasticity: The effects of environment on the development of the cerebral cortex. In S. M. Kosslyn (Ed.). *Perspectives in Cognitive Neuroscience.* Cambridge, Massachusetts: Harvard University Press.

Imada, T., Hari, R., Loveless, N., McEvoy, L., & Sams, M. (1993a). Determinants of the auditory mismatch response. *Electroencephalography and Clinical Neurophysiology*, *87*(3), 144–153. https://doi.org/10.1016/0013-4694(93)90120-K

Irvine, D. R. F., & Malmierca, M. S. (2005). Auditory Spectral Processing: An Overview. *International Review of Neurobiology,* 70, 1–6. https://doi.org/10.1016/S0074-7742(05)70015-5

Irwin, J., Avery, T., Turcios, J., Brancazio, L., Cook, B., & Landi, N. (2017). Electrophysiological indices of audiovisual speech perception in the broader autism phenotype. *Brain Sciences*, *7*(6). https://doi.org/10.3390/brainsci7060060

Irwin, R. J., Ball, A. K., Kay, N., Stillman, J. A., & Rosser, J. (1985). The development of auditory temporal acuity in children. *Child Development*, *56*(3), 614–620. https://doi.org/10.1111/j.1467-8624.1985.tb00135.x

Iverson, P. (1992). Auditory stream segregation by musical timbre. *The Journal of the Acoustical Society of America, 91*(4), 2333. https://doi.org/10.1121/1.403521

Iverson, P., Wagner, A., Pinet, M., & Rosen, S. (2011). Cross-language specialization in phonetic processing: English and Hindi perception of /w/-/v/

speech and nonspeech. *The Journal of the Acoustical Society of America*, *130*(5), EL297–EL303. https://doi.org/10.1121/1.3632048

Jackson-Maldonado, D., Marchman, V. A., & Fernald, L. C. H. (2013). Short-form versions of the Spanish MacArthur-Bates Communicative Development Inventories. *Applied Psycholinguistics*, *34*(4), 837–868. https://doi.org/10.1017/S0142716412000045

Jacobsen, T., Schroger, E., & Alter, K. (2004). Preattentive perception of vowel phonemes from variable speech stimuli. *Psychophysiology*, *41*(4), 654–659. https://doi.org/10.1111/1469-8986.2004.00175.x

Jacobsen, T., Schröger, E., & Sussman, E. (2004). Preattentive categorization of vowel formant structure in complex tones. *Cognitive Brain Research*, *20*(3), 473–479. https://doi.org/10.1016/j.cogbrainres.2004.03.021

Jakoby, H., Goldstein, A., & Faust, M. (2011). Electrophysiological correlates of speech perception mechanisms and individual differences in second language attainment. *Psychophysiology*, *48*(11), 1517–1531. https://doi.org/10.1111/j.1469-8986.2011.01227.x

Jannesari, M., Saeedi, A., Zare, M., Ortiz-Mantilla, S., Plenz, D., & Benasich, A. A. (2019). Stability of neuronal avalanches and long-range temporal correlations during the first year of life in human infant. *Brain Structure and Function*, *224*(7), 2453–2465. https://doi.org/10.1007/s00429-019-01918-5

Jansson-Verkasalo, E., Korpilahti, P., Jäntti, V., Valkama, M., Vainionpää, L., Alku, P., Suominen, K., & Näätänen, R. (2004). Neurophysiologic correlates of deficient phonological representations and object naming in prematurely born children. *Clinical Neurophysiology*, *115*(1), 179–187. https://doi.org/10.1016/S1388-2457(03)00319-5

Jansson-Verkasalo, E., Ruusuvirta, T., Huotilainen, M., Alku, P., Kushnerenko, E., Suominen, K., Rytky, S., Luotonen, M., Kaukola, T., Tolonen, U., & Hallman, M. (2010). Atypical perceptual narrowing in prematurely born infants is associated with compromised language acquisition at 2 years of age. *BMC Neuroscience*, *11*(88), 88. https://doi.org/10.1186/1471-2202-11-88

Jansson-Verkasalo, E., Valkama, M., Vainionpää, L., Pääkkö, E., Ilkko, E., & Lehtihalmes, M. (2004). Language Development in Very Low Birth Weight Preterm Children: A Follow-Up Study. *Folia Phoniatrica et Logopaedica*, *56*(2), 108–119. https://doi.org/10.1159/000076062

Jardri, R., Houfflin-Debarge, V., Delion, P., Pruvo, J. P., Thomas, P., & Pins, D. (2012). Assessing fetal response to maternal speech using a non-invasive functional brain imaging technique. *International Journal of Developmental Neuroscience*, *30*(2), 159–161. https://doi.org/10.1016/j.ijdevneu.2011.11.002

Jarkiewicz, M., & Wichniak, A. (2015). Can new paradigms bring new perspectives for mismatch negativity studies in schizophrenia? *Neuropsychiatric Electrophysiology*, *1*(1), 12. https://doi.org/10.1186/s40810-015-0010-z

Jasper, H. H. (1958). The ten twenty electrode system of the International Federation. *Committee on Clinical Examination in EEG,* 370-375.

Javitt, D. C., Grochowski, S., Shelley, A.-M., & Ritter, W. (1998). Impaired mismatch negativity (MMN) generation in schizophrenia as a function of stimulus deviance, probability, and interstimulus/interdeviant interval. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *108*(2), 143–153. https://doi.org/10.1016/S0168-5597(97)00073-7

Javitt, D. C., & Sweet, R. A. (2015). Auditory dysfunction in schizophrenia: Integrating clinical and basic features. *Nature Reviews Neuroscience*, *16*(9), 535–550. https://doi.org/10.1038/nrn4002

Jia, G., & Fuse, A. (2007). Acquisition of English grammatical morphology by native mandarin-speaking children and adolescents: Age-related differences. *Journal of Speech, Language, and Hearing Research*, *50*(5), 1280–1299. https://doi.org/10.1044/1092-4388(2007/090)

Johnson, M. H., & de Haan, M. (2011). Building a Brain. *Developmental Cognitive Neuroscience*, pp. 42–80. https://doi.org/10.1126/stke.2001.73.tw3

Jones, P. R., Moore, D. R., & Amitay, S. (2015). Development of auditory selective attention: Why children struggle to hear in noisy environments. *Developmental Psychology*, *51*(3), 353–369. https://doi.org/10.1037/a0038570

Jost, L. B., Eberhard-Moscicka, A. K., Pleisch, G., Heusser, V., Brandeis, D., Zevin, J. D., & Maurer, U. (2015). Native and non-native speech sound processing and the neural mismatch responses: A longitudinal study on classroom-based foreign language learning. *Neuropsychologia*, *72*, 94–104. https://doi.org/10.1016/j.neuropsychologia.2015.04.029

Junghöfer, M., Elbert, T., Tucker, D. M., & Braun, C. (1999). The polar average reference effect: A bias in estimating the head surface integral in EEG recording. *Clinical Neurophysiology*, *110*(6), 1149–1155. https://doi.org/10.1016/S1388-2457(99)00044-9

Justen, C., & Herbert, C. (2018). The spatio-temporal dynamics of deviance and target detection in the passive and active auditory oddball paradigm: a sLORETA study. *BMC Neuroscience*, *19*(1), 25. https://doi.org/10.1186/s12868-018-0422-3

Kaas, J. H., & Hackett, T. A. (2010). The Functional Neuroanatomy of the Auditory Cortex. In B. Fritzsch (Ed.). *The Senses: A Comprehensive* Reference, Volume 3 (pp. 765–780). Elsevier. https://doi.org/10.1016/B978-012370880-9.00057-8

Kabdebon, C., Pena, M., Buiatti, M., & Dehaene-Lambertz, G. (2015). Electrophysiological evidence of statistical learning of long-distance dependencies in 8-month-old preterm and full-term infants. *Brain and Language*, *148*, 25–36. https://doi.org/10.1016/j.bandl.2015.03.005

Kabel, A. H., Mesallam, T., & Ghandour, H. H. (2009). Follow up of P1 peak amplitude and peak latency in a group of specific language-impaired children. *International Journal of Pediatric Otorhinolaryngology*, *73*(11), 1525–1531. https://doi.org/10.1016/j.ijporl.2009.07.008

Kalinli, O., & Narayanan, S. (2009). Prominence detection using auditory attention cues and task-dependent high level information. *IEEE Transactions on Audio, Speech and Language Processing*, *17*(5), 1009–1024. https://doi.org/10.1109/TASL.2009.2014795

Kalinli, O., & Narayanan, S. (2007). A saliency-based auditory attention model with applications to unsupervised prominent syllable detection in speech. *International Speech Communication Association - 8th Annual Conference of the International Speech Communication Association, Interspeech 2007, 4*, 2452–2455. https://doi.org/10.21437/interspeech.2007-44

Kalinli, O., & Narayanan, S. (2008). Combining task-dependent information with auditory attention cues for prominence detection in speech. *Proceedings of the Annual Conference of the International Speech Communication Association, INTERSPEECH*, 1064–1067.

Karmiloff-Smith, A. (2010). Neuroimaging of the developing brain: Taking "developing" seriously. *Human Brain Mapping*, *31*(6), 934–941. https://doi.org/10.1002/hbm.21074

Karns, C. M., Isbell, E., Giuliano, R. J., & Neville, H. J. (2015). Auditory attention in childhood and adolescence: An event-related potential study of spatial selective attention to one of two simultaneous stories. *Developmental Cognitive Neuroscience*, *13*, 53–67. https://doi.org/10.1016/j.dcn.2015.03.001

Karousou, A., & López-Ornat, S. (2013). Prespeech vocalizations and the emergence of speech: A study of 1005 Spanish children. *Spanish Journal of Psychology*, *16*, 1–21. https://doi.org/10.1017/sjp.2013.27

Kasai, K., Nakagome, K., Iwanami, A., Fukuda, M., Itoh, K., Koshida, I., & Kato, N. (2002). No effect of gender on tonal and phonetic mismatch negativity in normal adults assessed by a high-resolution EEG recording. *Cognitive Brain Research*, *13*(3), 305–312. https://doi.org/10.1016/S0926-6410(01)00125-2

Kaser, M., Soltesz, F., Lawrence, P., Miller, S., Dodds, C., Croft, R., Dudas, R. B., Zaman, R., Fernandez-Egea, E., Müller, U., Dean, A., Bullmore, E. T., & Nathan, P. J. (2013). Oscillatory underpinnings of mismatch negativity and their relationship with cognitive function in patients with schizophrenia. *PLoS ONE*, *8*(12), e83255. https://doi.org/10.1371/journal.pone.0083255

Kathmann, N., Frodl-Bauch, T., & Hegerl, U. (1999). Stability of the mismatch negativity under different stimulus and attention conditions. *Clinical Neurophysiology*, *110*(2), 317–323. https://doi.org/10.1016/S1388-2457(98)00011-X

Katsipis, M. (2016). *Situation models and children's reading comprehension: what role does visual imagery play?* (Unpublished Doctoral thesis, Murdoch

University, Perth, Australia). Available from Semantic Scholar database. (Corpus ID: 152278384)

Kaya, E. M., & Elhilali, M. (2014). Investigating bottom-up auditory attention. *Frontiers in Human Neuroscience*, *8*, 327. https://doi.org/10.3389/fnhum.2014.00327

Kaya, E. M., & Elhilali, M. (2017). Modelling auditory attention. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*(1714), 20160101. https://doi.org/10.1098/rstb.2016.0101

Kaya, E. M., & Elhilali, M. (2012). A temporal saliency map for modeling auditory attention. *2012 46th Annual Conference on Information Sciences and Systems, CISS 2012*, 1–6. https://doi.org/10.1109/CISS.2012.6310945

Kayser, C., Petkov, C. I., Lippert, M., & Logothetis, N. K. (2005). Mechanisms for allocating auditory attention: An auditory saliency map. *Current Biology*, *15*(21), 1943–1947. https://doi.org/10.1016/j.cub.2005.09.040

Kent, R. D., Read, C. (1992). *The Acoustic Analysis of Speech*. United Kingdom: Singular Publishing Group.

Key, A. P. F., Ferguson, M., Molfese, D. L., Peach, K., Lehman, C., & Molfese, V. J. (2007). Smoking during pregnancy affects speech-processing ability in newborn infants. *Environmental Health Perspectives*, *115*(4), 623–629. https://doi.org/10.1289/ehp.9521

Kim, J., Kwon, J.-T., Kim, H.-S., & Han, J.-H. (2013). CREB and neuronal selection for memory trace. *Frontiers in Neural Circuits*, *7*, 44. https://doi.org/10.3389/fncir.2013.00044

Kinney, D. K., & Kagan, J. (1976). Infant attention to auditory discrepancy. *Child Development*, *47*(1), 155–164. https://doi.org/10.1111/j.1467-8624.1976.tb03404.x

Kisilevsky, B. S. (2016). Fetal auditory processing: Implications for language development? In N. Reissland, B. S. Kisilevsky (Eds.). *Fetal Development: Research on Brain and Behavior, Environmental Influences, and Emerging Technologies* (pp. 133–152). Springer International Publishing. https://doi.org/10.1007/978-3-319-22023-9_8

Knowland, V. C. P., Mercure, E., Karmiloff-Smith, A., Dick, F., & Thomas, M. S. C. (2014). Audio-visual speech perception: A developmental ERP investigation. *Developmental Science*, *17*(1), 110–124. https://doi.org/10.1111/desc.12098

Koegel, L. K., Koegel, R. L., Ashbaugh, K., & Bradshaw, J. (2014). The importance of early identification and intervention for children with or at risk for autism spectrum disorders. *International Journal of Speech-Language Pathology*, *16*(1), 50–56. https://doi.org/10.3109/17549507.2013.861511

Koelsch, S., Schröger, E., & Tervaniemi, M. (1999). Superior preattentive auditory processing in musicians. *NeuroReport*, *10*(6), 1309–1313. https://doi.org/10.1097/00001756-199904260-00029

Koerner, T. K., Zhang, Y., Nelson, P. B., Wang, B., & Zou, H. (2017). Neural indices of phonemic discrimination and sentence-level speech intelligibility in quiet and noise: A P3 study. *Hearing Research*, *350*, 58–67. https://doi.org/10.1016/j.heares.2017.04.009

Kolesnik, A., Begum Ali, J., Gliga, T., Guiraud, J., Charman, T., Johnson, M. H., & Jones, E. J. H. (2019). Increased cortical reactivity to repeated tones at 8 months in infants with later ASD. *Translational Psychiatry*, *9*(1), 46. https://doi.org/10.1038/s41398-019-0393-x

Korkman, M., Kirk, U., & Kemp, S. (2007b). *NEPSY-II: Administrative Manual.* San Antonio, TX: The Psychological Corporation.

Korkman, M., Kirk, U., & Kemp, S. (2007c). *NEPSY-II Second Edition. Clinical and Interpretive Manual*. San Antonio, TX: The Psychological Corporation.

Korkman, M., Kirk, U., & Kemp, S. (2007a). Test review of NEPSY-II—Second Edition. In R. A. Spies, J. F. Carlson, & K. F. Geisinger (Eds.). *The eighteenth mental measurements yearbook.* Lincoln, NE: Buros Center for Testing.

Korpilahti, P., Krause, C. M., Holopainen, I., & Lang, A. H. (2001). Early and late mismatch negativity elicited by words and speech-like stimuli in children. *Brain and Language*, *76*(3), 332–339. https://doi.org/10.1006/brln.2000.2426

Korpilahti, P., & Lang, H. A. (1994). Auditory ERP components and mismatch negativity in dysphasic children. *Electroencephalography and Clinical Neurophysiology*, *91*(4), 256–264. https://doi.org/10.1016/0013-4694(94)90189-9

Kostilainen, K., Wikström, V., Pakarinen, S., Videman, M., Karlsson, L., Keskinen, M., Scheinin, N. M., Karlsson, H., & Huotilainen, M. (2018). Healthy full-term infants' brain responses to emotionally and linguistically relevant sounds using a multi-feature mismatch negativity (MMN) paradigm. *Neuroscience Letters*, *670*, 110–115. https://doi.org/10.1016/j.neulet.2018.01.039

Kovacs, A. M., & Mehler, J. (2009). Cognitive gains in 7-month-old bilingual infants. *Proceedings of the National Academy of Sciences*, *106*(16), 6556–6560. https://doi.org/10.1073/pnas.0811323106

Kozou, H., Kujala, T., Shtyrov, Y., Toppila, E., Starck, J., Alku, P., & Näätänen, R. (2005). The effect of different noise types on the speech and non-speech elicited mismatch negativity. *Hearing Research*, *199*(1–2), 31–39. https://doi.org/10.1016/j.heares.2004.07.010

Kraus, N., & Banai, K. (2006). Neurobiology of (central) auditory processing disorder and language-based learning disability. In G. D. Chermak, & F. E. Musiek (Eds.) *Handbook of Central Auditory Processing Disorder: Volume I: Auditory Neuroscience and Diagnosis*, (March, pp. 89–116). San Diego: Plural Publishing Inc.

Kraus, N., McGee, T. J., Carrell, T. D., Zecker, S. G., Nicol, T. G., & Koch, D. B. (1996). Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science*, *273*(5277), 971–973. https://doi.org/10.1126/science.273.5277.971

Kraus, N., McGee, T., Micco, A., Sharma, A., Carrell, T., & Nicol, T. (1993). Mismatch negativity in school-age children to speech stimuli that are just perceptibly different. *Electroencephalography and Clinical Neurophysiology*, *88*(2), 123–130. https://doi.org/10.1016/0168-5597(93)90063-U

Krishnan, A., & Gandour, J. T. (2009). The role of the auditory brainstem in processing linguistically-relevant pitch patterns. In *Brain and Language* (Vol. 110, Issue 3, pp. 135–148). https://doi.org/10.1016/j.bandl.2009.03.005

Krishnan, L., Elhilali, M., & Shamma, S. (2014). Segregating complex sound sources through temporal coherence. *PLoS Computational Biology*, *10*(12), e1003985. https://doi.org/10.1371/journal.pcbi.1003985

Kudo, N., Nonaka, Y., Mizuno, N., Mizuno, K., & Okanoya, K. (2011). On-line statistical segmentation of a non-speech auditory stream in neonates as demonstrated by event-related brain potentials. *Developmental Science*, *14*(5), 1100–1106. https://doi.org/10.1111/j.1467-7687.2011.01056.x

Kuhl, P. K. (1983). Perception of auditory equivalence classes for speech in early infancy. *Infant Behavior and Development*, *6*(2–3), 263–285. https://doi.org/10.1016/S0163-6383(83)80036-8

Kuhl, P. K. (2004). Early language acquisition: Cracking the speech code. *Nature Reviews Neuroscience*, *5*(11), 831–843. https://doi.org/10.1038/nrn1533

Kuhl, P. K. (2010a). Brain Mechanisms in Early Language Acquisition. *Neuron*, *67*(5), 713–727. https://doi.org/10.1016/j.neuron.2010.08.038

Kuhl, P. K. (2010b). Brain Mechanisms in Early Language Acquisition. *Neuron*, *67*(5), 713–727. https://doi.org/10.1016/j.neuron.2010.08.038

Kuhl, P. K., Conboy, B. T., Padden, D., Nelson, T., & Pruitt, J. (2005). Early Speech Perception and Later Language Development: Implications for the "Critical Period." *Language Learning and Development*, *1*(3–4), 237–264. https://doi.org/10.1080/15475441.2005.9671948

Kuhl, P. K., Ramírez, R. R., Bosseler, A., Lin, J. F. L., & Imada, T. (2014). Infants' brain responses to speech suggest Analysis by Synthesis. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(31), 11238–11245. https://doi.org/10.1073/pnas.1410963111

Kuhl, P. K., Stevens, E., Hayashi, A., Deguchi, T., Kiritani, S., & Iverson, P. (2006). Infants show a facilitation effect for native language phonetic perception between 6 and 12 months. *Developmental Science*, *9*(2), F13–F21. https://doi.org/10.1111/j.1467-7687.2006.00468.x

Kuhl, P. K., Williams, K. A., Lacerda, F., Stevens, K. N., & Lindblom, B. (1992). Linguistic experience alters phonetic perception in infants by 6 months of age. *Science*, *255*(5044), 606–608. https://doi.org/10.1126/science.1736364

Kuhl, P., & Rivera-Gaxiola, M. (2008). Neural substrates of language acquisition. *Annual Review of Neuroscience*, *31*(1), 511–534. https://doi.org/10.1146/annurev.neuro.30.051606.094321

Kujala, T., Kallio, J., Tervaniemi, M., & Näätänen, R. (2001). The mismatch negativity as an index of temporal processing in audition. *Clinical Neurophysiology*, *112*(9), 1712–1719. https://doi.org/10.1016/S1388-2457(01)00625-3

Kujala, T., Kuuluvainen, S., Saalasti, S., Jansson-Verkasalo, E., Wendt, L. von, & Lepistö, T. (2010). Speech-feature discrimination in children with Asperger syndrome as determined with the multi-feature mismatch negativity paradigm. *Clinical Neurophysiology*, *121*(9), 1410–1419. https://doi.org/10.1016/J.CLINPH.2010.03.017

Kushnerenko, E. (2003). Maturation of the cortical auditory event-related brain potentials in infancy. In *Department of Psychology, University of Helsinki*. University of Helsinki.

Kushnerenko, E., Čeponiené, R., Balan, P., Fellman, V., Huotilainen, M., & Näätänen, R. (2002). Maturation of the auditory event-related potentials during the first year of life. *NeuroReport*, *13*(1), 47–51. https://doi.org/10.1097/00001756-200201210-00014

Kushnerenko, E., Čeponiené, R., Balan, P., Fellman, V., & Näätänen, R. (2002). Maturation of the auditory change detection response in infants: a longitudinal

ERP study. *NeuroReport*, *13*(15), 1843–1848. https://doi.org/10.1097/00001756-200210280-00002

Kushnerenko, E., Teinonen, T., Volein, A., & Csibra, G. (2008). Electrophysiological evidence of illusory audiovisual speech percept in human infants. *Proceedings of the National Academy of Sciences*, *105*(32), 11442–11445. https://doi.org/10.1073/pnas.0804275105

Kushnerenko, E., Tomalski, P., Ballieux, H., Potton, A., Birtles, D., Frostick, C., & Moore, D. G. (2013). Brain responses and looking behavior during audiovisual speech integration in infants predict auditory speech comprehension in the second year of life. *Frontiers in Psychology*, *4*(JUL), 1–8. https://doi.org/10.3389/fpsyg.2013.00432

Kushnerenko, E., Tomalski, P., Ballieux, H., Ribeiro, H., Potton, A., Axelsson, E. L., Murphy, E., & Moore, D. G. (2013). Brain responses to audiovisual speech mismatch in infants are associated with individual differences in looking behaviour. *European Journal of Neuroscience*, *38*(9), 3363–3369. https://doi.org/10.1111/ejn.12317

Kushnerenko, E., Winkler, I., Horváth, J., Näätänen, R., Pavlov, I., Fellman, V., & Huotilainen, M. (2007). Processing acoustic change and novelty in newborn infants. *European Journal of Neuroscience*, *26*(1), 265–274. https://doi.org/10.1111/j.1460-9568.2007.05628.x

Kushnerenko, E. V, Van den Bergh, B. R. H. H., & Winkler, I. (2013). Separating acoustic deviance from novelty during the first year of life: a review of event-related potential evidence. *Frontiers in Psychology*, *4*(SEP), 1–16. https://doi.org/10.3389/fpsyg.2013.00595

Kuuluvainen, S., Nevalainen, P., Sorokin, A., Mittag, M., Partanen, E., Putkinen, V., Seppänen, M., Kähkönen, S., & Kujala, T. (2014). The neural basis of sublexical speech and corresponding nonspeech processing: A combined EEG-MEG study. *Brain and Language*, *130*, 19–32. https://doi.org/10.1016/j.bandl.2014.01.008

Laasonen, M., Smolander, S., Lahti-Nuuttila, P., Leminen, M., Lajunen, H. R., Heinonen, K., Pesonen, A. K., Bailey, T. M., Pothos, E. M., Kujala, T., Leppänen, P. H. T., Bartlett, C. W., Geneid, A., Lauronen, L., Service, E., Kunnari, S., & Arkkila, E. (2018). Understanding developmental language disorder -The Helsinki longitudinal SLI study (HelSLI): A study protocol. *BMC Psychology*, *6*(1), 1–13. https://doi.org/10.1186/s40359-018-0222-7

Lachmann, T., Berti, S., Kujala, T., Schrfger, E., & Schröger, E. (2005). Diagnostic subgroups of developmental dyslexia have different deficits in neural processing of tones and phonemes. *International Journal of Psychophysiology*, *56*(2), 105–120. https://doi.org/10.1016/j.ijpsycho.2004.11.005

Lamm, C., Zelazo, P. D., & Lewis, M. D. (2006). Neural correlates of cognitive control in childhood and adolescence: Disentangling the contributions of age and executive function. *Neuropsychologia*, *44*(11), 2139–2148. https://doi.org/10.1016/j.neuropsychologia.2005.10.013

Law, F., Mahr, T., Schneeberg, A., & Edwards, J. (2017). Vocabulary size and auditory word recognition in preschool children. *Applied Psycholinguistics*, *38*(1), 89–125. https://doi.org/10.1017/S0142716416000126

Law, J., Charlton, J., & Asmussen, K. (2017). Language As a Child Wellbeing Indicator. *Early Intervention Foundation*. Retrieved from https://www.eif.org.uk/report/language-as-a-child-wellbeing-indicator

Lecanuet, J. P., & Schaal, B. (1996). Fetal sensory competencies. *European Journal of Obstetrics Gynecology and Reproductive Biology*, *68*(1–2), 1–23. https://doi.org/10.1016/0301-2115(96)02509-2

Lee, C. Y., Yen, H. ling, Yeh, P. wen, Lin, W. H., Cheng, Y. Y., Tzeng, Y. L., & Wu, H. C. (2012). Mismatch responses to lexical tone, initial consonant, and vowel in Mandarin-speaking preschoolers. *Neuropsychologia*, *50*(14), 3228–3239. https://doi.org/10.1016/j.neuropsychologia.2012.08.025

Lee, G. Y., & Kisilevsky, B. S. (2014). Fetuses respond to father's voice but prefer mother's voice after birth. *Developmental Psychobiology*, *56*(1), 1–11. https://doi.org/10.1002/dev.21084

Lehnhoff, R. J., Strange, W., & Long, G. (2004). Differentiating speech and nonspeech sounds via amplitude envelope cues. *The Journal of the Acoustical Society of America*, *115*(5), 2459–2459. https://doi.org/10.1121/1.4782327

Lei, X., & Liao, K. (2017). Understanding the influences of EEG reference: A large-scale brain network perspective. *Frontiers in Neuroscience*, *11*, 205. https://doi.org/10.3389/fnins.2017.00205

Leibold, L. J. (2012). *Development of Auditory Scene Analysis and Auditory Attention* (pp. 137–161). https://doi.org/10.1007/978-1-4614-1421-6_5

Leipälä, J. A., Partanen, E., Kushnerenko, E., Huotilainen, M., & Fellman, V. (2011). Perinatal cerebral insults alter auditory event-related potentials. *Early Human Development*, *87*(2), 89–95. https://doi.org/10.1016/j.earlhumdev.2010.11.009

Leppänen, P. H., Pihko, E., Eklund, K. M., & Lyytinen, H. (1999). Cortical responses of infants with and without a genetic risk for dyslexia: II. Group effects. *NeuroReport*, *10*(5), 969–973.

Leppänen, P. H. T., Guttorm, T. K., Pihko, E., Takkinen, S., Eklund, K. M., & Lyytinen, H. (2004). Maturational effects on newborn ERPs measured in the mismatch negativity paradigm. *Experimental Neurology*, *190*(SUPPL. 1), 91–101. https://doi.org/10.1016/j.expneurol.2004.06.002

Leppänen, P. H. T., & Lyytinen, H. (1997). Auditory event-related potentials in the study of developmental language-related disorders. *Audiology and Neurotology*, *2*(5), 308–340. https://doi.org/10.1159/000259254

Leppänen, P. H. T., Richardson, U., Pihko, E., Eklund, K. M., Guttorm, T. K., Aro, M., & Lyytinen, H. (2002). Brain responses to changes in speech sound durations differ between infants with and without familial risk for dyslexia. *Developmental Neuropsychology*, *22*(1), 407–422. https://doi.org/10.1207/S15326942dn2201_4

Leventhal, A. S., & Lipsitt, L. P. (1964). Adaptation, pitch discrimination, and sound localization in the neonate. *Child Development*, *35*(3), 759. https://doi.org/10.2307/1126501

Levin, K. A. (2006). Study design III: Cross-sectional studies. *Evidence-Based Dentistry*, *7*(1), 24–25. https://doi.org/10.1038/sj.ebd.6400375

Levy, A. K. (1984). A review of literature. *Early Child Development and Care*, *17*(1), 49–61. https://doi.org/10.1080/0300443840170106

Leung S, Greenwood L, Michie P and Croft R (2015). The role of stimulus train length in mismatch negativity (MMN) abnormalities in schizophrenia: A comparison of the 'roving' and 'oddball' MMN paradigms. *XII International Conference on Cognitive Neuroscience (ICON-XII).* doi: 10.3389/conf.fnhum.2015.217.00153

Liebenthal, E., Ellingson, M. L., Spanaki, M. V., Prieto, T. E., Ropella, K. M., & Binder, J. R. (2003). Simultaneous ERP and fMRI of the auditory cortex in a passive oddball paradigm. *NeuroImage*, *19*(4), 1395–1404. https://doi.org/10.1016/S1053-8119(03)00228-3

Lieder, F., Daunizeau, J., Garrido, M. I., Friston, K. J., & Stephan, K. E. (2013). Modelling trial-by-trial changes in the mismatch negativity. *PLoS Computational Biology*, *9*(2), e1002911. https://doi.org/10.1371/journal.pcbi.1002911

Lindell, M. K., & Whitney, D. J. (2001). Accounting for common method variance in cross-sectional research designs. *Journal of Applied Psychology*, *86*(1), 114–121. https://doi.org/10.1037/0021-9010.86.1.114

Lindsay, G., & Strand, S. (2016). Children with language impairment: prevalence, associated difficulties, and ethnic disproportionality in an English population. *Frontiers in Education*, *1*(2). https://doi.org/10.3389/feduc.2016.00002

Linnavalli, T., Putkinen, V., Huotilainen, M., & Tervaniemi, M. (2018a). Maturation of Speech-Sound ERPs in 5–6-Year-Old Children: A Longitudinal Study. *Frontiers in Neuroscience*, *12*, 814. https://doi.org/10.3389/fnins.2018.00814

Linnavalli, T., Putkinen, V., Huotilainen, M., & Tervaniemi, M. (2018b). Maturation of speech-sound ERPs in 5-6-year-old children: A longitudinal study. *Frontiers in Neuroscience*, *12*(NOV), 1–12. https://doi.org/10.3389/fnins.2018.00814

Lippe, S. (2009). Differential maturation of brain signal complexity in the human auditory and visual system. *Frontiers in Human Neuroscience*, *3*(4), 48. https://doi.org/10.3389/neuro.09.048.2009

Litovsky, R. (2015). Development of the auditory system. *Handbook of Clinical Neurology*, *129*, 55–72. https://doi.org/10.1016/B978-0-444-62630-1.00003-2

Lloyd-Fox, S., Blasi, A., & Elwell, C. E. (2010). Illuminating the developing brain: The past, present and future of functional near infrared spectroscopy. *Neuroscience and Biobehavioral Reviews*, *34*(3), 269–284. https://doi.org/10.1016/j.neubiorev.2009.07.008

LoCasto, P. C., Krebs-Noble, D., Gullapalli, R. P., & Burton, M. W. (2004). An fMRI investigation of speech and tone segmentation. *Journal of Cognitive Neuroscience*, *16*(9), 1612–1624. https://doi.org/10.1162/0898929042568433

Locke, A., Ginsborg, J., & Peers, I. (2002). Development and disadvantage: implications for the early years and beyond. *International Journal of Language and Communication Disorders*, *37*(1), 3–15. https://doi.org/10.1080/13682820110089911

Lohvansuu, K., Hämäläinen, J. A., Tanskanen, A., Bartling, J., Bruder, J., Honbolygó, F., Schulte-Körne, G., Démonet, J. F., Csépe, V., & Leppänen, P. H. T. (2013). Separating mismatch negativity (MMN) response from auditory obligatory brain responses in school-aged children. *Psychophysiology*, *50*(7), 640–652. https://doi.org/10.1111/psyp.12048

Long, P., Wan, G., Roberts, M. T., & Corfas, G. (2018, February). Myelin development, plasticity, and pathology in the auditory system. *Developmental Neurobiology,78*, 80–92. https://doi.org/10.1002/dneu.22538

Lopes da Silva, F. H., Gonçalves, S. I., & De Munck, J. C. (2009). Electroencephalography (EEG). In L. R. Squire (Ed.). *Encyclopedia of Neuroscience* (pp. 849–855). London, UK: Academic Press. https://doi.org/10.1016/B978-008045046-9.00304-1

López-Caballero, F., Zarnowiec, K., & Escera, C. (2016). Differential deviant probability effects on two hierarchical levels of the auditory novelty system.

Biological Psychology, *120*, 1–9. https://doi.org/10.1016/j.biopsycho.2016.08.001

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience*, *8*, 213. https://doi.org/10.3389/fnhum.2014.00213

Love, B. C., Rouder, J. N., & Wisniewski, E. J. (1999). A structural account of global and local processing. *Cognitive Psychology*, *38*(2), 291–316. https://doi.org/10.1006/cogp.1998.0697

Lovio, R., Näätänen, R., & Kujala, T. (2010). Abnormal pattern of cortical speech feature discrimination in 6-year-old children at risk for dyslexia. *Brain Research*, *1335*, 53–62. https://doi.org/10.1016/j.brainres.2010.03.097

Luck, S. J. (2004). Ten Simple Rules for Designing and Interpreting ERP Experiments. In T. Handy (Ed.), *Event-Related Potentials: A Methods Handbook*. MIT Press. Cambridge, Massachusetts. http://www.indiana.edu/~pcl/busey/eegseminar/pdfs/Luck_Ten_Simple_Rules.pdf

Luck, S. J. (2014). *An Introduction to the Event-Related Potential Technique.* (2nd ed.). The MIT Press.

Luck, S. J., & Gaspelin, N. (2017). How to get statistically significant effects in any ERP experiment (and why you shouldn't). *Psychophysiology*, *54*(1), 146–157. https://doi.org/10.1111/psyp.12639

Luo, H., Husain, F. T., Horwitz, B., & Poeppel, D. (2005). Discrimination and categorization of speech and non-speech sounds in an MEG delayed-match-to-sample study. *NeuroImage*, *28*(1), 59–71. https://doi.org/10.1016/j.neuroimage.2005.05.040

Luo, H., Ni, J.-T., Li, Z.-H., Li, X.-O., Zhang, D.-R., Zeng, F.-G., & Chen, L. (2006). Opposite patterns of hemisphere dominance for early auditory processing of lexical tones and consonants. *Proceedings of the National Academy of Sciences*, *103*(51), 19558–19563. https://doi.org/10.1073/pnas.0607065104

Luttikhuizen dos Santos, E. S., de Kieviet, J. F., Königs, M., van Elburg, R. M., & Oosterlaan, J. (2013). Predictive value of the Bayley Scales of Infant Development on development of very preterm/very low birth weight children: A meta-analysis. *Early Human Development*, *89*(7), 487–496. https://doi.org/10.1016/j.earlhumdev.2013.03.008

Lyytinen, H., Ahonen, T., Eklund, K., Guttorm, T. K., Laakso, M. L., Leppänen, P. H. T., Lyytinen, P., Poikkeus, A. M., Puolakanaho, A., Richardson, U., & Viholainen, H. (2001). Developmental pathways of children with and without familial risk for dyslexia during the first years of life. *Developmental Neuropsychology*, *20*(2), 535–554. https://doi.org/10.1207/S15326942DN2002_5

Lyytinen, H., Aro, M., Eklund, K., Erskine, J., Guttorm, T., Laakso, M. L., Leppänen, P. H. T., Lyytinen, P., Poikkeus, A. M., Richardson, U., & Torppa, M. (2004). The development of children at familial risk for dyslexia: Birth to early school age. *Annals of Dyslexia*, *54*(2), 184–220. https://doi.org/10.1007/s11881-004-0010-3

Madaschi, V., Mecca, T. P., Macedo, E. C., & Paula, C. S. (2016). Bayley-III scales of infant and toddler development: Transcultural adaptation and psychometric properties. *Paideia, 26*(64), 189–197. https://doi.org/10.1590/1982-43272664201606

Mahajan, Y., & McArthur, G. (2012). Maturation of auditory event-related potentials across adolescence. *Hearing Research*, *294*(1–2), 82–94. https://doi.org/10.1016/j.heares.2012.10.005

Mahajan, Y., Peter, V., & Sharma, M. (2017). Effect of EEG referencing methods on auditory mismatch negativity. *Frontiers in Neuroscience*, *11*(OCT), 560. https://doi.org/10.3389/fnins.2017.00560

Mai, X., Xu, L., Li, M., Shao, J., Zhao, Z., Lamm, C., Fox, N. A., Nelson, C. A., & Lozoff, B. (2014). Sounds elicit relative left frontal alpha activity in 2-month-old infants. *International Journal of Psychophysiology*, *94*(3), 287–291. https://doi.org/10.1016/j.ijpsycho.2014.09.008

Makeig, S., Debener, S., Onton, J., & Delorme, A. (2004). Mining event-related brain dynamics. *Trends in Cognitive Sciences*, *8*(5), 204–210. https://doi.org/10.1016/j.tics.2004.03.008

Mampe, B., Friederici, A. D., Christophe, A., & Wermke, K. (2009). Newborns' Cry Melody Is Shaped by Their Native Language. *Current Biology*, *19*(23), 1994–1997. https://doi.org/10.1016/j.cub.2009.09.064

Mancini, F., Pepe, A., Bernacchia, A., Di Stefano, G., Mouraux, A., & Iannetti, G. D. (2018). Characterizing the Short-Term Habituation of Event-Related Evoked Potentials. *ENeuro*, *5*(5). https://doi.org/10.1523/ENEURO.0014-18.2018

Mandel, D. R., Jusczyk, P. W., & Pisoni, D. B. (1995). Infants' recognition of the sound patterns of their own names. *Psychological Science*, *6*(5), 314–317. https://doi.org/10.1111/j.1467-9280.1995.tb00517.x

Mann, C. J. (2003). Observational research methods. Research design II: cohort, cross sectional, and case-control studies. *Emergency Medicine Journal*, *20*(1), 54–60. https://doi.org/10.1136/emj.20.1.54

Marchman, V. A., Adams, K. A., Loi, E. C., Fernald, A., & Feldman, H. M. (2016). Early language processing efficiency predicts later receptive vocabulary outcomes in children born preterm. *Child Neuropsychology*, *22*(6), 649–665. https://doi.org/10.1080/09297049.2015.1038987

Marchman, V. A., Loi, E. C., Adams, K. A., Ashland, M., Fernald, A., & Feldman, H. M. (2018). Speed of Language Comprehension at 18 Months Old Predicts School-Relevant Outcomes at 54 Months Old in Children Born Preterm. *Journal of Developmental & Behavioral Pediatrics*, 1. https://doi.org/10.1097/DBP.0000000000000541

Marchman, V. A., Martinez-Sussmann, C., & Dale, P. S. (2004). The language-specific nature of grammatical development: evidence from bilingual language learners. *Developmental Science*, *7*(2), 212–224. https://doi.org/10.1111/j.1467-7687.2004.00340.x

Marcus, G. F., Vijayan, S., Bandi Rao, S., & Vishton, P. M. (1999). Rule learning by seven-month-old infants. *Science*, *283*(5398), 77–80. https://doi.org/10.1126/science.283.5398.77

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190. https://doi.org/10.1016/j.jneumeth.2007.03.024

Marshall, P. J., Reeb, B. C., & Fox, N. A. (2009). Electrophysiological responses to auditory novelty in temperamentally different 9-month-old infants. *Developmental Science*, *12*(4), 568–582. https://doi.org/10.1111/j.1467-7687.2008.00808.x

Martynova, O., Kirjavainen, J., & Cheour, M. (2003). Mismatch negativity and late discriminative negativity in sleeping human newborns. *Neuroscience Letters*, *340*(2), 75–78. https://doi.org/10.1016/S0304-3940(02)01401-5

Matsumoto, R., Nair, D. R., LaPresto, E., Najm, I., Bingaman, W., Shibasaki, H., & Lüders, H. O. (2004). Functional connectivity in the human language system: A cortico-cortical evoked potential study. *Brain*, *127*(10), 2316–2330. https://doi.org/10.1093/brain/awh246

Maurer, U., Bucher, K., Brem, S., Benz, R., Kranz, F., Schulz, E., van der Mark, S., Steinhausen, H. C., & Brandeis, D. (2009). Neurophysiology in preschool improves behavioral prediction of reading ability throughout primary school. *Biological Psychiatry*, *66*(4), 341–348. https://doi.org/10.1016/j.biopsych.2009.02.031

Maurer, U., Bucher, K., Brem, S., & Brandeis, D. (2003a). Development of the automatic mismatch response: From frontal positivity in kindergarten children to the mismatch negativity. *Clinical Neurophysiology*, *114*(5), 808–817. https://doi.org/10.1016/S1388-2457(03)00032-4

Maurer, U., Bucher, K., Brem, S., & Brandeis, D. (2003b). Altered responses to tone and phoneme mismatch in kindergartners at familial dyslexia risk. *NeuroReport*, *14*(17), 2245–2250. https://doi.org/10.1097/00001756-200312020-00022

Maxon, A. B., & Hochberg, I. (1982). Development of psychoacoustic behavior: Sensitivity and discrimination. *Ear and Hearing*, *3*(6), 301–308. https://doi.org/10.1097/00003446-198211000-00003

May, P. J. C., & Tiitinen, H. (2010). Mismatch negativity (MMN), the deviance-elicited auditory deflection, explained. In *Psychophysiology* (Vol. 47, Issue 1, pp. 66–122). https://doi.org/10.1111/j.1469-8986.2009.00856.x

Mcduffie, A. S., Yoder, P. J., & Stone, W. L. (2006). Labels increase attention to novel objects in children with autism and comprehension-matched children with typical development. *Autism*, *10*(3), 288–301. https://doi.org/10.1177/1362361306063287

McFarland, D. J., McCane, L. M., David, S. V., & Wolpaw, J. R. (1997). Spatial filter selection for EEG-based communication. *Electroencephalography and Clinical Neurophysiology*, *103*(3), 386–394. https://doi.org/10.1016/S0013-4694(97)00022-2

McGettigan, C., & Scott, S. K. (2012). Cortical asymmetries in speech perception: What's wrong, what's right and what's left? *Trends in Cognitive Sciences*, *16*(5), 269–276. https://doi.org/10.1016/j.tics.2012.04.006

McGillion, M., Pine, J. M., Herbert, J. S., & Matthews, D. (2017). A randomised controlled trial to test the effect of promoting caregiver contingent talk on language development in infants from diverse socioeconomic status backgrounds. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *58*(10), 1122–1131. https://doi.org/10.1111/jcpp.12725

McKean, C., Reilly, S., Bavin, E. L., Bretherton, L., Cini, E., Conway, L., Cook, F., Eadie, P., Prior, M., Wake, M., & Mensah, F. (2017). Language outcomes at 7 years: Early predictors and co-occurring difficulties. *Pediatrics*, *139*(3), e20161684. https://doi.org/10.1542/peds.2016-1684

Meng, X., Jian, J., Shu, H., Tian, X., & Zhou, X. (2008). ERP correlates of the development of orthographical and phonological processing during Chinese sentence reading. *Brain Research*, *1219*, 91–102. https://doi.org/10.1016/J.BRAINRES.2008.04.052

Meng, X., Sai, X., Wang, C., Wang, J., Sha, S., & Zhou, X. (2005). Auditory and speech processing and reading development in Chinese school children: Behavioural and ERP evidence. *Dyslexia*, *11*(4), 292–310. https://doi.org/10.1002/dys.309

Meng, X., Tian, X., Jian, J., & Zhou, X. (2007). Orthographic and phonological processing in Chinese dyslexic children: An ERP study on sentence reading. *Brain Research*, *1179*, 119–130. https://doi.org/10.1016/J.BRAINRES.2007.08.046

Menn, Lise., & Ratner, N. Bernstein. (2000). *Methods for studying language production*. Lawrence Erlbaum Associates.

Mersad, K., & Dehaene-Lambertz, G. (2016). Electrophysiological evidence of phonetic normalization across coarticulation in infants. *Developmental Science*, *19*(5), 710–722. https://doi.org/10.1111/desc.12325

Micheyl, C., Carlyon, R. P., Gutschalk, A., Melcher, J. R., Oxenham, A. J., Rauschecker, J. P., Tian, B., & Courtenay Wilson, E. (2007). The role of auditory cortex in the formation of auditory streams. *Hearing Research*, *229*(1–2), 116–131. https://doi.org/10.1016/j.heares.2007.01.007

Micheyl, C., Hanson, C., Demany, L., Oxenham, A. J., & Shamma, S. (2013). Auditory stream segregation for alternating and synchronous tones. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(6), 1568–1580. https://doi.org/10.1037/a0032241

Millett, D. (2001). Hans Berger: From psychic energy to the EEG. *Perspectives in Biology and Medicine*, *44*(4), 522–542. https://doi.org/10.1353/pbm.2001.0070

Mills, D. L., Coffey-Corina, S. A., & Neville, H. J. (1993). Language acquisition and cerebral specialization in 20-Month-Old infants. *Journal of Cognitive Neuroscience*, *5*(3), 317–334. https://doi.org/10.1162/jocn.1993.5.3.317

Millward, K. E., Hall, R. L., Ferguson, M. A., & Moore, D. R. (2011). Training speech-in-noise perception in mainstream school children. *International Journal of Pediatric Otorhinolaryngology*, *75*(11), 1408–1417. https://doi.org/10.1016/j.ijporl.2011.08.003

Minagawa-Kawai, Y., Mori, K., Naoi, N., & Kojima, S. (2007). Neural attunement processes in infants during the acquisition of a language-specific phonemic Contrast. *Journal of Neuroscience*, *27*(2), 315–321. https://doi.org/10.1523/jneurosci.1984-06.2007

Moerel, M., De Martino, F., & Formisano, E. (2012). Processing of natural sounds in human auditory cortex: Tonotopy, spectral tuning, and relation to voice sensitivity. *Journal of Neuroscience*, *32*(41), 14205–14216. https://doi.org/10.1523/JNEUROSCI.1388-12.2012

Molfese, D. L. (1989). The use of auditory evoked responses recorded from newborn infants to predict later language skills. *Birth Defects: Original Article Series*, *25*(6), 47–62. https://nebraska.pure.elsevier.com/en/publications/the-use-of-auditory-evoked-responses-recorded-from-newborn-infant

Molfese, D. L. (1990). Auditory evoked responses recorded from 16-month-old human infants to words they did and did not know. *Brain and Language*, *38*(3), 345–363. https://doi.org/10.1016/0093-934X(90)90120-6

Molfese, D. L. (2000). Predicting dyslexia at 8 years of age using neonatal brain responses. *Brain and Language*, *72*(3), 238–245. https://doi.org/10.1006/brln.2000.2287

Molfese, D. L., & Molfese, V. J. (1985). Electrophysiological indices of auditory discrimination in newborn infants: The bases for predicting later language development? *Infant Behavior and Development*, *8*(2), 197–211. https://doi.org/10.1016/S0163-6383(85)80006-0

Molfese, D. L., & Molfese, V. J. (1997). Discrimination of language skills at five years of age using event-related potentials recorded at birth. *Developmental Neuropsychology*, *13*(2), 135–156. https://doi.org/10.1080/87565649709540674

Molfese, D. L., & Searock, K. J. (1986). The use of auditory evoked responses at one-year-of-age to predict language skills at 3-years. *Australian Journal of Human Communication Disorders*, *14*(2), 35–46. https://doi.org/10.3109/asl2.1986.14.issue-2.03

Molfese, V. J., Modglin, A., & Molfese, D. L. (2003). The role of environment in the development of reading skills: A longitudinal study of preschool and school-age measures. *Journal of Learning Disabilities*, *36*(1), 59–67. https://doi.org/10.1177/00222194030360010701

Molfese, V. J., Molfese, D. L., & Modgline, A. A. (2001). Newborn and preschool predictors of second-grade reading scores: An evaluation of categorical and continuous scores. *Journal of Learning Disabilities*, *34*(6), 545–554. https://doi.org/10.1177/002221940103400607

Molholm, S., Gomes, H., & Ritter, W. (2001). The detection of constancy amidst change in children: a dissociation of preattentive and intentional processing. *Psychophysiology*, *38*(6), 969–978. https://doi.org/10.1111/1469-8986.3860969

Molholm, S., Mercier, M. R., Liebenthal, E., Schwartz, T. H., Ritter, W., Foxe, J. J., & De Sanctis, P. (2014). Mapping phonemic processing zones along human perisylvian cortex: An electro-corticographic investigation. *Brain Structure and Function*, *219*(4), 1369–1383. https://doi.org/10.1007/s00429-013-0574-y

Molnár, M., Skinner, J. E., Csepe, V., Winkler, I., & Karmos, G. (1995). Correlation dimension changes accompanying the occurrence of the mismatch negativity and the P3 event-related potential component. *Electroencephalography and Clinical Neurophysiology*, *95*(2), 118–126. https://doi.org/10.1016/0013-4694(95)00039-2

Moon, C. (2017). Prenatal experience with the maternal voice. In M. Filippa, P. Kuhn, B. Westrup (Eds.). *Early Vocal Contact and Preterm Infant Brain Development: Bridging the Gaps Between Research and Practice* (pp. 25–37). Springer International Publishing. https://doi.org/10.1007/978-3-319-65077-7_2

Moore, B. C. J., & Gockel, H. E. (2012). Properties of auditory stream formation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1591), 919–931. https://doi.org/10.1098/rstb.2011.0355

Journal of Intellectual Disability Research, 52(6), 554–561. https://doi.org/10.1111/j.1365-2788.2008.01064.x

Moore, D. G., Goodwin, J. E., & Oates, J. M. (2008). A modified version of the Bayley Scales of Infant Development-II for cognitive matching of infants with and without Down syndrome. *Journal of Intellectual Disability Research, 52*(6), 554–561. https://doi.org/10.1111/j.1365-2788.2008.01064.x

Moore, D. R., Ferguson, M. A., Halliday, L. F., & Riley, A. (2008). Frequency discrimination in children: Perception, learning and attention. *Hearing Research*, *238*(1–2), 147–154. https://doi.org/10.1016/j.heares.2007.11.013

Moore, J. K., & Linthicum, F. H. (2001). Myelination of the human auditory nerve: different time. *Annals of Otology, Rhinology & Laryngology*, *110*(7), 655–661. https://doi.org/10.1177/000348940111000711

Moore, J. K., Perazzo, L. M., & Braun, A. (1995). Time course of axonal myelination in the human brainstem auditory pathway. *Hearing Research*, *91*(1–2), 208–209. https://doi.org/10.1016/0378-5955(95)00218-9

Morlet, D., Demarquay, G., Brudon, F., Fischer, C., & Caclin, A. (2014). Attention orienting dysfunction with preserved automatic auditory change detection in migraine. *Clinical Neurophysiology*, 500–511.

Morr, M. L., Shafer, V. L., Kreuzer, J. A., & Kurtzberg, D. (2002). Maturation of mismatch negativity in typically developing infants and preschool children. *Ear and Hearing*, *23*(2), 118–136. https://doi.org/10.1097/00003446-200204000-00005

Morrongiello, B. A., Fenwick, K. D., Hillier, L., & Chance, G. (1994). Sound localization in newborn human infants. *Developmental Psychobiology*, *27*(8), 519–538. https://doi.org/10.1002/dev.420270805

Morse, P. A. (1972). The discrimination of speech and nonspeech stimuli in early infancy. *Journal of Experimental Child Psychology*, *14*(3), 477–492. https://doi.org/10.1016/0022-0965(72)90066-5

Movshon, J. A., & Lennis, P. (1979). Pattern-selective adaptation in visual cortical neurones. *Nature*, 278 (5707), 850–852. https://doi.org/10.1038/278850a0

Muenssinger, J., Matuz, T., Schleger, F., Kiefer-Schmidt, I., Goelz, R., Wacker-Gussmann, A., Birbaumer, N., & Preissl, H. (2013a). Auditory habituation in the fetus and neonate: An fMEG study. *Developmental Science*, *16*(2), 287–295. https://doi.org/10.1111/desc.12025

Muenssinger, J., Stingl, K. T., Matuz, T., Binder, G., Ehehalt, S., & Preissl, H. (2013b). Auditory habituation to simple tones: reduced evidence for habituation in children compared to adults. *Frontiers in Human Neuroscience*, *7*, 377. https://doi.org/10.3389/fnhum.2013.00377

Müller, D., Widmann, A., & Schröger, E. (2005). Auditory streaming affects the processing of successive deviant and standard sounds. *Psychophysiology*, *42*(6), 668–676. https://doi.org/10.1111/j.1469-8986.2005.00355.x

Mundy, P., & Crowson, M. (1997). Joint attention and early social communication: Implications for research on intervention with autism. *Journal of Autism and Developmental Disorders*, *27*(6), 653–676. https://doi.org/10.1023/A:1025802832021

Mundy, P., Fox, N., & Card, J. (2003). EEG coherence, joint attention and language development in the second year. *Developmental Science*, *6*(1), 48–54. https://doi.org/10.1111/1467-7687.00253

Musacchia, G., Choudhury, N. A., Ortiz-Mantilla, S., Realpe-Bonilla, T., Roesler, C. P., & Benasich, A. A. (2013). Oscillatory support for rapid frequency change processing in infants. *Neuropsychologia*, *51*(13), 2812–2824. https://doi.org/10.1016/j.neuropsychologia.2013.09.006

Musacchia, G., Ortiz-Mantilla, S., Choudhury, N., Realpe-Bonilla, T., Roesler, C., & Benasich, A. A. (2017). Active auditory experience in infancy promotes brain plasticity in Theta and Gamma oscillations. *Developmental Cognitive Neuroscience*, *26*, 9–19. https://doi.org/10.1016/j.dcn.2017.04.004

Musacchia, G., Ortiz-Mantilla, S., Realpe-Bonilla, T., Roesler, C. P., & Benasich, A. A. (2015). Infant Auditory Processing and Event-related Brain Oscillations. *Journal of Visualized Experiments*, *101*, e52420. https://doi.org/10.3791/52420

Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioral and Brain Sciences*, *13*(2), 201–233. https://doi.org/10.1017/S0140525X00078407

Näätänen, R., & Alho, K. (1997). Mismatch negativity – The measure for central sound representation accuracy. *Audiology and Neuro-Otology*, *2*(5), 341–353. https://doi.org/10.1159/000259255

Näätänen, R., Astikainen, P., Ruusuvirta, T., & Huotilainen, M. (2010). Automatic auditory intelligence: An expression of the sensory-cognitive core of cognitive processes. *Brain Research Reviews*, *64*(1), 123–136. https://doi.org/10.1016/j.brainresrev.2010.03.001

Näätänen, R., Gaillard, A. W. K. W. K., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, *42*(4), 313–329. https://doi.org/10.1016/0001-6918(78)90006-9

Näätänen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., Iivonen, A., Vainio, M., Alku, P., Ilmoniemi, R. J., Luuk, A., Allik, J., Sinkkonen, J., & Alho, K. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature*, *385*(6615), 432–434. https://doi.org/10.1038/385432a0

Näätänen, R., Paavilainen, P., Rinne, T., & Alho, K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: a review. *Clinical Neurophysiology*, *118*(12), 2544–2590. https://doi.org/10.1016/j.clinph.2007.04.026

Näätänen, R., Paavilainen, P., Titinen, H., Jiang, D., & Alho, K. (1993). Attention and mismatch negativity. *Psychophysiology*, *30*(5), 436–450. https://doi.org/10.1111/j.1469-8986.1993.tb02067.x

Näätänen, R., Pakarinen, S., Rinne, T., & Takegata, R. (2004). The mismatch negativity (MMN): towards the optimal paradigm. *Clinical Neurophysiology*, *115*(1), 140–144. https://doi.org/10.1016/J.CLINPH.2003.04.001

Näätänen, R., & Picton, T. (1987). The N1 Wave of the Human Electric and Magnetic Response to Sound: A Review and an Analysis of the Component Structure. *Psychophysiology*, *24*(4), 375–425. https://doi.org/10.1111/j.1469-8986.1987.tb00311.x

Näätänen, R., Schröger, E., Karakas, S., Tervaniemi, M., & Paavilainen, P. (1993). Development of a memory trace for a complex sound in the human brain. *NeuroReport*, *4*(5), 503–506.

Näätänen, R., & Teder, W. (1991). Attention effects on the auditory event-related potential. *Acta Oto-Laryngologica. Supplementum*, *491*, 161–166; discussion 167. https://doi.org/10.3109/00016489109136794

Näätänen, R., Tervaniemi, M., Sussman, E., Paavilainen, P., & Winkler, I. (2001). "Primitive intelligence" in the auditory cortex. *Trends in Neurosciences*, *24*(5), 283–288. https://doi.org/10.1016/S0166-2236(00)01790-2

Näätänen, R., & Winkler, I. (1999). The concept of auditory stimulus representation in cognitive neuroscience. *Psychological Bulletin*, *125*(6), 826–859. https://doi.org/10.1037/0033-2909.125.6.826

Nacar Garcia, L., Guerrero-Mosquera, C., Colomer, M., & Sebastian-Galles, N. (2018). Evoked and oscillatory EEG activity differentiates language discrimination in young monolingual and bilingual infants. *Scientific Reports*, *8*(1), 2770. https://doi.org/10.1038/s41598-018-20824-0

Nager, W., Teder-Sälejärvi, W., Kunze, S., & Münte, T. F. (2003). Preattentive evaluation of multiple perceptual streams in human audition. *NeuroReport*, *14*(6), 871–874. https://doi.org/10.1097/00001756-200305060-00019

Nath, A. R., Fava, E. E., & Beauchamp, M. S. (2011). Neural Correlates of Interindividual Differences in Children's Audiovisual Speech Perception. *Journal of Neuroscience*, *31*(39), 13963–13971. https://doi.org/10.1523/JNEUROSCI.2605-11.2011

Nayak, B. K. (2010). Understanding the relevance of sample size calculation. *Indian Journal of Ophthalmology*, *58*(6), 469–470. https://doi.org/10.4103/0301-4738.71673

Nazzi, T., Poltrock, S., & Von Holzen, K. (2016). The Developmental Origins of the Consonant Bias in Lexical Processing. *Current Directions in Psychological Science*, *25*(4), 291–296. https://doi.org/10.1177/0963721416655786

Neill, W. T. (1979). Switching attention within and between categories: Evidence for intracategory inhibition. *Memory & Cognition*, *7*(4), 283–290. https://doi.org/10.3758/BF03197601

Nelken, I. (1997). Demonstrations of auditory scene analysis: The perceptual organization of sound. *Trends in Neurosciences*, 20(4), 185. https://doi.org/10.1016/S0166-2236(96)01022-3

Nelson, R. H. W., & Franzen, H. W. R. M. D. (1997). *Biological and Neuropsychological Mechanisms: Life-Span Developmental Psychology*. L. Erlbaum Associates.

Newman, R. S. (2005). The cocktail party effect in infants revisited: Listening to one's name in noise. *Developmental Psychology*, *41*(2), 352–362. https://doi.org/10.1037/0012-1649.41.2.352

Newman, R. S. (2011). 2-year-olds' speech understanding in multitalker environments. *Infancy*, *16*(5), 447–470. https://doi.org/10.1111/j.1532-7078.2010.00062.x

Newman, R. S., Morini, G., & Chatterjee, M. (2013). Infants' name recognition in on- and off-channel noise. *The Journal of the Acoustical Society of America*, *133*(5), EL377–EL383. https://doi.org/10.1121/1.4798269

Nie, Y., Zhang, Y., & Nelson, P. B. (2014). Auditory stream segregation using bandpass noises: Evidence from event-related potentials. *Frontiers in Neuroscience*, *8*(SEP), 277. https://doi.org/10.3389/fnins.2014.00277

Noble, K. G., Houston, S. M., Brito, N. H., Bartsch, H., Kan, E., Kuperman, J. M., Akshoomoff, N., Amaral, D. G., Bloss, C. S., Libiger, O., Schork, N. J., Murray, S. S., Casey, B. J., Chang, L., Ernst, T. M., Frazier, J. A., Gruen, J. R., Kennedy, D. N., Van Zijl, P., Mostofsky, S., Kaufmann, W. E., Kenet, T., Dale, A. M., Jernigan, T. L., & Sowell, E. R. (2015). Family income, parental education and brain structure in children and adolescents. *Nature Neuroscience*, *18*(5), 773–778. https://doi.org/10.1038/nn.3983

Noble, K. G., Norman, M. F., & Farah, M. J. (2005). Neurocognitive correlates of socioeconomic status in kindergarten children. *Developmental Science*, *8*(1), 74–87. https://doi.org/10.1111/j.1467-7687.2005.00394.x

Nordt, M., Hoehl, S., & Weigelt, S. (2016). The use of repetition suppression paradigms in developmental cognitive neuroscience. *Cortex*, *80*, 61–75. https://doi.org/10.1016/J.CORTEX.2016.04.002

Nozza, R. J. (1987). The binaural masking level difference in infants and adults: Developmental change in binaural hearing. *Infant Behavior and Development*, *10*(1), 105–110. https://doi.org/10.1016/0163-6383(87)90010-5

Nozza, R. J., Miller, S. L., Rossman, R. N., & Bond, L. C. (1991). Reliability and validity of infant speech-sound discrimination-in-noise thresholds. *Journal of Speech and Hearing Research*, *34*, 643–650. https://doi.org/10.1044/jshr.3403.643

Nozza, R. J., Rossman, R. N. F., Bond, L. C., & Miller, S. L. (1990). Infant speech-sound discrimination in noise. *The Journal of the Acoustical Society of America*, *87*(1), 339–350. https://doi.org/10.1121/1.399301

Nozza, R. J., & Wilson, W. R. (1984). Masked and unmasked pure-tone thresholds of infants and adults: development of auditory frequency selectivity and sensitivity. *Journal of Speech and Hearing Research*, *27*(4), 613–622. https://doi.org/10.1044/jshr.2704.613

Odabaee, M., Tokariev, A., Layeghy, S., Mesbah, M., Colditz, P. B., Ramon, C., & Vanhatalo, S. (2014). Neonatal EEG at scalp is focal and implies high skull conductivity in realistic neonatal head models. *NeuroImage*, *96*, 73–80. https://doi.org/10.1016/j.neuroimage.2014.04.007

Oldoni, D., De Coensel, B., Boes, M., Rademaker, M., De Baets, B., Van Renterghem, T., & Botteldooren, D. (2013). A computational model of auditory attention for use in soundscape research. *The Journal of the Acoustical Society of America*, *134*(1), 852–861. https://doi.org/10.1121/1.4807798

Olguin, A., Bekinschtein, T. A., & Bozic, M. (2018). Neural encoding of attended continuous speech under different types of interference. *Journal of Cognitive Neuroscience, 30*(11), 1606-1619. https://doi.org/10.1162/jocn_a_01303

Olsho, L. W. (1984). Infant frequency discrimination. *Infant Behavior and Development*, *7*(1), 27–35. https://doi.org/10.1016/S0163-6383(84)80020-X

Olsho, L. W., Koch, E. G., & Halpin, C. F. (1987). Level and age effects in infant frequency discrimination. *The Journal of the Acoustical Society of America*, *82*(2), 454–464. https://doi.org/10.1121/1.395446

Olsho, L. W., Schoon, C., Sakai, R., Turpin, R., & Sperduto, V. (1982). Auditory frequency discrimination in infancy. *Developmental Psychology*, *18*(5), 721–726.

Olswang, L. B., Rodriguez, B., & Timler, G. (1998). Recommending intervention for toddlers with specific language learning difficulties. *American Journal of Speech-Language Pathology*, *7*(1), 23–32. https://doi.org/10.1044/1058-0360.0701.23

Ortiz-Mantilla, S., Hämäläinen, J. A., & Benasich, A. A. (2012). Time course of ERP generators to syllables in infants: A source localization study using age-appropriate brain templates. *NeuroImage*, *59*(4), 3275–3287. https://doi.org/10.1016/j.neuroimage.2011.11.048

Ortiz-Mantilla, S., Hamalainen, J. A., Musacchia, G., & Benasich, A. A. (2013). Enhancement of gamma oscillations indicates preferential processing of native over foreign phonemic contrasts in infants. *Journal of Neuroscience*, *33*(48), 18746–18754. https://doi.org/10.1523/JNEUROSCI.3260-13.2013

Ortiz-Mantilla, S., Hamalainen, J. A., Realpe-Bonilla, T., & Benasich, A. A. (2016). Oscillatory dynamics underlying perceptual narrowing of native phoneme mapping from 6 to 12 months of age. *Journal of Neuroscience*, *36*(48), 12095–12105. https://doi.org/10.1523/jneurosci.1162-16.2016

Otero, G. A., Harmony, T., Pliego-Rivero, F. B., Ricardo-Garcell, J., Bosch-Bayard, J., Porcayo-Mercado, R., Fernández-Bouzas, A., Díaz-Comas, L., Galán, L., Vieyra-Reyes, P., & Fernández, T. (2011). QEEG norms for the first year of life. *Early Human Development*, *87*(10), 691–703. https://doi.org/10.1016/j.earlhumdev.2011.05.010

Otte, R. A., Winkler, I., Braeken, M. A. K. A., Stekelenburg, J. J., van der Stelt, O., & Van den Bergh, B. R. H. (2013). Detecting violations of temporal regularities in waking and sleeping two-month-old infants. *Biological Psychology*, *92*(2), 315–322. https://doi.org/10.1016/j.biopsycho.2012.09.009

Paavilainen, P. (2013). The mismatch-negativity (MMN) component of the auditory event-related potential to violations of abstract regularities: A review. *International Journal of Psychophysiology, 88*(2), 109–123. Elsevier. https://doi.org/10.1016/j.ijpsycho.2013.03.015

Paavilainen, P., Kaukinen, C., Koskinen, O., Kylmälä, J., & Rehn, L. (2018). Mismatch negativity (MMN) elicited by abstract regularity violations in two concurrent auditory streams. *Heliyon*, *4*(4), e00608. https://doi.org/10.1016/j.heliyon.2018.e00608

Paavilainen, P., Saarinen, J., Tervaniemi, M., & Näätänen, R. (1995). Mismatch negativity to changes in abstract sound features during dichotic listening. *Journal of Psychophysiology*, *9*(3), 243–249.

Pakarinen, S., Lovio, R., Huotilainen, M., Alku, P., Näätänen, R., & Kujala, T. (2009). Fast multi-feature paradigm for recording several mismatch negativities (MMNs) to phonetic and acoustic changes in speech sounds. *Biological Psychology*, *82*(3), 219–226. https://doi.org/10.1016/J.BIOPSYCHO.2009.07.008

Parise, E., & Csibra, G. (2012). Electrophysiological evidence for the understanding of maternal speech by 9-month-old infants. *Psychological Science*, *23*(7), 728–733. https://doi.org/10.1177/0956797612438734

Parise, E., Handl, A., Palumbo, L., & Friederici, A. D. (2011). Influence of eye gaze on spoken word processing: An ERP study with infants. *Child Development*, *82*(3), 842–853. https://doi.org/10.1111/j.1467-8624.2010.01573.x

Parise, E., Reid, V. M., Stets, M., & Striano, T. (2008). Direct eye contact influences the neural processing of objects in 5-month-old infants. *Social Neuroscience*, *3*(2), 141–150. https://doi.org/10.1080/17470910701865458

Partanen, E. (2013). *The neural basis of speech sound discrimination from infancy to adulthood*. (Unpublished Doctoral thesis, University of Helsinki, Finland). Retrieved from https://core.ac.uk/download/pdf/18616356.pdf

Partanen, E., Pakarinen, S., Kujala, T., & Huotilainen, M. (2013). Infants' brain responses for speech sound changes in fast multifeature MMN paradigm. *Clinical Neurophysiology*, *124*(8), 1578–1585. https://doi.org/10.1016/j.clinph.2013.02.014

Partanen, E., Vainio, M., Kujala, T., & Huotilainen, M. (2011). Linguistic multifeature MMN paradigm for extensive recording of auditory discrimination profiles. *Psychophysiology*, *48*(10), 1372–1380. https://doi.org/10.1111/j.1469-8986.2011.01214.x

Parviainen, T., Helenius, P., & Salmelin, R. (2005). Cortical differentiation of speech and nonspeech sounds at 100 ms: Implications for dyslexia. *Cerebral Cortex*, *15*(7), 1054–1063. https://doi.org/10.1093/cercor/bhh206

Paterson, S. J., Heim, S., Thomas Friedman, J., Choudhury, N., & Benasich, A. A. (2006). Development of structure and function in the infant brain: Implications for cognition, language and social behaviour. *Neuroscience and Biobehavioral Reviews*, *30*(8), 1087–1105. https://doi.org/10.1016/j.neubiorev.2006.05.001

Patil, K., & Elhilali, M. (2013). Task-driven attentional mechanisms for auditory scene recognition. *ICASSP, IEEE International Conference on Acoustics, Speech and Signal Processing - Proceedings*, 828–832. https://doi.org/10.1109/ICASSP.2013.6637764

Pearce, J. W., Crowell, D. H., Tokioka, A., & Pacheco, G. P. (1989). Childhood developmental changes in the auditory P300. *Journal of Child Neurology*, *4*(2), 100–106. https://doi.org/10.1177/088307388900400204

Peck, J. E. (1995). Development of hearing. Part III. Postnatal development. *Journal of the American Academy of Audiology*, *6*(2), 113–123.

Pekkonen, E., Katila, H., Ahveninen, J., Karhu, J., Huotilainen, M., & Tiihonen, J. (2002). Impaired temporal lobe processing of preattentive auditory discrimination in schizophrenia. *Schizophrenia Bulletin*, *28*(3), 467–474.

Pekkonen, E., Rinne, T., & Näätänen, R. (1995). Variability and replicability of the mismatch negativity. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *96*(6), 546–554. https://doi.org/10.1016/0013-4694(95)00148-R

Pekkonen, E., Rinne, T., Reinikainen, K., Kujala, T., Alho, K., & Näätänen, R. (1996). Aging effects on auditory processing: An event-related potential study. *Experimental Aging Research*, *22*(2), 171–184. https://doi.org/10.1080/03610739608254005

Perani, D., Saccuman, M. C., Scifo, P., Anwander, A., Spada, D., Baldoli, C., Poloniato, A., Lohmann, G., & Friederici, A. D. (2011). Neural language networks at birth. *Proceedings of the National Academy of Sciences*, *108*(38), 16056–16061. https://doi.org/10.1073/pnas.1102991108

Petanjek, Z., Judas, M., Simic, G., Rasin, M. R., Uylings, H. B. M., Rakic, P., & Kostovic, I. (2011). Extraordinary neoteny of synaptic spines in the human prefrontal cortex. *Proceedings of the National Academy of Sciences*, *108*(32), 13281–13286. https://doi.org/10.1073/pnas.1105108108

Pham, M. T., Rajić, A., Greig, J. D., Sargeant, J. M., Papadopoulos, A., & Mcewen, S. A. (2014). A scoping review of scoping reviews: Advancing the approach and enhancing the consistency. *Research Synthesis Methods*, *5*(4), 371–385. https://doi.org/10.1002/jrsm.1123

Phélip, M., Donnot, J., & Vauclair, J. (2016). Auditory orienting of attention: Effects of cues and verbal workload with children and adults. *Child Neuropsychology*, *22*(6), 692–706. https://doi.org/10.1080/09297049.2015.1041368

Phillips, C., Pellathy, T., Marantz, A., Yellin, E., Wexler, K., Poeppel, D., McGinnis, M., & Roberts, T. (2000). Auditory cortex accesses phonological categories: An MEG mismatch study. *Journal of Cognitive Neuroscience*, *12*(6), 1038–1055. https://doi.org/10.1162/08989290051137567

Picton, T. W. (1992). The P300 wave of the human event-related potential. *Journal of Clinical Neurophysiology*, *9*(4), 456–479. https://doi.org/10.1097/00004691-199210000-00002

Picton, T. W. (1994). Hallowell Davis and evoked potential audiometry. *The Journal of the Acoustical Society of America*, *95*(5), 2866–2867. https://doi.org/10.1121/1.408722

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., Miller, G. A., Ritter, W., Ruchkin, D. S., Rugg, M. D., & Taylor, M. J. (2000).

Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology*, *37*(2), 127–152.

Picton, T. W., Lins, O. G., & Scherg, M. (1995). The recording and analysis of event-related potentials. *Handbook of Neuropsychology*, *10*(August 2015), 3–73.

Picton, T. W., & Taylor, M. J. (2007). Electrophysiological evaluation of human brain development. *Developmental Neuropsychology*, *31*(3), 249–278. https://doi.org/10.1080/87565640701228732

Piñon, M. (2010). Theoretical background and structure of the Bayley Scales of Infant and Toddler Development, Third Edition. *Bayley-III Clinical Use and Interpretation*, 1–28. https://doi.org/10.1016/B978-0-12-374177-6.10001-7

Polka, L., Rvachew, S., & Molnar, M. (2008). Speech perception by 6- to 8-month-olds in the presence of distracting sounds. *Infancy*, *13*(5), 421–439. https://doi.org/10.1080/15250000802329297

Ponton, C. W., Eggermont, J. J., Kwong, B., & Don, M. (2000). Maturation of human central auditory system activity: Evidence from multi-channel evoked potentials. *Clinical Neurophysiology*, *111*(2), 220–236. https://doi.org/10.1016/S1388-2457(99)00236-9

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Poulsen, C., Picton, T. W., & Paus, T. (2009). Age-related changes in transient and oscillatory brain responses to auditory stimulation during early adolescence. *Developmental Science*, *12*(2), 220–235. https://doi.org/10.1111/j.1467-7687.2008.00760.x

Preissl, H., Lowery, C. L., & Eswaran, H. (2004). Fetal magnetoencephalography: Current progress and trends. *Experimental Neurology*, *190*(SUPPL. 1), S28-36. https://doi.org/10.1016/j.expneurol.2004.06.016

Presacco, A., Simon, J. Z., & Anderson, S. (2016). Evidence of degraded representation of speech in noise, in the aging midbrain and cortex. *Journal of Neurophysiology*, *116*(5), 2346–2355. https://doi.org/10.1152/jn.00372.2016

Pressnitzer, D., Sayles, M., Micheyl, C., & Winter, I. M. (2008). Perceptual Organization of sound begins in the auditory periphery. *Current Biology*, *18*(15), 1124–1128. https://doi.org/10.1016/j.cub.2008.06.053

Puolakanaho, A., Ahonen, T., Aro, M., Eklund, K., Leppänen, P. H. T., Poikkeus, A. M., Tolvanen, A., Torppa, M., & Lyytinen, H. (2008). Developmental links of very early phonological and language skills to second grade reading outcomes: Strong to accuracy but only minor to fluency. *Journal of Learning Disabilities*, *41*(4), 353–370. https://doi.org/10.1177/0022219407311747

Putkinen, V., Niinikuru, R., Lipsanen, J., Tervaniemi, M., & Huotilainen, M. (2012). Fast measurement of auditory event-related potential profiles in 2-3-year-olds. *Developmental Neuropsychology*, *37*(1), 51–75. https://doi.org/10.1080/87565641.2011.615873

Putkinen, V., Tervaniemi, M., & Huotilainen, M. (2013). Informal musical activities are linked to auditory discrimination and attention in 2-3-year-old children: An event-related potential study. *European Journal of Neuroscience*, *37*(4), 654–661. https://doi.org/10.1111/ejn.12049

Putkinen, V., Tervaniemi, M., & Huotilainen, M. (2019). Musical playschool activities are linked to faster auditory development during preschool-age: a longitudinal ERP study. *Scientific Reports*, *9*(1), 11310. https://doi.org/10.1038/s41598-019-47467-z

Qin, Y., Xin, X., Zhu, H., Li, F., Xiong, H., Zhang, T., & Lai, Y. (2017). A comparative study on the dynamic EEG center of mass with different references. *Frontiers in Neuroscience*, *11*, 509. https://doi.org/10.3389/fnins.2017.00509

Ragó, A., Honbolygó, F., Róna, Z., Beke, A., & Csépe, V. (2014). Effect of maturation on suprasegmental speech processing in full- and preterm infants: A mismatch negativity study. *Research in Developmental Disabilities*, *35*(1), 192–202. https://doi.org/10.1016/j.ridd.2013.10.006

Ramus, F., Nespor, M., & Mehler, J. (1999). Correlates of linguistic rhythm in the speech signal. *Cognition*, *73*(3), 265–292. https://doi.org/10.1016/S0010-0277(99)00058-X

Rand, K., & Lahav, A. (2014). Maternal sounds elicit lower heart rate in preterm newborns in the first month of life. *Early Human Development*, *90*(10), 679–683. https://doi.org/10.1016/j.earlhumdev.2014.07.016

Rauschecker, J. P. (1998). Cortical processing of complex sounds. *Current Opinion in Neurobiology*, *8*(4), 516–521. https://doi.org/10.1016/S0959-4388(98)80040-8

Rescorla, L., Mirak, J., & Singh, L. (2000). Vocabulary growth in late talkers: Lexical development from 2;0 to 3;0. *Journal of Child Language*, *27*(2), 293–311. https://doi.org/10.1017/S030500090000413X

Rickman, P. P. (1964). Human Experimentation: Code of Ethics of The World Medical Association. Declaration of Helsinki. *British Medical Journal*, *2*(5402), 177.

Ridgeway, D., Waters, E., & Kuczaj, S. A. (1985). Acquisition of emotion-descriptive language. Receptive and productive vocabulary norms for ages 18 months to 6 years. *Developmental Psychology*, *21*(5), 901–908. https://doi.org/10.1037/0012-1649.21.5.901

Rihs, T. A., Tomescu, M. I., Britz, J., Rochas, V., Custo, A., Schneider, M., Debbané, M., Eliez, S., & Michel, C. M. (2013). Altered auditory processing in frontal and left temporal cortex in 22q11.2 deletion syndrome: A group at high genetic risk for schizophrenia. *Psychiatry Research - Neuroimaging*, *212*(2), 141–149. https://doi.org/10.1016/j.pscychresns.2012.09.002

Rinne, T., Alho, K., Ilmoniemi, R. J., Virtanen, J., & Näätänen, R. (2000). Separate time behaviors of the temporal and frontal mismatch negativity sources. *NeuroImage*, *12*(1), 14–19. https://doi.org/10.1006/nimg.2000.0591

Ritter, W., Paavilainen, P., Lavikainen, J., Reinikainen, K., Alho, K., Sams, M., & Näätänen, R. (1992). Event-related potentials to repetition and change of auditory stimuli. *Electroencephalography and Clinical Neurophysiology*, *83*(5), 306–321. https://doi.org/10.1016/0013-4694(92)90090-5

Riva, V., Cantiani, C., Benasich, A. A., Molteni, M., Piazza, C., Giorda, R., Dionne, G., & Marino, C. (2018). From CNTNAP2 to early expressive language in infancy: The mediation role of rapid auditory processing. *Cerebral Cortex*, *28*(6), 1–9. https://doi.org/10.1093/cercor/bhx115

Rivera-Gaxiola, M., Silva-Pereyra, J., & Kuhl, P. K. (2005). Brain potentials to native and non-native speech contrasts in 7- and 11 -month-old American infants. *Developmental Science*, *8*(2), 162–172. https://doi.org/10.1111/j.1467-7687.2005.00403.x

Rocha-Muniz, C. N., Befi-Lopes, D. M., & Schochat, E. (2015). Mismatch negativity in children with specific language impairment and auditory processing disorder. *Brazilian Journal of Otorhinolaryngology*, *81*(4), 408–415. https://doi.org/10.1016/j.bjorl.2014.08.022

Romanski, L. M., Tian, B., Fritz, J., Mishkin, M., Goldman-Rakic, P. S., & Rauschecker, J. P. (1999). Dual streams of auditory afferents target multiple domains in the primate prefrontal cortex. *Nature Neuroscience*, *2*(12), 1131–1136. https://doi.org/10.1038/16056

Rosch, R. E., Auksztulewicz, R., Leung, P. D., Friston, K. J., & Baldeweg, T. (2017). NMDA receptor blockade causes selective prefrontal disinhibition in a roving auditory oddball paradigm. *BioRxiv*. https://doi.org/10.5281/zenodo.570595

Rosch, R. E., Auksztulewicz, R., Leung, P. D., Friston, K. J., & Baldeweg, T. (2019). Selective Prefrontal Disinhibition in a Roving Auditory Oddball Paradigm Under N-Methyl-D-Aspartate Receptor Blockade. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *4*(2), 140–150. https://doi.org/10.1016/j.bpsc.2018.07.003

Rosselli, M., Ardila, A., Matute, E., & Vélez-Uribe, I. (2014). Language Development across the Life Span: A Neuropsychological/Neuroimaging Perspective. *Neuroscience Journal*, *2014*, 1–21. https://doi.org/10.1155/2014/585237

Rost, G. C., & McMurray, B. (2009). Speaker variability augments phonological processing in early word learning. *Developmental Science*, *12*(2), 339–349. https://doi.org/10.1111/j.1467-7687.2008.00786.x

Roth, G., & Dicke, U. (2005). Evolution of the brain and intelligence. *Trends in Cognitive Sciences*, *9*(5), 250–257. https://doi.org/10.1016/j.tics.2005.03.005

Roulstone, S., Law, J., Rush, R., Clegg, J., & Peters, T. (2011). *DFE-RB134 The role of language in children's early educational outcomes*.

Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., & Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia*, *42*(8), 1029–1040. https://doi.org/10.1016/j.neuropsychologia.2003.12.012

Ruggles, D., Bharadwaj, H., & Shinn-Cunningham, B. G. (2011). Normal hearing is not enough to guarantee robust encoding of suprathreshold features important in everyday communication. *Proceedings of the National Academy of Sciences*, *108*(37), 15516–15521. https://doi.org/10.1073/pnas.1108912108

Sakabe, N., Arayama, T., & Suzuki, T. (1969). Human fetal evoked response to acoustic stimulation. *Acta Oto-Laryngologica. Supplementum*, *252*(sup252), 29–36. https://doi.org/10.3109/00016486909120512

Sampallo Pedroza, R. M., Cardona Lopez, L. F., & Ramirez Gomez, K. E. (2015). Description of oral-motor development from birth to six years of age. *Revista de La Facultad de Medicina*, *62*(4), 593–604. https://doi.org/10.15446/revfacmed.v62n4.45211

Sams, M., Hari, R., Rif, J., & Knuutila, J. (1993). The human auditory sensory memory trace persists about 10 sec: Neuromagnetic evidence. *Journal of Cognitive Neuroscience*, *5*(3), 363–370. https://doi.org/10.1162/jocn.1993.5.3.363

Sams, M., Paavilainen, P., Alho, K., & Näätänen, R. (1985). Auditory frequency discrimination and event-related potentials. *Electroencephalography and*

Clinical Neurophysiology/ Evoked Potentials, *62*(6), 437–448. https://doi.org/10.1016/0168-5597(85)90054-1

Sanders, L. D., Stevens, C., Coch, D., & Neville, H. J. (2006). Selective auditory attention in 3- to 5-year-old children: An event-related potential study. *Neuropsychologia*, *44*(11), 2126–2138. https://doi.org/10.1016/j.neuropsychologia.2005.10.007

Sawyer, R. (1997). Pretend play as improvisation: conversation in the preschool classroom. *Choice Reviews Online*, 35(1). https://doi.org/10.5860/choice.35-0592

Schaadt, G., Männel, C., van der Meer, E., Pannekamp, A., Oberecker, R., & Friederici, A. D. (2015). Present and past: Can writing abilities in school children be associated with their auditory discrimination capacities in infancy? *Research in Developmental Disabilities*, *47*, 318–333. https://doi.org/10.1016/j.ridd.2015.10.002

Schaadt, G., Pannekamp, A., & van der Meer, E. (2014). Gaining mismatch negativity! Improving auditory phoneme discrimination by literacy training – A pre-post event-related potential study. *International Journal of School and Cognitive Psychology*, *1*(1), 1–8. https://doi.org/10.4172/2469-9837.1000101

Scherg, M., Vajsar, J., & Picton, T. W. (1989). A source analysis of the late human auditory evoked potentials. *Journal of Cognitive Neuroscience*, *1*(4), 336–355. https://doi.org/10.1162/jocn.1989.1.4.336

Schneider, B. A., Li, L., & Daneman, M. (2007). How competing speech interferes with speech comprehension in everyday listening situations. *Journal of the American Academy of Audiology*, *18*(7), 559–572. https://doi.org/10.3766/jaaa.18.7.4

Schneider, B. A., Morrongiello, B. A., & Trehub, S. E. (1990). Size of critical band in infants, children, and adults. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(3), 642–652. https://doi.org/10.1037/0096-1523.16.3.642

Schneider, B. A., Parker, S., & Murphy, D. (2011). A model of top-down gain control in the auditory system. *Attention, Perception, and Psychophysics*, *73*(5), 1562–1578. https://doi.org/10.3758/s13414-011-0097-7

Schneider, B. A., Trehub, S. E., & Bull, D. (1979). The development of basic auditory processes in infants. *Canadian Journal of Psychology*, *33*(4), 306–319. https://doi.org/10.1037/h0081728

Schneider, B. A., Trehub, S. E., Morrongiello, B. A., & Thorpe, L. A. (1989). Developmental changes in masked thresholds. *The Journal of the Acoustical Society of America*, *86*(5), 1733–1742. https://doi.org/10.1121/1.398604

Schneider, W. F. (1938). Reading, Writing and Speech Problems in Children. (1938). *Nature, 141*(3579), 997–997. https://doi.org/10.1038/141997c0

Schoenemann, P. T. (2009). Brain Evolution Relevant to Language. In J. W., Minett, W. S-Y. Wang (Eds.). *Language, Evolution, and the Brain*. City University of Hong Kong Press.

Schröger, E. (1997). On the detection of auditory deviations: A preattentive activation model. *Psychophysiology*, *34*(3), 245–257. https://doi.org/10.1111/j.1469-8986.1997.tb02395.x

Schröger, E. (1998). Measurement and interpretation of the mismatch negativity. *Behavior Research Methods, Instruments, & Computers*, *30*(1), 131–145. https://doi.org/10.3758/BF03209423

Schröger, E., & Winkler, I. (1995). Presentation rate and magnitude of stimulus deviance effects on human preattentive change detection. *Neuroscience Letters*, *193*(3), 185–188. https://doi.org/10.1016/0304-3940(95)11696-T

Schuele, C. M. (1998). Socioeconomic Influences on Children's Language Acquisition Incidences socioeconomiques sur l'acquisition du langage chez les enfants. *Revue*, *25*(2).

Schulte-Körne, G., Deimel, W., Bartling, J., & Remschmidt, H. (2001). Speech perception deficit in dyslexic adults as measured by mismatch negativity (MMN). *International Journal of Psychophysiology*, *40*(1), 77–87. https://doi.org/10.1016/S0167-8760(00)00152-5

Scott, S. K. (2000). Identification of a pathway for intelligible speech in the left temporal lobe. *Brain*, *123*(12), 2400–2406. https://doi.org/10.1093/brain/123.12.2400

Scott, S. K., & Wise, R. J. S. (2004). The functional neuroanatomy of prelexical processing in speech perception. *Cognition*, *92*(1–2), 13–45. https://doi.org/10.1016/j.cognition.2002.12.002

Sculthorpe, L. D., & Campbell, K. B. (2011). Evidence that the mismatch negativity to pattern violations does not vary with deviant probability. *Clinical Neurophysiology*, *122*(11), 2236–2245. https://doi.org/10.1016/j.clinph.2011.04.018

Seeck, M., Koessler, L., Bast, T., Leijten, F., Michel, C., Baumgartner, C., He, B., & Beniczky, S. (2017). The standardized EEG electrode array of the IFCN. *Clinical Neurophysiology*, *128*(10), 2070–2077. https://doi.org/10.1016/j.clinph.2017.06.254

Seery, A., Tager-Flusberg, H., & Nelson, C. A. (2014). Event-related potentials to repeated speech in 9-month-old infants at risk for autism spectrum disorder. *Journal of Neurodevelopmental Disorders*, *6*(1), 1–12. https://doi.org/10.1186/1866-1955-6-43

Segalowitz, S. J., & Barnes, K. L. (1993). The reliability of ERP components in the auditory oddball paradigm. *Psychophysiology*, *30*(5), 451–459. https://doi.org/10.1111/j.1469-8986.1993.tb02068.x

Shafer, V. L., Morr, M. L., Kreuzer, J. A., & Kurtzberg, D. (2000). Maturation of mismatch negativity in school-age children. *Ear and Hearing*, *21*(3), 242–251. https://doi.org/10.1097/00003446-200006000-00008

Shafer, V. L., Ponton, C., Datta, H., Morr, M. L., & Schwartz, R. G. (2007). Neurophysiological indices of attention to speech in children with specific language impairment. *Clinical Neurophysiology*, *118*(6), 1230–1243. https://doi.org/10.1016/j.clinph.2007.02.023

Shafer, V. L., Yu, Y. H., & Datta, H. (2010). Maturation of speech discrimination in 4- to 7-yr-old children as indexed by event-related potential mismatch responses. *Ear and Hearing*, *31*(6), 735–745. https://doi.org/10.1097/AUD.0b013e3181e5d1a7

Shafer, V. L., Yu, Y. H., & Datta, H. (2011). The development of English vowel perception in monolingual and bilingual infants: Neurophysiological correlates. *Journal of Phonetics*, *39*(4), 527–545. https://doi.org/10.1016/j.wocn.2010.11.010

Shafer, V. L., Yu, Y. H., & Garrido-Nag, K. (2012). Neural mismatch indices of vowel discrimination in monolingually and bilingually exposed infants: Does attention matter? *Neuroscience Letters, 526*(1), 10-14. https://doi.org/10.1016/j.neulet.2012.07.064

Shafer, V. L., Yu, Y. H., & Wagner, M. (2015). Maturation of cortical auditory evoked potentials (CAEPs) to speech recorded from frontocentral and temporal sites: Three months to eight years of age. *International Journal of Psychophysiology*, *95*(2), 77–93. https://doi.org/10.1016/j.ijpsycho.2014.08.1390

Shah, A. S., Bressler, S. L., Knuth, K. H., Ding, M., Mehta, A. D., Ulbert, I., & Schroeder, C. E. (2004). Neural dynamics and the fundamental mechanisms of event-related brain potentials. *Cerebral Cortex*, *14*(5), 476–483. https://doi.org/10.1093/cercor/bhh009

Shankarnarayan, V. C., & Maruthy, S. (2007). Mismatch negativity in children with dyslexia speaking Indian languages. *Behavioral and Brain Functions*, *3*, 36. https://doi.org/10.1186/1744-9081-3-36

Shannon, C. E. (1949). Communication in the presence of noise. *Proceedings of the Institute of Radio Engineers*, *37*(1), 10–21.

Sharma, A., Kraus, N., J. McGee, T., & Nicol, T. G. (1997). Developmental changes in P1 and N1 central auditory responses elicited by consonant-vowel syllables. *Electroencephalography and Clinical Neurophysiology - Evoked Potentials*, *104*(6), 540–545. https://doi.org/10.1016/S0168-5597(97)00050-6

Sharma, M., Purdy, S. C., Munro, K. J., Sawaya, K., & Peter, V. (2013). Effects of broadband noise on cortical evoked auditory responses at different loudness levels in young adults. *NeuroReport*, 1. https://doi.org/10.1097/WNR.0000000000000089

Sharma, M., Purdy, S. C., Newall, P., Wheldall, K., Beaman, R., & Dillon, H. (2006). Electrophysiological and behavioral evidence of auditory processing deficits in children with reading disorder. *Clinical Neurophysiology*, *117*(5), 1130–1144. https://doi.org/10.1016/j.clinph.2006.02.001

Shaw, K., Baart, M., Depowski, N., & Bortfeld, H. (2015). Infants' preference for native audiovisual speech dissociated from congruency preference. *PLoS ONE*, *10*(4), e0126059. https://doi.org/10.1371/journal.pone.0126059

Shestakova, A., Huotilainen, M., Čeponiené, R., & Cheour, M. (2003). Event-related potentials associated with second language learning in children. *Clinical Neurophysiology*, *114*(8), 1507–1512. https://doi.org/10.1016/S1388-2457(03)00134-2

Shields, M. M. (1979). Dialogue, monologue and egocentric speech by children in nursery schools. In O.K.Garnica, M. L. King (Eds.). *Language, Children and Society*, 249–269. Pergamon. https://doi.org/10.1016/b978-0-08-023716-9.50023-9

Shimpi, P., & Waterfall, H. (2019). Spatial terms: The acquisition of multiple referential and syntactic mappings. *Frontiers in Communication*, *4*, 66. https://doi.org/10.3389/fcomm.2019.00066

Shinn-Cunningham, B. (2009). Auditory attention and the active listener. *The Journal of the Acoustical Society of America*, *125*(4), 2651–2651. https://doi.org/10.1121/1.4784150

Shinn-Cunningham, B. G. (2006). Spatial auditory attention. *The Journal of the Acoustical Society of America*, *119*(5), 3416. https://doi.org/10.1121/1.4786819

Shultz, S., & Vouloumanos, A. (2010). Three-month-olds prefer speech to other naturally occurring signals. *Language Learning and Development*, *6*(4), 241–257. https://doi.org/10.1080/15475440903507830

Shultz, S., Vouloumanos, A., Bennett, R. H., & Pelphrey, K. (2014). Neural specialization for speech in the first months of life. *Developmental Science*, *17*(5), 766–774. https://doi.org/10.1111/desc.12151

Sigman, M., & McGovern, C. W. (2005). Improvement in cognitive and language skills from preschool to adolescence in autism. *Journal of Autism and Developmental Disorders*, *35*(1), 15–23. https://doi.org/10.1007/s10803-004-1027-5

Šimleša, S., & Cepanec, M. (2015). Development of executive functions during childhood. In J. Wright (Ed.). *International Encyclopedia of the Social & Behavioral Sciences: Second Edition* (pp. 489–496). Elsevier. https://doi.org/10.1016/B978-0-08-097086-8.23083-3

Skoe, E., Krizman, J., & Kraus, N. (2013). The impoverished brain: disparities in maternal education affect the neural response to sound. *Journal of Neuroscience*, *33*(44), 17221–17231. https://doi.org/10.1523/JNEUROSCI.2102-13.2013

Smith, N. A., & Trainor, L. J. (2011). Auditory stream segregation improves infants' selective attention to target tones amid distracters. *Infancy*, *16*(6), 655–668. https://doi.org/10.1111/j.1532-7078.2011.00067.x

Snell, J., & Andrews, R. (2017). To what extent does a regional dialect and accent impact on the development of reading and writing skills? *Cambridge Journal of Education*, 47(3), 489-496. https://doi.org/10.1080/0305764X.2016.1159660

Snyder, J. S., & Alain, C. (2005). Age-related changes in neural activity associated with concurrent vowel segregation. *Cognitive Brain Research*, *24*(3), 492–499. https://doi.org/10.1016/j.cogbrainres.2005.03.002

Snyder, J. S., & Alain, C. (2007). Toward a neurophysiological theory of auditory stream segregation. *Psychological Bulletin*, *133*(5), 780–799. https://doi.org/10.1037/0033-2909.133.5.780

Snyder, J. S., Alain, C., & Picton, T. W. (2006). Effects of attention on neuroelectric correlates of auditory stream segregation. *Journal of Cognitive Neuroscience*, *18*(1), 1–13. https://doi.org/10.1162/089892906775250021

Snyder, J. S., Holder, W. T., Weintraub, D. M., Carter, O. L., & Alain, C. (2009). Effects of prior stimulus and prior perception on neural correlates of auditory stream segregation. *Psychophysiology*, *46*(6), 1208–1215. https://doi.org/10.1111/j.1469-8986.2009.00870.x

Soleimani, F., Azari, N., Vameghi, R., Sajedi, F., Shahshahani, S., Karimi, H., Kraskian, A., Shahrokhi, A., Teymouri, R., & Gharib, M. (2016). Is the Bayley Scales of Infant and Toddler Developmental Screening Test, valid and reliable for Persian speaking children? *Iranian Journal of Pediatrics*, *26*(5), e5540. https://doi.org/10.5812/ijp.5540

Sorokin, A., Alku, P., & Kujala, T. (2010). Change and novelty detection in speech and non-speech sound streams. *Brain Research*, *1327*, 77–90. https://doi.org/10.1016/J.BRAINRES.2010.02.052

Specht, K. (2014). Neuronal basis of speech comprehension. *Hearing Research*, *307*(0378), 121–135. https://doi.org/10.1016/j.heares.2013.09.011

Spencer, S., Clegg, J., & Stackhouse, J. (2012). Language and disadvantage: A comparison of the language abilities of adolescents from two different socioeconomic areas. *International Journal of Language and Communication Disorders, 47*(3), 274–284. https://doi.org/10.1111/j.1460-6984.2011.00104.x

Sperdin, H. F., & Schaer, M. (2016). Aberrant development of speech processing in young children with autism: New insights from neuroimaging biomarkers. *Frontiers in Neuroscience*, *10*(AUG), 393. https://doi.org/10.3389/fnins.2016.00393

Spinelli, M., Fasolo, M., Shah, P. E., Genovese, G., & Aureli, T. (2018). The influence of early temperament on language development: The moderating role of maternal input. *Frontiers in Psychology*, *9*, 1527. https://doi.org/10.3389/fpsyg.2018.01527

Squires, N. K., Squires, K. C., & Hillyard, S. A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and Clinical Neurophysiology*, *38*(4), 387–401. https://doi.org/10.1016/0013-4694(75)90263-1

Starr, A., & Brannon, E. M. (2015). Evolutionary and developmental continuities in numerical cognition. *Evolutionary Origins and Early Development of Number Processing*, *1*, 123–144. https://doi.org/10.1016/B978-0-12-420133-0.00005-3

Starr, A., Libertus, M. E., & Brannon, E. M. (2013). Number sense in infancy predicts mathematical abilities in childhood. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(45), 18116–18120. https://doi.org/10.1073/pnas.1302751110

Stefanics, G., Háden, G. P., Sziller, I., Balázs, L., Beke, A., & Winkler, I. (2009). Newborn infants process pitch intervals. *Clinical Neurophysiology*, *120*(2), 304–308. https://doi.org/10.1016/j.clinph.2008.11.020

Steinbrink, C., Zimmer, K., Lachmann, T., Dirichs, M., & Kammer, T. (2014). Development of rapid temporal processing and its impact on literacy skills in primary school children. *Child Development*, *85*(4), 1711–1726. https://doi.org/10.1111/cdev.12208

Sterne, J. A. C., Smith, G. D., & Cox, D. R. (2001). Sifting the evidence-what's wrong with significance tests? *Physical Therapy*, *81*(8), 1464–1469. https://doi.org/10.1136/bmj.322.7280.226

Stevens, C., & Bavelier, D. (2012). The role of selective attention on academic foundations: A cognitive neuroscience perspective. *Developmental Cognitive Neuroscience*, *2*(SUPPL. 1), S30–S48. https://doi.org/10.1016/j.dcn.2011.11.001

Stevens, C., Fanning, J., Coch, D., Sanders, L., & Neville, H. (2008). Neural mechanisms of selective auditory attention are enhanced by computerized training: Electrophysiological evidence from language-impaired and typically developing children. *Brain Research*, *1205*, 55–69. https://doi.org/10.1016/j.brainres.2007.10.108

Stevens, C., Lauinger, B., & Neville, H. (2009). Differences in the neural mechanisms of selective attention in children from different socioeconomic backgrounds: An event-related brain potential study. *Developmental Science*, *12*(4), 634–646. https://doi.org/10.1111/j.1467-7687.2009.00807.x

Stevens, C., Paulsen, D., Yasen, A., & Neville, H. (2015). Atypical auditory refractory periods in children from lower socio-economic status backgrounds: ERP evidence for a role of selective attention. *International Journal of Psychophysiology*, *95*(2), 156–166. https://doi.org/10.1016/j.ijpsycho.2014.06.017

Stevens, C., Sanders, L., & Neville, H. (2006). Neurophysiological evidence for selective auditory attention deficits in children with specific language impairment. *Brain Research*, *1111*(1), 143–152. https://doi.org/10.1016/j.brainres.2006.06.114

Stewart, H. J. (2016). *Auditory selective attention in typical development and auditory processing disorder*. (Unpublished Doctoral thesis, University of Nottingham). Retrieved from HJSthesis_DONEonesided_eClinks.pdf (nottingham.ac.uk)

Stiles, J., & Jernigan, T. L. (2010). The basics of brain development. *Neuropsychology Review*, *20*(4), 327–348. https://doi.org/10.1007/s11065-010-9148-4

Stokes, S. F., & Klee, T. (2009). Factors that influence vocabulary development in two-year-old children. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *50*(4), 498–505. https://doi.org/10.1111/j.1469-7610.2008.01991.x

Strait, D. L., Slater, J., Abecassis, V., & Kraus, N. (2014). Cortical response variability as a developmental index of selective auditory attention. *Developmental Science*, *17*(2), 175–186. https://doi.org/10.1111/desc.12107

Strotseva-Feinschmidt, A., Cunitz, K., Friederici, A. D., & Gunter, T. C. (2015). Auditory discrimination between function words in children and adults: A mismatch negativity study. *Frontiers in Psychology*, *6*(DEC), 1930. https://doi.org/10.3389/fpsyg.2015.01930

Su, P., Kuan, C. C., Kaga, K., Sano, M., & Mima, K. (2008). Myelination progression in language-correlated regions in brain of normal children determined by quantitative MRI assessment. *International Journal of Pediatric*

Otorhinolaryngology, *72*(12), 1751–1763. https://doi.org/10.1016/j.ijporl.2008.05.017

Sugase-Miyamoto, Y., Liu, Z., Wiener, M. C., Optican, L. M., & Richmond, B. J. (2008). Short-term memory trace in rapidly adapting synapses of inferior temporal cortex. *PLoS Computational Biology*, *4*(5), e1000073. https://doi.org/10.1371/journal.pcbi.1000073

Sur, S., & Sinha, V. K. (2009). Event-related potential: An overview. *Industrial Psychiatry Journal*, *18*(1), 70–73. https://doi.org/10.4103/0972-6748.57865

Sussman, E., Ritter, W., & Vaughan, H. G. (1998). Attention affects the organization of auditory input associated with the mismatch negativity system. *Brain Research*, *789*(1), 130–138. https://doi.org/10.1016/S0006-8993(97)01443-1

Sussman, E. S. (2004). Integration and segregation in auditory scene analysis. *Journal of the Acoustical Society of America*, *117*(3), 1285–1298. https://doi.org/10.1121/1.1854312

Sussman, E. S. (2017). Auditory scene analysis: An attention perspective. *Journal of Speech, Language, and Hearing Research: JSLHR*, *60*(10), 2989–3000. https://doi.org/10.1044/2017_JSLHR-H-17-0041

Sussman, E. S., Bregman, A. S., Wang, W. J., & Khan, F. J. (2005). Attentional modulation of electrophysiological activity in auditory cortex for unattended sounds within multistream auditory environments. *Cognitive, Affective and Behavioral Neuroscience*, *5*(1), 93–110. https://doi.org/10.3758/CABN.5.1.93

Sussman, E. S., Chen, S., Sussman-Fort, J., & Dinces, E. (2014). The five myths of MMN: Redefining how to Use MMN in basic and clinical research. *Brain Topography*, *27*(4), 553–564. https://doi.org/10.1007/s10548-013-0326-6

Sussman, E. S., Horváth, J., Winkler, I., & Orr, M. (2007). The role of attention in the formation of auditory streams. *Perception & Psychophysics*, *69*(1), 136–152. https://doi.org/10.3758/BF03194460

Sussman, E. S., Ritter, W., & Vaughan, H. G. (1999). An investigation of the auditory streaming effect using event-related brain potentials. *Psychophysiology*, *36*(1), 22–34. https://doi.org/10.1017/S0048577299971056

Sussman, E. S., Winkler, I., & Wang, W. (2003). MMN and attention: Competition for deviance detection. *Psychophysiology*, *40*(3), 430–435. https://doi.org/10.1111/1469-8986.00045

Sussman, E., & Steinschneider, M. (2009). Attention effects on auditory scene analysis in children. *Neuropsychologia*, *47*(3), 771–785. https://doi.org/10.1016/j.neuropsychologia.2008.12.007

Sussman, E., Steinschneider, M., Gumenyuk, V., Grushko, J., & Lawson, K. (2008). The maturation of human evoked brain potentials to sounds presented at different stimulus rates. *Hearing Research*, *236*(1–2), 61–79. https://doi.org/10.1016/j.heares.2007.12.001

Sussman, Elyse, S., Čeponiené, R., Shestakova, A., Näätänen, R., & Winkler, I. (2001). Auditory stream segregation processes operate similarly in school-aged children and adults. *Hearing Research*, *153*(1–2), 108–114. https://doi.org/10.1016/S0378-5955(00)00261-6

Sussman, Elyse, S., Steinschneider, M., Lee, W., & Lawson, K. (2015). Auditory scene analysis in school-aged children with developmental language disorders. *International Journal of Psychophysiology*, *95*(2), 113–124. https://doi.org/10.1016/j.ijpsycho.2014.02.002

Sutcliffe, P. A., Bishop, D. V. M., Houghton, S., & Taylor, M. (2006). Effect of attentional state on frequency discrimination: A comparison of children with ADHD on and off medication. *Journal of Speech, Language, and Hearing Research*, *49*(5), 1072–1084. https://doi.org/10.1044/1092-4388(2006/076)

Sutton, S., Braren, M., Zubin, J., & John, E. R. (1965). Evoked-potential correlates of stimulus uncertainty. *Science*, *150*(3700), 1187–1188. https://doi.org/10.1126/science.150.3700.1187

Sweller, J. (1988). Cognitive load during problem solving: effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1207/s15516709cog1202_4

Swingley, D., Pinto, J. P., & Fernald, A. (1999). Continuous processing in word recognition at 24 months. *Cognition*, *71*(2), 73–108. https://doi.org/10.1016/S0010-0277(99)00021-9

Szycik, G. R., Stadler, J., Brechmann, A., & Münte, T. F. (2013). Preattentive mechanisms of change detection in early auditory cortex: A 7Tesla fMRI study. *Neuroscience*, *253*, 100–109. https://doi.org/10.1016/j.neuroscience.2013.08.039

Szymanski, M. D., Yund, E. W., & Woods, D. L. (1999). Phonemes, intensity and attention: Differential effects on the mismatch negativity (MMN). *The Journal of the Acoustical Society of America*, *106*(6), 3492–3505. https://doi.org/10.1121/1.428202

Takaura, K., & Fujii, N. (2016). Facilitative effect of repetitive presentation of one stimulus on cortical responses to other stimuli in macaque monkeys - a possible neural mechanism for mismatch negativity. *European Journal of Neuroscience*, *43*(4), 516–528. https://doi.org/10.1111/ejn.13136

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language*, *9*(2), 182–198. https://doi.org/10.1016/0093-934X(80)90139-X

Tallal, P., & Gaab, N. (2006). Dynamic auditory processing, musical experience and language development. *Trends in Neurosciences*, *29*(7), 382–390. https://doi.org/10.1016/j.tins.2006.06.003

Tamura, K., Mizuba, T., & Iramina, K. (2016). Hearing subjects own name induces the late positive component of event-related potential and beta power suppression. *Brain Research*, *1635*, 130–142. https://doi.org/10.1016/j.brainres.2016.01.032

Taylor, M. J. (2012). Neural bases of cognitive development. In E. Bialystok, F. I. M. Craik (Eds.). *Lifespan Cognition: Mechanisms of Change*. Oxford Scholarship Online. https://doi.org/10.1093/acprof:oso/9780195169539.003.0002

Taylor, M. J., & Baldeweg, T. (2002). Application of EEG, ERP and intracranial recordings to the investigation of cognitive functions in children. *Developmental Science*, *5*(3), 318–334. https://doi.org/10.1111/1467-7687.00372

Teas, D. C., Klein, A. J., & Kramer, S. J. (1982). An analysis of auditory brainstem responses in infants. *Hearing Research*, *7*(1), 19–54. https://doi.org/10.1016/0378-5955(82)90080-6

Teinonen, T., Aslin, R. N., Alku, P., & Csibra, G. (2008). Visual speech contributes to phonetic learning in 6-month-old infants. *Cognition*, *108*(3), 850–855. https://doi.org/10.1016/j.cognition.2008.05.009

Teinonen, T., Fellman, V., Näätänen, R., Alku, P., & Huotilainen, M. (2009). Statistical language learning in neonates revealed by event-related brain potentials. *BMC Neuroscience*, *10*(1), 21. https://doi.org/10.1186/1471-2202-10-21

Teismann, I. K., Sörös, P., Manemann, E., Ross, B., Pantev, C., & Knecht, S. (2004). Responsiveness to repeated speech stimuli persists in left but not right auditory cortex. *NeuroReport*, *15*(8), 1267–1270. https://doi.org/10.1097/01.wnr.0000129856.58404.2d

Telkemeyer, S., Rossi, S., Koch, S. P., Nierhaus, T., Steinbrink, J., Poeppel, D., Obrig, H., & Wartenburger, I. (2009). Sensitivity of newborn auditory cortex to the temporal structure of sounds. *Journal of Neuroscience*, *29*(47), 14726–14733. https://doi.org/10.1523/JNEUROSCI.1246-09.2009

Tervaniemi, M., Sinkkonen, J., Virtanen, J., Kallio, J., Ilmoniemi, R. J., Salonen, O., & Näätänen, R. (2005). Test-retest stability of the magnetic mismatch response (MMNm). *Clinical Neurophysiology*, *116*(8), 1897–1905. https://doi.org/10.1016/j.clinph.2005.03.025

Tharpe, A. M., & Ashmead, D. H. (2001). A longitudinal investigation of infant auditory sensitivity. *American Journal of Audiology*, *10*(2), 104–112. https://doi.org/10.1044/1059-0889(2001/011)

Thomas, M. S. C., Forrester, N. A., & Ronald, A. (2013). Modeling socioeconomic status effects on language development. *Developmental Psychology*, *49*(12), 2325–2343. https://doi.org/10.1037/a0032301

Thompson, E. C., Woodruff Carr, K., White-Schwoch, T., Otto-Meyer, S., & Kraus, N. (2017). Individual differences in speech-in-noise perception parallel neural speech processing and attention in preschoolers. *Hearing Research*, *344*, 148–157. https://doi.org/10.1016/j.heares.2016.11.007

Tiitinen, H., May, P., Reinikainen, K., & Näätänen, R. (1994). Attentive novelty detection in humans is governed by preattentive sensory memory. *Nature*, *372*(6501), 90–92. https://doi.org/10.1038/372090a0

Todd, J., Harms, L., Schall, U., & Michie, P. T. (2013). Mismatch negativity: translating the potential. *Frontiers in Psychiatry*, *4*, 171. https://doi.org/10.3389/fpsyt.2013.00171

Todd, J., & Robinson, J. (2010). The use of conditional inference to reduce prediction error-A mismatch negativity (MMN) study. *Neuropsychologia*, *48*(10), 3009–3018. https://doi.org/10.1016/j.neuropsychologia.2010.06.009

Tomalski, P. (2015). Developmental trajectory of audiovisual speech integration in early infancy. A review of studies using the McGurk paradigm. *Psychology of Language and Communication*, *19*(2), 77–100. https://doi.org/10.1515/plc-2015-0006

Tomberg, C., Noël, P., Ozaki, I., & Desmedt, J. E. (1990). Inadequacy of the average reference for the topographic mapping of focal enhancements of brain potentials. *Electroencephalography and Clinical Neurophysiology/ Evoked Potentials*, *77*(4), 259–265. https://doi.org/10.1016/0168-5597(90)90064-K

Tóth, B., Kocsis, Z., Urbán, G., & Winkler, I. (2016). Theta oscillations accompanying concurrent auditory stream segregation. *International Journal of Psychophysiology*, *106*, 141–151. https://doi.org/10.1016/j.ijpsycho.2016.05.002

Trainor, L. J. (2010). Using electroencephalography (EEG) to measure maturation of auditory cortex in infants: Processing pitch, duration and sound location. In J. B. Benson (Ed.). *Encyclopedia Early Childhood Development.* Brain.

Trainor, L. J., Samuel, S. C., Desjardins, R. N., Sonnadara, R. R., Samuel, S. S., Desjardins, R. N., & Sonnadara, R. R. (2001). Measuring temporal resolution in infants using mismatch negativity. *NeuroReport*, *12*(11), 2443–2448. https://doi.org/10.1097/00001756-200108080-00031

Trainor, L., McFadden, M., Hodgson, L., Darragh, L., Barlow, J., Matsos, L., & Sonnadara, R. (2003). Changes in auditory cortex and the development of mismatch negativity between 2 and 6 months of age. *International Journal of Psychophysiology*, *51*(1), 5–15. https://doi.org/10.1016/S0167-8760(03)00148-X

Trehub, S. E., Schneider, B. A., & Henderson, J. L. (1995). Gap detection in infants, children, and adults. *The Journal of the Acoustical Society of America*, *98*(5), 2532–2541. https://doi.org/10.1121/1.414396

Trejo, L. J., Ryan-Jones, D. L., & Kramer, A. F. (1995). Attentional modulation of the mismatch negativity elicited by frequency differences between binaurally presented tone bursts. *Psychophysiology*, *32*(4), 319–328. https://doi.org/10.1111/j.1469-8986.1995.tb01214.x

Tsuchida, T., & Cottrell, G. W. (2012). Auditory saliency using natural statistics. *Proc. Annual Meeting of the Cognitive Science*, *34*(34), 1048–1053.

Tsuji, S., & Cristia, A. (2014). Perceptual attunement in vowels: A meta-analysis. *Developmental Psychobiology*, *56*(2), 179–191. https://doi.org/10.1002/dev.21179

Tucker, D. M. (1993). Spatial sampling of head electrical fields: the geodesic sensor net. *Electroencephalography and Clinical Neurophysiology*, *87*(3), 154–163. https://doi.org/10.1016/0013-4694(93)90121-B

Turk-Browne, N. B., Scholl, B. J., & Chun, M. M. (2008). Babies and brains: habituation in infant cognition and functional neuroimaging. *Frontiers in Human Neuroscience*, *2*, 16. https://doi.org/10.3389/neuro.09.016.2008

Uhler, K. M., Hunter, S. K., Tierney, E., & Gilley, P. M. (2018). The relationship between mismatch response and the acoustic change complex in normal hearing infants. *Clinical Neurophysiology*, *129*(6), 1148–1160. https://doi.org/10.1016/J.CLINPH.2018.02.132

UNESCO Institute for Statistics. (2018). Primary school starting age (years). In *The World Bank*. https://data.worldbank.org/indicator/SE.PRM.AGES

Uwer, R., Albrecht, R., & Von Suchodoletz, W. (2002). Automatic processing of tones and speech stimuli in children with specific language impairment. *Developmental Medicine and Child Neurology*, *44*(8), 527–532. https://doi.org/10.1017/S001216220100250X

van de Weijer-Bergsma, E., Wijnroks, L., & Jongmans, M. J. (2008). Attention development in infants and preschool children born preterm: A review. *Infant Behavior and Development*, *31*(3), 333–351. https://doi.org/10.1016/j.infbeh.2007.12.003

van den Heuvel, M. I., Otte, R. A., Braeken, M. A. K. A., Winkler, I., Kushnerenko, E., & Van den Bergh, B. R. H. (2015). Differences between human auditory event-related potentials (AERPs) measured at 2 and 4months after birth. International Journal of Psychophysiology, 97(1), 75–83. https://doi.org/10.1016/j.ijpsycho.2015.04.003

Vandermosten, M., Boets, B., Luts, H., Poelmans, H., Wouters, J., & Ghesquière, P. (2011). Impairments in speech and nonspeech sound categorization in children with dyslexia are driven by temporal processing difficulties. *Research in Developmental Disabilities*, *32*(2), 593–603. https://doi.org/10.1016/j.ridd.2010.12.015

Vannest, J., Karunanayaka, P. R., Schmithorst, V. J., Szaflarski, J. P., & Holland, S. K. (2009). Language networks in children: evidence from functional MRI studies. *American Journal of Roentgenology*, *192*(5), 1190–1196. https://doi.org/10.2214/AJR.08.2246.Language

Vantanen, P. (2004). Development of event-related potentials (ERPs) in infants and preschool children with and without familial risk for dyslexia. (Unpublished Masters dissertation, University of Jyväskylä, Finland). Retrieved from https://jyx.jyu.fi/bitstream/handle/123456789/19968/URN_NBN_fi_jyu-200904201472.pdf?isAllowed=y&sequence=1

Venezia, J. H., Vaden, K. I., Rong, F., Maddox, D., Saberi, K., & Hickok, G. (2017). Auditory, visual and audiovisual speech processing streams in superior temporal sulcus. *Frontiers in Human Neuroscience*, *11*, 174. https://doi.org/10.3389/fnhum.2017.00174

Vigliocco, G., Ponari, M., & Norbury, C. (2018). Learning and processing abstract words and concepts: Insights from typical and atypical development. *Topics in Cognitive Science*, *10*(3), 533–549. https://doi.org/10.1111/tops.12347

Virtala, P., Huotilainen, M., Partanen, E., Fellman, V., & Tervaniemi, M. (2013). Newborn infants' auditory system is sensitive to Western music chord categories. *Frontiers in Psychology*, *4*(AUG), 492. https://doi.org/10.3389/fpsyg.2013.00492

Vissers, C., Koolen, S., Hermans, D., Scheper, A., & Knoors, H. (2015). Executive functioning in preschoolers with specific language impairment. *Frontiers in Psychology*, *6*, 1574. https://doi.org/10.3389/fpsyg.2015.01574

Vivona, J. M. (2012). Is there a nonverbal period of development? *Journal of the American Psychoanalytic Association*, *60*(2), 227–229. https://doi.org/10.1177/0003065112444126

Vliegen, J., Moore, B. C. J., & Oxenham, A. J. (1999). The role of spectral and periodicity cues in auditory stream segregation, measured using a temporal discrimination task. *The Journal of the Acoustical Society of America*, *106*(2), 938–945. https://doi.org/10.1121/1.427140

Vliegen, J., & Oxenham, A. J. (1999). Sequential stream segregation in the absence of spectral cues. *The Journal of the Acoustical Society of America*, *105*(1), 339–346. https://doi.org/10.1121/1.424503

Voegtline, K. M., Costigan, K. A., Pater, H. A., & DiPietro, J. A. (2013). Near-term fetal response to maternal spoken voice. *Infant Behavior and Development*, *36*(4), 526–533. https://doi.org/10.1016/j.infbeh.2013.05.002

Volden, J., Smith, I. M., Szatmari, P., Bryson, S., Fombonne, E., Mirenda, P., Roberts, W., Vaillancourt, T., Waddell, C., Zwaigenbaum, L., Georgiades, S., Duku, E., & Thompson, A. (2011). Using the preschool language scale, fourth edition to characterize language in preschoolers with autism spectrum disorders. *American Journal of Speech-Language Pathology*, *20*(3), 200–208. https://doi.org/10.1044/1058-0360(2011/10-0035)

Volkmer, S., & Schulte-Körne, G. (2018). Cortical responses to tone and phoneme mismatch as a predictor of dyslexia? A systematic review. *Schizophrenia Research*, *191*, 148–160.

Von Berger, H. (1934). Über das elektrenkephalogramm des menschen. In *Archiv für Psychiatrie und Nervenkrankheiten, 60*(51), 1947-1949.

Vouloumanos, A., Kiehl, K. A., Werker, J. F., & Liddle, P. F. (2001). Detection of sounds in the auditory stream: Event-related fMRI evidence for differential activation to speech and nonspeech. *Journal of Cognitive Neuroscience*, *13*(7), 994–1005. https://doi.org/10.1162/089892901753165890

Wacongne, C., Labyt, E., Van Wassenhove, V., Bekinschtein, T., Naccache, L., & Dehaene, S. (2011). Evidence for a hierarchy of predictions and prediction errors in human cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(51), 20754–20759. https://doi.org/10.1073/pnas.1117807108

Walker, K. C. (1994). Book Review: Preschool Language Scale-3 (PLS-3). *Journal of Psychoeducational Assessment*, *12*(1), 92–97. https://doi.org/10.1177/073428299401200112

Walter, W. G., Cooper, R., Aldridge, V. J., McCallum, W. C., & Winter, A. L. (1964). Contingent negative variation: An electric sign of sensori-motor association and expectancy in the human brain. *Nature*, *203*(4943), 380–384. https://doi.org/10.1038/203380a0

Wang, D., & Brown, G. J. (2006). *Computational Auditory Scene Analysis: Principles, Algorithms, and Applications*, 1–395. Wiley-IEEE Press https://doi.org/10.1109/9780470043387

Wang, J., Zhang, K., Madani, K., & Sabourin, C. (2015). Salient environmental sound detection framework for machine awareness. *Neurocomputing*, *152*, 444–454. https://doi.org/10.1016/j.neucom.2014.09.046

Wang, W., Datta, H., & Sussman, E. (2005). The development of the length of the temporal window of integration for rapidly presented auditory information as indexed by MMN. *Clinical Neurophysiology*, *116*(7), 1695–1706. https://doi.org/10.1016/j.clinph.2005.03.008

Wanrooij, K., Boersma, P., & Zuijen, T. L. van. (2014). Fast phonetic learning occurs already in 2-to-3-month-old infants: an ERP study. *Frontiers in Psychology*, *5*(FEB), 77. https://doi.org/10.3389/fpsyg.2014.00077

Warner-Czyz, A. D., Houston, D. M., & Hynan, L. S. (2014). Vowel discrimination by hearing infants as a function of number of spectral channels. *The Journal of the Acoustical Society of America*, *135*(5), 3017–3024. https://doi.org/10.1121/1.4870700

Warrier, C., Wong, P., Penhune, V., Zatorre, R., Parrish, T., Abrams, D., & Kraus, N. (2009). Relating structure to function: Heschl's Gyrus and acoustic processing. *Journal of Neuroscience*, *29*(1), 61–69. https://doi.org/10.1523/JNEUROSCI.3489-08.2009

Washbrook, E., Waldfogel, J., Bradbury, B., Corak, M., & Akbar Ghangro, A. (2012). The development of young children of immigrants in Australia, Canada, the United Kingdom and the United States. *Child Development*, *83*(5), 1591–1607. https://doi.org/10.1038/jid.2014.371

Wass, S. V., Daubney, K., Golan, J., Logan, F., & Kushnerenko, E. (2018). Elevated physiological arousal is associated with larger but more variable neural responses to small acoustic change in children during a passive auditory attention task. *Developmental Cognitive Neuroscience*, *37*, 100612. https://doi.org/10.1016/j.dcn.2018.12.010

Weber, C., Hahne, A., Friedrich, M., & Friederici, A. D. (2004). Discrimination of word stress in early infant perception: Electrophysiological evidence. *Cognitive Brain Research*, *18*(2), 149–161. https://doi.org/10.1016/j.cogbrainres.2003.10.001

Weber-Fox, C. M., & Neville, H. J. (1996). Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. *Journal of Cognitive Neuroscience*, *8*(3), 231–256. https://doi.org/10.1162/jocn.1996.8.3.231

Weise, A., Grimm, S., Müller, D., & Schröger, E. (2010). A temporal constraint for automatic deviance detection and object formation: A mismatch negativity study. *Brain Research*, *1331*, 88–95. https://doi.org/10.1016/j.brainres.2010.03.049

Wemer. (2001). *Development of auditory attention.*

Werker, J. F., Byers-Heinlein, K., & Fennell, C. T. (2009). Bilingual beginnings to learning words. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1536), 3649–3663. https://doi.org/10.1098/rstb.2009.0105

Werker, J. F., & Hensch, T. K. (2015). Critical Periods in Speech Perception: New Directions. *Annual Review of Psychology*, *66*(1), 173–196. https://doi.org/10.1146/annurev-psych-010814-015104

Werker, J. F., & Tees, R. C. (1999). INFLUENCES ON INFANT SPEECH PROCESSING: Toward a new synthesis. *Annual Review of Psychology*, *50*(1), 509–535. https://doi.org/10.1146/annurev.psych.50.1.509

Werner, L. A. (1996). The development of auditory behavior (or what the anatomists and physiologists have to explain). *Ear and Hearing*, *17*(5), 438–446. https://doi.org/10.1097/00003446-199610000-00010

Werner, L. A. (2007). Issues in human auditory development. *Journal of Communication Disorders*, *40*(4), 275–283. https://doi.org/10.1016/j.jcomdis.2007.03.004

Werner, L. A. (2010). Human Auditory Development. In *The Senses: A Comprehensive Reference* (Vol. 3, pp. 871–893). https://doi.org/10.1016/B978-012370880-9.00386-8

Werner, L. A. (2012). Overview and Issues in Human Auditory Development. In L. Werner, R. R. Fay, N. Popper (Eds.). *Human Auditory Development* (Vol. 42, pp. 1–18). Springer. https://doi.org/10.1007/978-1-4614-1421-6

Werner, L. A. (2013). Infants' detection and discrimination of sounds in modulated maskers. *The Journal of the Acoustical Society of America*, *133*(6), 4156–4167. https://doi.org/10.1121/1.4803903

Werner, L. A., Mancl, L. R., & Constantino, J. (1994). Gap detection by human infants. *The Journal of the Acoustical Society of America*, *95*(5), 2940–2940. https://doi.org/10.1121/1.409130

Werner, L. A., Marean, G. C., Halpin, C. F., Spetner, N. B., & Gillenwater, J. M. (1992). Infant auditory temporal acuity: gap detection. *Child Development*, *63*(2), 260–272. https://doi.org/10.1111/j.1467-8624.1992.tb01625.x

Wernicke, C. (1874). Der aphasiche Symptomenkomplex: eine psyschologische Studie auf anatomischer Basis. In *Cohen and Weigert, Breslau*. Cohn & Weigert.

Wetzel, N., & Schröger, E. (2014). On the development of auditory distraction: a review. *PsyChological Journal*, *3*(1), 72–91. https://doi.org/10.1002/pchj.49

Whalen, D. H., Benson, R. R., Richardson, M., Swainson, B., Clark, V. P., Lai, S., Mencl, W. E., Fulbright, R. K., Constable, R. T., & Liberman, A. M. (2006).

Differentiation of speech and nonspeech processing within primary auditory cortex. *The Journal of the Acoustical Society of America*, *119*(1), 575–581. https://doi.org/10.1121/1.2139627

Wightman, F., Allen, P., Dolan, T., Kistler, D., & Jamieson, D. (1989). Temporal resolution in children. *Child Development*, *60*(3), 611. https://doi.org/10.2307/1130727

Winkler, I. (2007a). Interpreting the mismatch negativity. *Journal of Psychophysiology*, *21*(3–4), 147–163. https://doi.org/10.1027/0269-8803.21.34.147

Winkler, I. (2007b). Interpreting the mismatch negativity. *Journal of Psychophysiology*, *21*(3–4), 147–163. https://doi.org/10.1027/0269-8803.21.34.147

Winkler, I., & Czigler, I. (1998). Mismatch negativity: Deviance detection or the maintenance of the "standard." *NeuroReport*, *9*(17), 3809–3813. https://doi.org/10.1097/00001756-199812010-00008

Winkler, I., Karmos, G., & Näätänen, R. (1996). Adaptive modeling of the unattended acoustic environment reflected in the mismatch negativity event-related potential. *Brain Research*, *742*(1–2), 239–252. https://doi.org/10.1016/S0006-8993(96)01008-6

Winkler, I., Kushnerenko, E., Horváth, J., Čeponienė, R., Fellman, V., Huotilainen, M., Näätänen, R., & Sussman, E. (2003). Newborn infants can organize the auditory world. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(20), 11812–11815. https://doi.org/10.1073/pnas.2031891100

Winkler, I., Lehtokoski, A., Alku, P., Vainio, M., Czigler, I., Csépe, V., Aaltonen, O., Raimo, I., Alho, K., Lang, H., Iivonen, A., & Näätänen, R. (1999). Preattentive detection of vowel contrasts utilizes both phonetic and auditory memory representations. *Cognitive Brain Research*, *7*(3), 357–369. https://doi.org/10.1016/S0926-6410(98)00039-1

Winkler, I., Sussman, E., Tervaniemi, M., Horváth, J., Ritter, W., & Näätänen, R. (2003). Preattentive auditory context effects. *Cognitive, Affective and Behavioral Neuroscience*, *3*(1), 57–77. https://doi.org/10.3758/CABN.3.1.57

Winkler, M., Mueller, J. L., Friederici, A. D., & Männel, C. (2018). Infant cognition includes the potentially human-unique ability to encode embedding. *Science Advances*, *4*(11). https://doi.org/10.1126/sciadv.aar8334

WMA, & World Medical Association. (2013). WMA Declaration of Helsinki - Ethical Principles for Medical Research Involving Human Subjects. *Journal of American Medical Association*, *310*(20), 2191–2194. https://doi.org/10.1001/jama.2013.281053

Woldorff, M. G., & Hillyard, S. A. (1991). Modulation of early auditory processing during selective listening to rapidly presented tones. *Electroencephalography and Clinical Neurophysiology*, *79*(3), 170–191. https://doi.org/10.1016/0013-4694(91)90136-R

Wood, C. C., Goff, W. R., & Day, R. S. (1971). Auditory evoked potentials during speech perception. *Science*, *173*(3), 1248–1251.

Wood, N., & Cowan, N. (1995). The cocktail party phenomenon revisited: How frequent are attention shifts to one's name in an irrelevant auditory channel? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(1), 255–260. https://doi.org/10.1037/0278-7393.21.1.255

Wood, N. L., & Cowan, N. (1995). The cocktail party phenomenon revisited: Attention and memory in the classic selective listening procedure of cherry (1953). *Journal of Experimental Psychology: General*, *124*(3), 243–262. https://doi.org/10.1037/0096-3445.124.3.243

Woodman, G. F. (2010). A brief introduction to the use of event-related potentials in studies of perception and attention. *Attention, Perception & Psychophysics*, *72*(8), 2031–2046. https://doi.org/10.3758/APP.72.8.2031

Woods, K. J. P., & McDermott, J. H. (2015). Attentive Tracking of Sound Sources. *Current Biology*, *25*(17), 2238–2246. https://doi.org/10.1016/j.cub.2015.07.043

Wormith, S. J., Pankhurst, D., & Moffitt, A. R. (1975). Frequency discrimination by young infants. *Child Development*, *46*(1), 272–275. https://doi.org/10.2307/1128864

Wrigley, S. N. (2002). *A Theory and computational model of auditory selective attention*. (Unpublished Doctoral thesis, University of Sheffield, United Kingdom). Retrieved from http://staffwww.dcs.shef.ac.uk/people/S.Wrigley/pdf/phd_sngl.pdf

Wrigley, S. N., & Brown, G. J. (2004). A computational model of auditory selective attention. *IEEE Transactions on Neural Networks*, *15*(5), 1151–1163. https://doi.org/10.1109/TNN.2004.832710

Wu, C. T., Weissman, D. H., Roberts, K. C., & Woldorff, M. G. (2007). The neural circuitry underlying the executive control of auditory spatial attention. *Brain Research*, *1134*(1), 187–198. https://doi.org/10.1016/j.brainres.2006.11.088

Wunderlich, J. L., & Cone-Wesson, B. K. (2006). Maturation of CAEP in infants and children: A review. *Hearing Research*, *212*(1–2), 212–223. https://doi.org/10.1016/j.heares.2005.11.008

Wunderlich, J. L., Cone-Wesson, B. K., & Shepherd, R. (2006). Maturation of the cortical auditory evoked potential in infants and young children. *Hearing Research*, *212*(1–2), 185–202. https://doi.org/10.1016/j.heares.2005.11.010

Xi, J., Zhang, L., Shu, H., Zhang, Y., & Li, P. (2010). Categorical perception of lexical tones in Chinese revealed by mismatch negativity. *Neuroscience*, *170*(1), 223–231. https://doi.org/10.1016/j.neuroscience.2010.06.077

Xu, J., & Ma, H. (2009). Applications of URANS on predicting unsteady turbulent separated flows. *Acta Mechanica Sinica/Lixue Xuebao*, *25*(3), 319–324. https://doi.org/10.1007/s10409-008-0217-3

Yabe, H., Tervaniemi, M., Reinikainen, K., & Näätänen, R. (1997). Temporal window of integration revealed by MMN to sound omission. *NeuroReport*, *8*(8), 1971–1974. https://doi.org/10.1097/00001756-199705260-00035

Yabe, H., Tervaniemi, M., Sinkkonen, J., Huotilainen, M., Ilmoniemi, R. J., & Näätänen, R. (1998). Temporal window of integration of auditory information in the human brain. *Psychophysiology*, *35*(5), 615–619. https://doi.org/10.1017/S0048577298000183

Yang, L., Dai, M., Xu, C., Zhang, G., Li, W., Fu, F., Shi, X., & Dong, X. (2017). The frequency spectral properties of electrode-skin contact impedance on human head and its frequency-dependent effects on frequency-difference EIT in stroke detection from 10Hz to 1MHz. *PLoS ONE*, *12*(1), e0170563. https://doi.org/10.1371/journal.pone.0170563

Yang, P., Fan, C., Wang, M., & Li, L. (2017). A comparative study of average, linked mastoid, and rest references for ERP components acquired during fMRI. *Frontiers in Neuroscience*, *11*(MAY), 247. https://doi.org/10.3389/fnins.2017.00247

Yang, X., & Pan, Y. (2021). Spatial language of young children during block play in kindergartens in urban China. *Frontiers in Psychology*, *12*, 385. https://doi.org/10.3389/fpsyg.2021.568638

Yao, D., Wang, L., Arendt-Nielsen, L., & N Chen, A. C. (2007). The effect of reference choices on the spatio-temporal analysis of brain evoked potentials: The use of infinite reference. *Computers in Biology and Medicine*, *37*(11), 1529–1538. https://doi.org/10.1016/j.compbiomed.2007.02.002

Yau, S. H., Brock, J., & McArthur, G. (2016). The relationship between spoken language and speech and nonspeech processing in children with autism: a magnetic event-related field study. *Developmental Science*, *19*(5), 834–852. https://doi.org/10.1111/desc.12328

Yeung, H. H., Chen, L. M., & Werker, J. F. (2014). Referential labeling can facilitate Phonetic learning in infancy. *Child Development*, *85*(3), 1036–1049. https://doi.org/10.1111/cdev.12185

Yeung, H. H., & Nazzi, T. (2014). Object labeling influences infant phonetic learning and generalization. *Cognition*, *132*(2), 151–163. https://doi.org/10.1016/j.cognition.2014.04.001

Yoncheva, Y., Maurer, U., Zevin, J. D., & McCandliss, B. D. (2014). Selective attention to phonology dynamically modulates initial encoding of auditory words within the left hemisphere. *NeuroImage*, *97*, 262–270. https://doi.org/10.1016/j.neuroimage.2014.04.006

Yordanova, J., Heinrich, H., Kolev, V., & Rothenberger, A. (2006). Increased event-related theta activity as a psychophysiological marker of comorbidity in children with tics and attention-deficit/hyperactivity disorders. *NeuroImage*, *32*(2), 940–955. https://doi.org/10.1016/j.neuroimage.2006.03.056

Youssofzadeh, V., Williamson, B. J., & Kadis, D. S. (2017). Mapping critical language sites in children performing verb generation: Whole-brain connectivity and graph theoretical analysis in MEG. *Frontiers in Human Neuroscience*, *11*, 173. https://doi.org/10.3389/fnhum.2017.00173

Yu, W. M., & Goodrich, L. V. (2014). Morphological and physiological development of auditory synapses. *Hearing Research*, *311*, 3–16. https://doi.org/10.1016/j.heares.2014.01.007

Zaehle, T., Geiser, E., Alter, K., Jancke, L., & Meyer, M. (2008). Segmental processing in the human auditory dorsal stream. *Brain Research*, *1220*, 179–190. https://doi.org/10.1016/j.brainres.2007.11.013

Zatorre, R. J., & Belin, P. (2001). Spectral and temporal processing in human auditory cortex. *Cerebral Cortex*, *11*(10), 946–953. https://doi.org/10.1093/cercor/11.10.946

Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: Music and speech. *Trends in Cognitive Sciences*, 6(1), 37–46. https://doi.org/10.1016/S1364-6613(00)01816-7

Zhang, Q., Li, H., Zheng, A., Dong, X., & Tu, W. (2017). Evaluation of auditory perception development in neonates by event-related potential technique. *Brain and Development*, *39*(7), 564–572. https://doi.org/10.1016/j.braindev.2017.02.004

Zhang, Y., Zhang, L., Shu, H., Xi, J., Wu, H., Zhang, Y., & Li, P. (2012). Universality of categorical perception deficit in developmental dyslexia: An investigation of Mandarin Chinese tones. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *53*(8), 874–882. https://doi.org/10.1111/j.1469-7610.2012.02528.x

Zhao, T. C., & Kuhl, P. K. (2016). Musical intervention enhances infants' neural processing of temporal structure in music and speech. *Proceedings of the National Academy of Sciences*, *113*(19), 5212–5217. https://doi.org/10.1073/pnas.1603984113

Zimmerman, I. L., Steiner, V. G., & Pond, R. E. (2009). *Technical Report. Preschool Language Scale. Fourth Edition*.

Zubrick, S. R., Taylor, C. L., & Christensen, D. (2015). Patterns and predictors of language and literacy abilities 4-10 years in the longitudinal study of Australian children. *PLoS ONE*, *10*(9), e0135612. https://doi.org/10.1371/journal.pone.0135612

Appendices

Appendix A. MMR in Study 1 in infants

Table A.1

T-test Results Demonstrating MMR Significance to Deviance in the Phoneme Oddball Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/ba/ - /da/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	-.208	2.665	-.474	36	.638
		Right	-.430	2.038	-1.284	36	.207
	Temporal	Left	1.020	2.153	2.882	36	.007**
		Right	-.058	2.111	-.167	36	.868
150-200	Frontal	Left	.215	2.568	.509	36	.614
		Right	.117	2.353	.301	36	.765
	Temporal	Left	.811	2.325	2.122	36	.041*
		Right	-.132	2.527	-.319	36	.752
200-250	Frontal	Left	-.127	2.528	-.305	36	.762
		Right	.026	2.519	.063	36	.950
	Temporal	Left	.468	2.330	1.222	36	.229
		Right	.262	2.809	.567	36	.574
250-300	Frontal	Left	-.926	2.681	-2.101	36	.043*
		Right	-.471	2.691	-1.065	36	.294
	Temporal	Left	1.757	4.153	2.573	36	.014*
		Right	-.212	3.712	-.348	36	.730
300-350	Frontal	Left	-1.247	2.712	-2.796	36	.008**
		Right	-.780	3.363	-1.410	36	.167
	Temporal	Left	1.002	2.994	2.035	36	.049*
		Right	.722	3.294	1.333	36	.191
350-400	Frontal	Left	-1.302	2.374	-3.336	36	.002**
		Right	-.639	3.081	-1.261	36	.215
	Temporal	Left	.583	2.669	1.330	36	.192
		Right	.558	2.797	1.213	36	.233
400-450	Frontal	Left	-1.341	2.689	-3.035	36	.004**
		Right	-.304	3.169	-.584	36	.563
	Temporal	Left	.576	2.615	1.340	36	.189

		Right	.658	2.906	1.377	36	.177
450-500	Frontal	Left	-1.320	3.443	-2.333	36	.025*
		Right	-.498	3.614	-.838	36	.408
	Temporal	Left	.608	2.674	1.383	36	.175
		Right	.745	3.097	1.464	36	.152
500-550	Frontal	Left	-1.392	3.609	-2.346	36	.025*
		Right	-.683	3.235	-1.283	36	.208
	Temporal	Left	.525	2.760	1.156	36	.255
		Right	.279	2.997	.566	36	.575
550-600	Frontal	Left	-1.510	3.432	-2.676	36	.011*
		Right	-.619	3.601	-1.045	36	.303
	Temporal	Left	.242	3.080	.478	36	.635
		Right	.054	2.988	.110	36	.913
600-650	Frontal	Left	-1.323	3.328	-2.418	36	.021*
		Right	-.649	3.913	-1.010	36	.319
	Temporal	Left	.057	3.272	.107	36	.916
		Right	.109	2.844	.234	36	.816

Note. Paired-samples t-tests (two-tailed) statistical difference between grand-averaged ERPs to /ba/ deviant and /da/ standard phonemes in clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal regions in the phoneme oddball paradigm in infants (N=37). Significance at $p<0.05$ is indicated with *, while $p<0.01$ with ** and highlighted in green. Only the higher significance level was used in analyses.

Table A.2

T-test Results Demonstrating MMR Significance to Deviance in the Phoneme Roving Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (deviant - standard)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	-.244	2.156	-.688	36	.496
		Right	-.009	1.708	-.030	36	.976
	Temporal	Left	.086	2.051	.256	36	.799
		Right	.353	2.311	.930	36	.358
150-200	Frontal	Left	-.290	2.462	-.717	36	.478
		Right	-.105	2.216	-.289	36	.775
	Temporal	Left	.400	1.782	1.364	36	.181
		Right	.819	2.564	1.943	36	.060
200-250	Frontal	Left	-.400	2.382	-1.023	36	.313
		Right	-.122	2.278	-.327	36	.746
	Temporal	Left	.186	3.498	.323	36	.749
		Right	1.201	2.877	2.539	36	.016*
250-300	Frontal	Left	-.351	2.967	-.721	36	.476
		Right	-.239	2.722	-.534	36	.597
	Temporal	Left	.577	2.782	1.262	36	.215
		Right	1.104	3.049	2.202	36	.034*
300-350	Frontal	Left	-.259	3.120	-.504	36	.617
		Right	-.444	2.935	-.920	36	.364
	Temporal	Left	.593	2.847	1.266	36	.214
		Right	.727	2.840	1.558	36	.128
350-400	Frontal	Left	-.427	2.802	-.927	36	.360
		Right	-.428	2.514	-1.036	36	.307
	Temporal	Left	.448	2.270	1.200	36	.238
		Right	.592	2.685	1.342	36	.188
400-450	Frontal	Left	.923	1.695	3.311	36	.002**
		Right	1.031	1.661	3.777	36	.001**
	Temporal	Left	.189	2.329	.493	36	.625
		Right	.695	2.761	1.530	36	.135
450-500	Frontal	Left	-.260	3.301	-.478	36	.635
		Right	-.793	2.803	-1.720	36	.094
	Temporal	Left	.259	2.423	.650	36	.520

		Right	.692	2.887	1.459	36	.153
500-550	Frontal	Left	-.246	3.730	-.402	36	.690
		Right	-.558	3.190	-1.063	36	.295
	Temporal	Left	.403	2.786	.880	36	.384
		Right	.950	3.408	1.695	36	.099
550-600	Frontal	Left	.031	3.530	.054	36	.957
		Right	-.504	3.289	-.932	36	.357
	Temporal	Left	.402	2.990	.817	36	.419
		Right	.527	3.537	.906	36	.371
600-650	Frontal	Left	.245	3.612	.412	36	.683
		Right	-.342	3.091	-.672	36	.506
	Temporal	Left	.362	3.185	.691	36	.494
		Right	.244	3.257	.456	36	.651

Note. Paired-samples t-tests between grand-averaged ERPs to the deviant and standard phonemes in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal regions in the phoneme roving paradigm in infants (N=37). Significance at p<0.05 is indicated with *, while p<0.01 with ** and highlighted in green. Only the higher significance level was used in analyses.

Table A.3

T-test Results Demonstrating MMR Significance to Deviance in the Long ITI Tone Pair Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/low-high/ - /low-low/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.010	2.579	.023	36	.982
		Right	.079	2.002	.241	36	.811
	Temporal	Left	-.436	1.922	-1.381	36	.176
		Right	-.704	2.152	-1.990	36	.054
150-200	Frontal	Left	-.132	3.038	-.264	36	.793
		Right	-.241	2.392	-.612	36	.544
	Temporal	Left	-.904	2.362	-2.328	36	.026*
		Right	-1.192	2.680	-2.706	36	.010*
200-250	Frontal	Left	.851	3.334	1.552	36	.129
		Right	.868	2.625	2.012	36	.052
	Temporal	Left	-1.329	2.478	-3.263	36	.002**
		Right	-1.147	3.374	-2.068	36	.046*
250-300	Frontal	Left	.762	3.316	1.398	36	.171
		Right	.554	2.752	1.225	36	.229

	Temporal	Left	-.262	2.796	-.570	36	.572
		Right	.924	3.693	1.522	36	.137
300-350	Frontal	Left	.812	4.117	1.199	36	.238
		Right	-.045	3.652	-.075	36	.941
	Temporal	Left	-.334	4.491	-.452	36	.654
		Right	-.086	4.375	-.120	36	.905
350-400	Frontal	Left	1.620	4.979	1.979	36	.056
		Right	1.720	4.176	2.506	36	.017*
	Temporal	Left	.729	5.055	.878	36	.386
		Right	1.054	5.073	1.264	36	.214
400-450	Frontal	Left	.795	5.258	.920	36	.364
		Right	.687	4.682	.893	36	.378
	Temporal	Left	3.563	5.449	3.978	36	.000**
		Right	3.931	4.657	5.135	36	.000**
450-500	Frontal	Left	.073	4.733	.094	36	.926
		Right	-.480	4.135	-.706	36	.485
	Temporal	Left	4.326	5.425	4.850	36	.000**
		Right	4.261	4.398	5.894	36	.000**
500-550	Frontal	Left	-.380	4.368	-.530	36	.600
		Right	-.485	4.324	-.682	36	.500
	Temporal	Left	3.657	4.871	4.567	36	.000**
		Right	3.549	5.453	3.960	36	.000**
550-600	Frontal	Left	-.962	3.843	-1.523	36	.137
		Right	-.751	4.401	-1.038	36	.306
	Temporal	Left	3.083	4.582	4.094	36	.000**
		Right	3.267	5.441	3.652	36	.001**
600-650	Frontal	Left	-1.323	4.248	-1.895	36	.066
		Right	-.813	4.472	-1.106	36	.276
	Temporal	Left	1.840	4.794	2.335	36	.025*
		Right	2.536	4.417	3.493	36	.001**

Note. Paired-samples t-tests between averaged ERPs to the /low-high/ deviant and /low-low/ standard tone pairs in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal regions in the long ITI tone pair paradigm in infants (N=37). Significance at p<0.05 is indicated with *, while p<0.01 with ** and highlighted in green. Only the higher significance level was used in analyses.

Table A.4

T-test Results Demonstrating MMR Significance to Deviance in the Short ITI Tone Pair Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/low-high/ - /low-low/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	-.068	2.002	-.208	36	.837
		Right	.463	1.912	1.473	36	.150
	Temporal	Left	.101	2.819	.218	36	.829
		Right	.461	2.119	1.324	36	.194
150-200	Frontal	Left	-.077	2.005	-.233	36	.817
		Right	.282	1.899	.902	36	.373
	Temporal	Left	-.346	2.857	-.736	36	.466
		Right	.153	1.923	.483	36	.632
200-250	Frontal	Left	.701	2.476	1.722	36	.094
		Right	.951	2.200	2.630	36	.012*
	Temporal	Left	-1.322	3.123	-2.574	36	.014*
		Right	.252	2.152	.712	36	.481
250-300	Frontal	Left	.742	2.966	1.521	36	.137
		Right	.396	2.784	.865	36	.393
	Temporal	Left	.879	2.962	1.805	36	.079
		Right	2.362	3.363	4.271	36	.000**
300-350	Frontal	Left	.441	3.847	.697	36	.490
		Right	-.533	3.555	-.913	36	.367
	Temporal	Left	1.125	2.793	2.450	36	.019*
		Right	1.553	4.378	2.157	36	.038*
350-400	Frontal	Left	1.228	3.991	1.872	36	.069
		Right	1.190	3.705	1.954	36	.059
	Temporal	Left	1.310	3.306	2.411	36	.021*
		Right	1.475	4.295	2.088	36	.044*
400-450	Frontal	Left	1.189	4.156	1.740	36	.090
		Right	.902	3.641	1.506	36	.141
	Temporal	Left	3.120	4.054	4.681	36	.000**
		Right	3.547	4.512	4.781	36	.000**
450-500	Frontal	Left	.833	4.705	1.077	36	.289

		Right	.052	4.060	.078	36	.938
	Temporal	Left	4.042	4.788	5.135	36	.000**
		Right	4.473	4.371	6.225	36	.000**
500-550	Frontal	Left	.276	5.215	.322	36	.749
		Right	-.622	4.758	-.796	36	.432
	Temporal	Left	4.288	4.891	5.332	36	.000**
		Right	3.975	4.423	5.467	36	.000**
550-600	Frontal	Left	-.380	5.217	-.443	36	.660
		Right	-.718	4.948	-.883	36	.383
	Temporal	Left	3.792	5.163	4.468	36	.000**
		Right	3.548	4.474	4.824	36	.000**
600-650	Frontal	Left	-.795	4.836	-1.000	36	.324
		Right	-.648	4.732	-.834	36	.410
	Temporal	Left	2.470	4.561	3.294	36	.002**
		Right	2.707	4.322	3.810	36	.001**

Note. Paired-samples t-tests between averaged ERPs to the /low-high/ deviant and /low-low/ standard tone pairs in the clusters of s in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal regions in the short ITI tone pair paradigm in infants (N=37). Significance at $p<0.05$ is indicated with *, while $p<0.01$ with ** and highlighted in green. Only the higher significance level was used in analyses.

Appendix B. Scalp topomaps in Study 1 in infants

ODDBALL DEVIANCE

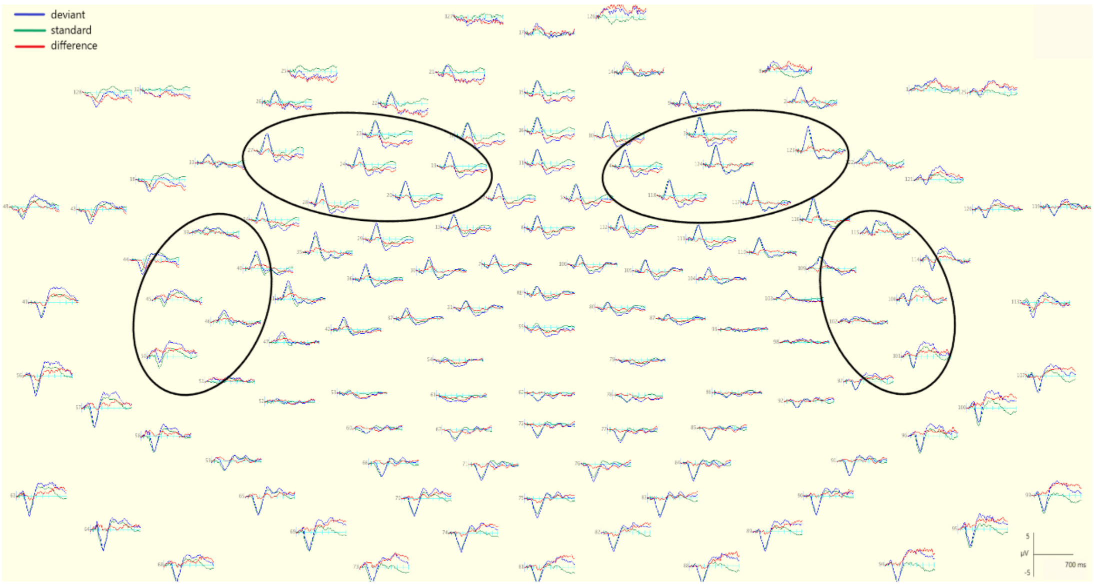

Figure B.1 Topomap of the sample-averaged ERPs to /ba/ deviant (blue line), /da/ standard (green line) and the difference wave (red line) between them in the phoneme oddball paradigm. The encircled channels were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

ROVING DEVIANCE

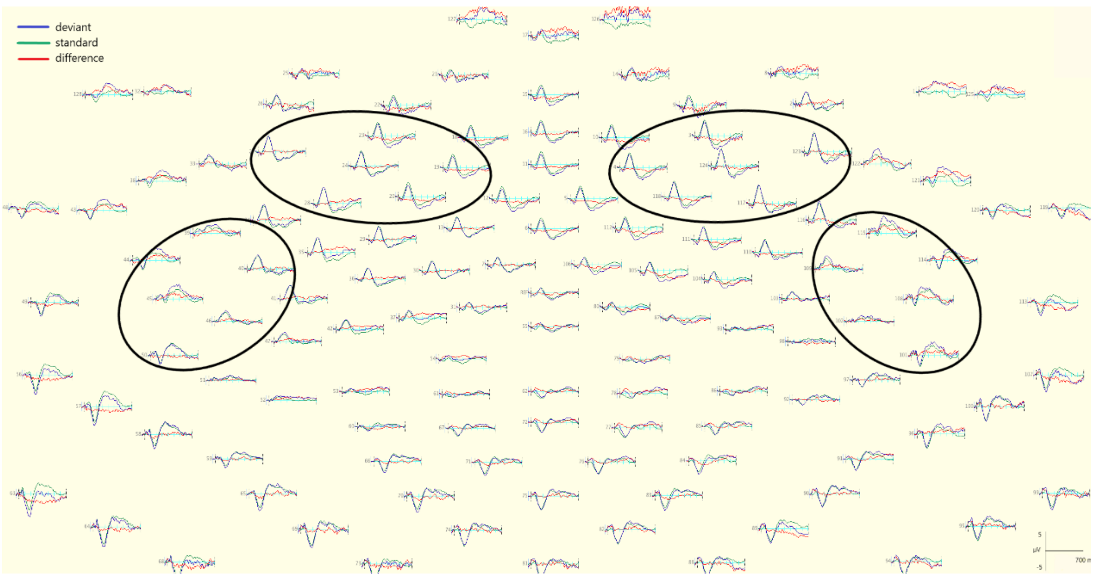

Figure B.2 Topomap of the sample-averaged ERPs to deviant (blue line), standard (green line) and the difference wave (red line) between them in the phoneme roving paradigm. The encircled channels were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

LONG ITI

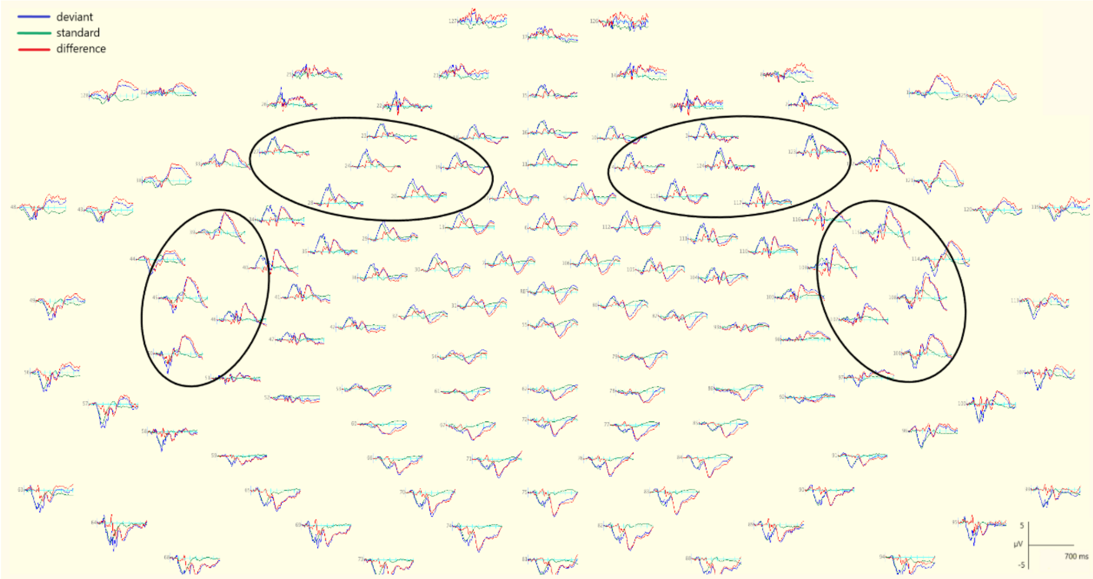

Figure B.3 Topomap of the sample-averaged ERPs to /low-high/ deviant (blue line), /low-low/ standard (green line) tone pairs and the difference wave (red line) between them in the tone pair paradigm with long ITI. The encircled channels were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal (101, 102, 108 and 115) clusters for statistical analysis.

SHORT ITI

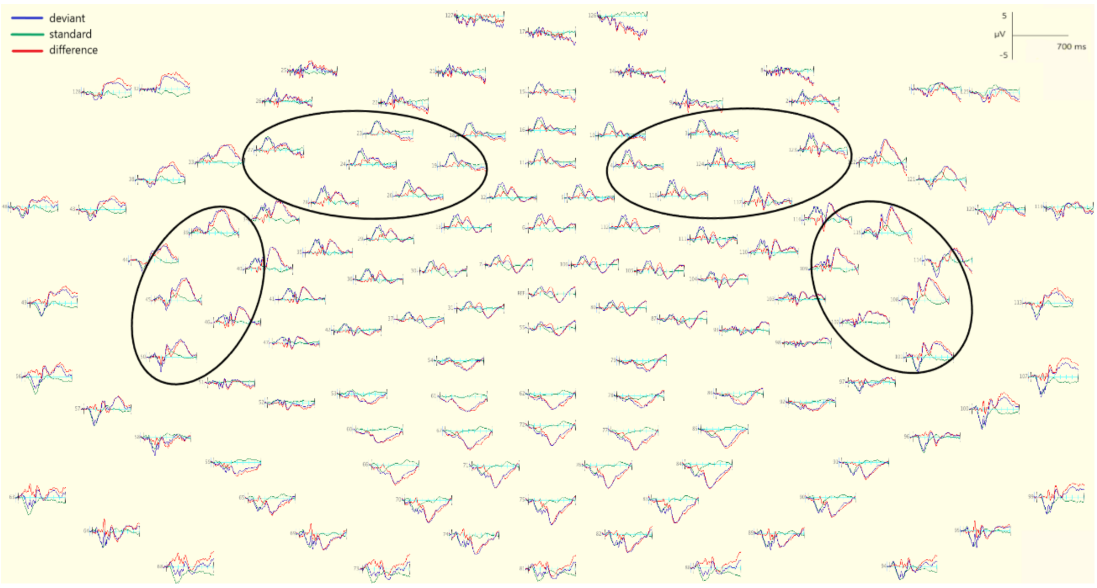

Figure B.4 Topomap of the sample-averaged ERPs to /low-high/ deviant (blue line), /low-low/ standard (green line) tone pairs and the difference wave (red line) between them in the tone pair paradigm with short ITI. The encircled channels were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal (101, 102, 108 and 115) clusters for statistical analysis.

MMR DIFFERENCE: ODDBALL VERSUS ROVING DEVIANCE

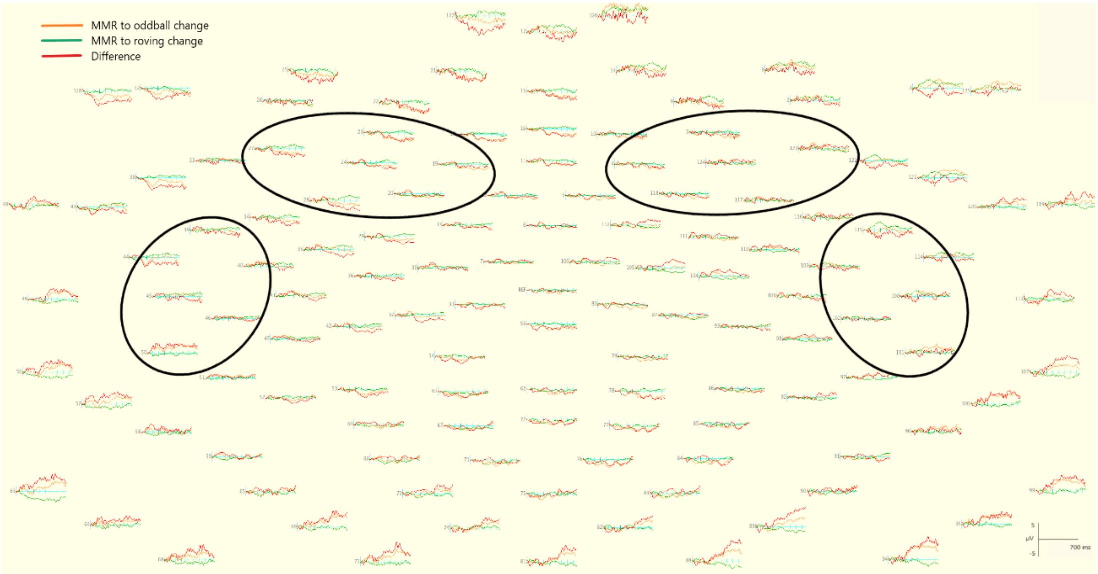

Figure B.5 Topomap of the sample-averaged MMR waveforms to oddball (orange line) and roving deviance (lime green line) and the difference wave (red line) between them. The encircled channels were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50), and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

MMR DIFFERENCE: LONG VERSUS SHORT ITI

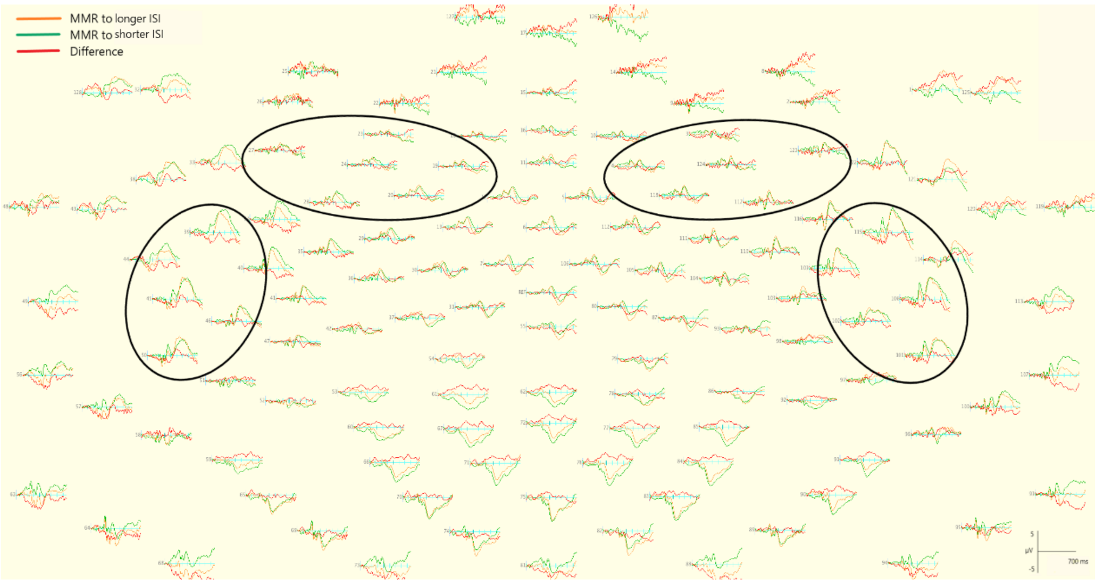

Figure B.6 Topomap of sample-averaged MMR waveforms to deviance in the long (orange line) and short ITI tone pair paradigms (lime green line) and the difference wave (red line) between them. The encircled channels were averaged into the left (19, 20, 23, 24, 27 and 28) and right (3, 4, 117, 118, 123 and 124) frontal and temporal clusters (39, 45, 46 and 50 and 101, 102, 108 and 115 in the left and right temporal areas respectively) for statistical analysis.

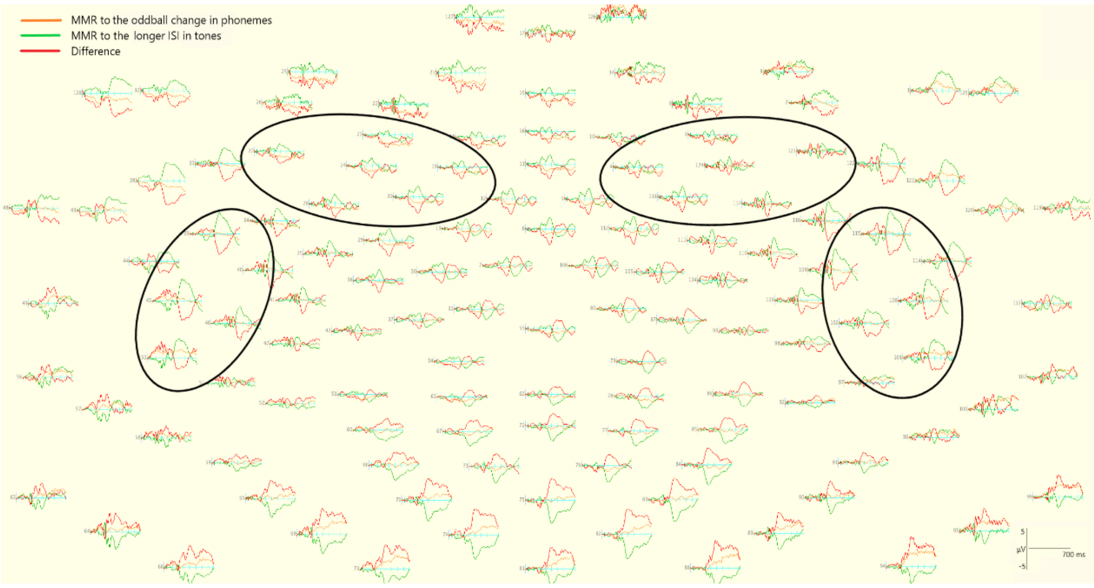

Figure B.7 Topomap of sample-averaged MMR waveforms to oddball deviance in the phoneme (orange line) and in the long ITI tone pair paradigm (green line) and the difference wave (red line) between them. The encircled channels were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50), and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

Appendix C. MMR in in Study 2 infants

Table C.1

T-test Results Demonstrating MMR Significance to Deviance in Phoneme Stream in the Streaming Paradigm

Bin (ms)	Region	Hemisphere	MMR (/ba/ - /da/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.381	2.536	.951	39	.347
		Right	.252	2.150	.740	39	.464
	Temporal	Left	.061	2.413	.160	39	.874
		Right	-.044	2.584	-.107	39	.915
150-200	Frontal	Left	.856	2.725	1.988	39	.054
		Right	.439	2.203	1.262	39	.215
	Temporal	Left	.266	2.650	.634	39	.530
		Right	.568	2.837	1.266	39	.213
200-250	Frontal	Left	1.239	2.975	2.633	39	.012*
		Right	.815	2.562	2.013	39	.051
	Temporal	Left	.442	2.858	.978	39	.334
		Right	1.026	2.959	2.194	39	.034*
250-300	Frontal	Left	1.196	3.078	2.458	39	.019*
		Right	1.025	2.651	2.445	39	.019*
	Temporal	Left	.784	2.883	1.720	39	.093
		Right	1.939	3.352	3.660	39	.001**
300-350	Frontal	Left	.718	2.951	1.539	39	.132
		Right	.343	2.509	.864	39	.393
	Temporal	Left	1.739	2.739	4.016	39	.000**
		Right	2.212	3.455	4.049	39	.000**
350-400	Frontal	Left	.541	3.228	1.060	39	.296
		Right	.046	2.590	.114	39	.910
	Temporal	Left	1.926	2.858	4.261	39	.000**
		Right	2.142	3.571	3.794	39	.001**

Note. Paired t-tests between averaged ERPs to the /ba/ deviant and /da/ standard phonemes in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in phoneme stream in streaming paradigm in infants (N=40). Significance at p<0.05 is indicated with *, while p<0.01 with ** and highlighted in green. Only the higher significance level was used in analyses.

Table C.2

T-test Results Demonstrating MMR Significance to Deviance in Tone Pair Stream in the Streaming Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/low-high/ - /low-low/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	1.147	2.262	3.207	39	.003**
		Right	.694	2.332	1.882	39	.067
	Temporal	Left	-.393	1.866	-1.331	39	.191
		Right	-.449	2.021	-1.405	39	.168
150-200	Frontal	Left	1.069	2.473	2.735	39	.009**
		Right	.663	2.569	1.631	39	.111
	Temporal	Left	-.372	2.002	-1.174	39	.248
		Right	-.443	2.111	-1.327	39	.192
200-250	Frontal	Left	.832	2.261	2.327	39	.025*
		Right	.555	2.625	1.336	39	.189
	Temporal	Left	-.685	2.300	-1.883	39	.067
		Right	-.289	2.303	-.794	39	.432
250-300	Frontal	Left	1.698	2.387	4.499	39	.000**
		Right	1.266	2.798	2.861	39	.007**
	Temporal	Left	-.673	2.857	-1.490	39	.144
		Right	.009	3.011	.018	39	.986
300-350	Frontal	Left	2.199	2.910	4.780	39	.000**
		Right	1.653	3.569	2.928	39	.006**
	Temporal	Left	.154	3.245	.299	39	.766
		Right	1.574	3.197	3.113	39	.003**
350-400	Frontal	Left	1.455	3.752	2.453	39	.019*
		Right	.858	3.995	1.359	39	.182
	Temporal	Left	1.889	4.125	2.896	39	.006**
		Right	1.699	3.030	3.547	39	.001**

Note. Paired t-tests (two-tailed) between averaged ERPs to /low-high/ deviant and /low-low/ standard tone pairs in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in tone pair stream in the streaming paradigm in infants (N=40). Significance at $p<0.05$ is indicated with *, while $p<0.01$ with ** and highlighted in green. Only the higher significance level was used in analyses.

Table C.3.

T-test Results Demonstrating MMR Significance to Deviance in the Phoneme Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/ba/ - /da/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.245	2.422	.639	39	.527
		Right	-.137	1.987	-.436	39	.666
	Temporal	Left	-.194	1.910	-.641	39	.525
		Right	-.178	1.929	-.583	39	.563
150-200	Frontal	Left	-.241	2.067	-.736	39	.466
		Right	.005	2.442	.012	39	.990
	Temporal	Left	.225	2.038	.698	39	.489
		Right	-.447	2.261	-1.251	39	.218
200-250	Frontal	Left	.285	2.164	.832	39	.410
		Right	.385	2.356	1.035	39	.307
	Temporal	Left	.007	2.598	.017	39	.987
		Right	-.238	2.111	-.714	39	.480
250-300	Frontal	Left	.483	2.417	1.262	39	.214
		Right	.353	2.063	1.081	39	.286
	Temporal	Left	-.038	2.709	-.089	39	.930
		Right	1.064	3.130	2.150	39	.038*
300-350	Frontal	Left	.281	2.340	.761	39	.451
		Right	.205	2.272	.570	39	.572
	Temporal	Left	.241	2.698	.564	39	.576
		Right	.071	2.641	.169	39	.866
350-400	Frontal	Left	.053	2.331	.144	39	.886
		Right	-.297	2.536	-.741	39	.463
	Temporal	Left	.509	3.186	1.010	39	.319
		Right	.047	2.815	.105	39	.917
400-450	Frontal	Left	-.046	2.348	-.123	39	.903
		Right	-.605	2.951	-1.297	39	.202
	Temporal	Left	.413	3.962	.660	39	.513
		Right	.439	2.722	1.020	39	.314
450-500	Frontal	Left	-.324	2.054	-.998	39	.325
		Right	-.606	3.136	-1.223	39	.229
	Temporal	Left	-.045	3.766	-.076	39	.939

		Right	.765	2.710	1.785	39	.082
500-550	Frontal	Left	-.406	2.250	-1.140	39	.261
		Right	-.566	3.133	-1.143	39	.260
	Temporal	Left	-.066	3.376	-.124	39	.902
		Right	.688	2.572	1.692	39	.099
550-600	Frontal	Left	-.435	2.483	-1.107	39	.275
		Right	-.868	2.995	-1.833	39	.074
	Temporal	Left	.166	3.578	.293	39	.771
		Right	.472	2.600	1.149	39	.258
600-650	Frontal	Left	-.184	2.608	-.447	39	.658
		Right	-.984	2.977	-2.091	39	.043*
	Temporal	Left	.358	3.673	.617	39	.541
		Right	.454	2.731	1.052	39	.299

Note. Paired t-tests between grand-averaged ERPs to /ba/ deviant and /da/ standard phonemes in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in the phoneme paradigm in infants (N=40). Significance at $p<0.05$ is indicated with *. As only significance level at $p<0.01$ was used in analyses, results in this paradigm were not considered sufficient.

Table C.4

T-test Results Demonstrating MMR Significance to Deviance in the Tone Pair Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/low-high/ - /low-low/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.447	3.061	.923	39	.362
		Right	.015	2.496	.038	39	.970
	Temporal	Left	.385	2.240	1.088	39	.283
		Right	-.052	2.895	-.113	39	.911
150-200	Frontal	Left	.435	2.778	.992	39	.328
		Right	-.013	2.894	-.028	39	.978
	Temporal	Left	.304	2.290	.840	39	.406
		Right	-.512	2.861	-1.132	39	.264
200-250	Frontal	Left	-.090	2.695	-.212	39	.833
		Right	.057	2.919	.123	39	.903
	Temporal	Left	-.417	2.793	-.945	39	.351
		Right	-.623	3.342	-1.180	39	.245
250-300	Frontal	Left	.912	3.082	1.872	39	.069
		Right	.949	3.034	1.978	39	.055

	Temporal	Left	-.677	3.051	-1.404	39	.168
		Right	.050	3.311	.096	39	.924
300-350	Frontal	Left	1.172	3.706	2.000	39	.052
		Right	.517	3.452	.947	39	.350
	Temporal	Left	1.085	3.337	2.056	39	.046*
		Right	1.823	3.893	2.961	39	.005**
350-400	Frontal	Left	.883	4.574	1.221	39	.230
		Right	.240	4.267	.356	39	.724
	Temporal	Left	1.845	3.986	2.927	39	.006**
		Right	.648	3.796	1.080	39	.287
400-450	Frontal	Left	1.683	4.686	2.271	39	.029*
		Right	1.253	4.095	1.935	39	.060
	Temporal	Left	2.134	4.273	3.158	39	.003**
		Right	2.239	4.022	3.520	39	.001**
450-500	Frontal	Left	1.415	4.339	2.062	39	.046*
		Right	.976	4.214	1.465	39	.151
	Temporal	Left	3.026	4.861	3.937	39	.000**
		Right	4.463	5.083	5.553	39	.000**
500-550	Frontal	Left	.740	4.041	1.158	39	.254
		Right	-.046	4.267	-.068	39	.946
	Temporal	Left	3.052	5.060	3.814	39	.000**
		Right	4.454	4.663	6.041	39	.000**
550-600	Frontal	Left	.025	4.288	.037	39	.971
		Right	-.851	3.936	-1.367	39	.180
	Temporal	Left	2.559	5.700	2.839	39	.007**
		Right	3.277	4.273	4.850	39	.000**
600-650	Frontal	Left	-.475	4.194	-.717	39	.478
		Right	-1.021	3.658	-1.766	39	.085
	Temporal	Left	2.087	5.394	2.448	39	.019*
		Right	2.188	4.455	3.106	39	.004**

Note. Paired t-tests (two-tailed) between averaged ERPs to /low-high/ deviant and /low-low/ standard tone pairs in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in the tone pair paradigm in infants (N=40). Significance at $p<0.05$ is indicated with *, while $p<0.01$ with ** and highlighted in green. Only the higher significance level was used in analyses.

Appendix D. Scalp topomaps in Study 2 in infants

Figure D.1 Topomap of sample-averaged ERPs to /ba/ deviant (blue line), /da/ standard phonemes (green line) and the difference wave (red line) between them in phoneme stream in the streaming paradigm. The encircled channels were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal (101, 102, 108 and 115) clusters for statistical analysis.

TONE PAIR STREAM IN STREAMING PARADIGM

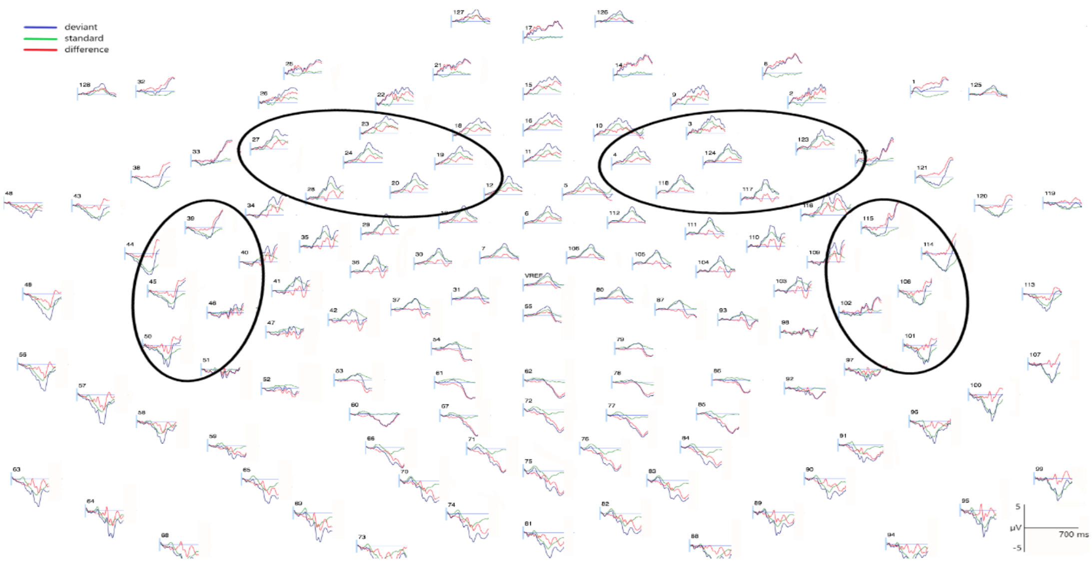

Figure D.2 Topomap of sample-averaged ERPs to /low-high/ deviant (blue line), /low-low/ standard (green line) ton pairs and the difference wave (red line) between them in the tone pair stream in the streaming paradigm. The channels circled around were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50), and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

PHONEME PARADIGM

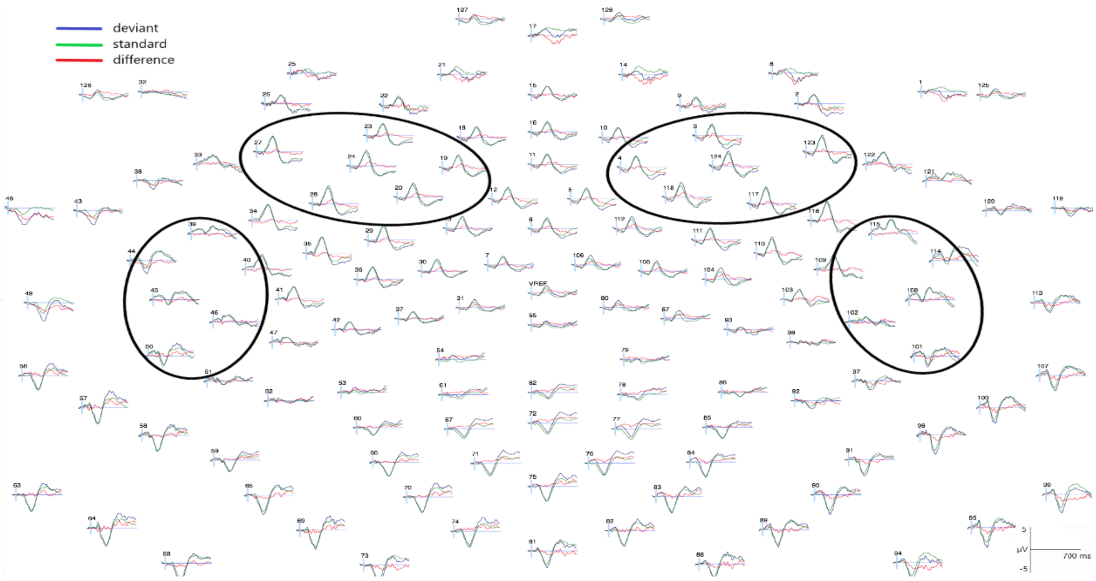

Figure D.3 Topomap of sample-averaged ERPs to /ba/ deviant (blue line), /da/ standard phonemes (green line) and the difference wave (red line) between them in the phoneme paradigm. The encircled channels were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal (101, 102, 108 and 115) clusters for statistical analysis.

TONE PAIR PARADIGM

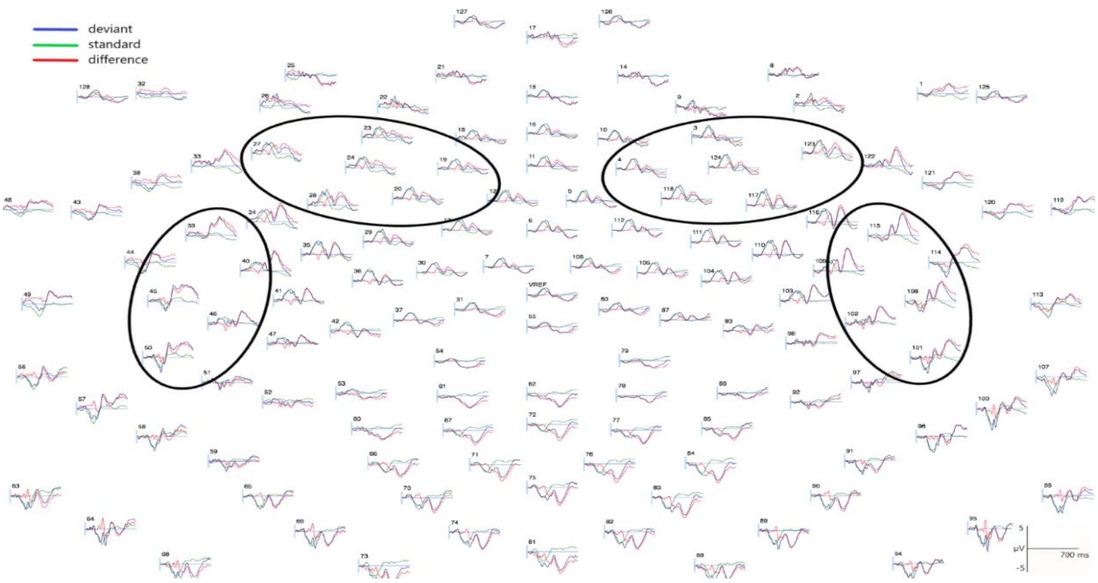

Figure D.4 Topomap of sample-average ERPs to /low-high/ deviant (blue line), /low-low/ standard (green line) stimuli and the difference wave (red line) between them in the tone pair paradigm. The channels circled around were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50), and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

MMR DIFFERENCE: PHONEME STREAM VS PHONEME PARADIGM

Figure D.5 Topomap of sample-averaged MMR waveforms to deviance in phoneme stream in the streaming paradigm (orange line) and in phoneme paradigm (emerald green line) and the difference wave (red line) between them. The channels circled around were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50), and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

MMR DIFFERENCE: TONE PAIR STREAM VS TONE PAIR PARADIGM

Figure D.6 Topomap of sample-averaged MMR waveforms to deviance in tone pair stream (orange line) in the streaming paradigm and in the tone pair paradigm (green line) and the difference wave (red line) between them. The channels circled around were averaged into the left (19, 20, 23, 24, 27 and 28) and right (3, 4, 117, 118, 123 and 124) frontal and temporal clusters (39, 45, 46 and 50 and 101, 102, 108 and 115 in the left and right temporal areas respectively) for statistical analysis.

MMR DIFFERENCE: PHONEME VERSUS TONE PAIR STREAM

Figure D.7 Topomap of sample-averaged MMR waveforms to deviance in phoneme (orange line) and tone pair (emerald green line) streams in the streaming paradigm and the difference wave (red line) between them. The channels circled around were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50), and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

MMR DIFFERENCE: PHONEME VERSUS TONE PAIR PARADIGM

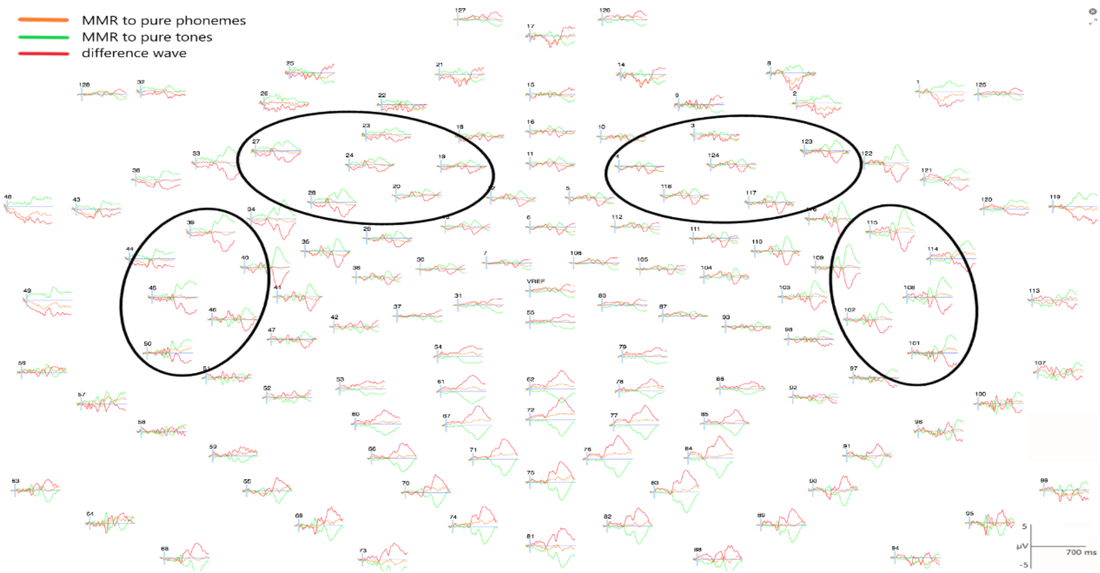

Figure D.8 Topomap of sample-averaged MMR waveforms to deviance in the phoneme (orange line) and tone pair (emerald green line) paradigms and the difference wave (red line) between them. The channels circled around were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50), and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

Appendix E. Language scores in Study 3 in infants

RECEPTIVE COMMUNICATION IN INFANTS

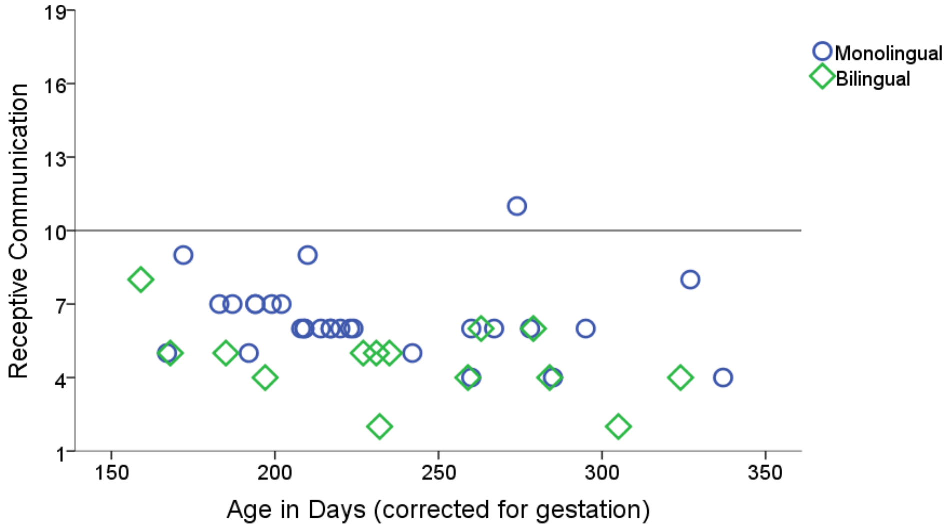

Figure E.1 Scatterplot illustrating the distribution of standardised scores on Bayley-III receptive communication subtest (Bayley, 2005) in infants. Both the scores and age were corrected for gestation. The shapes indicate monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis demonstrates the mean and 50th percentile as compared to the rest of the population.

EXPRESSIVE COMMUNICATION IN INFANTS

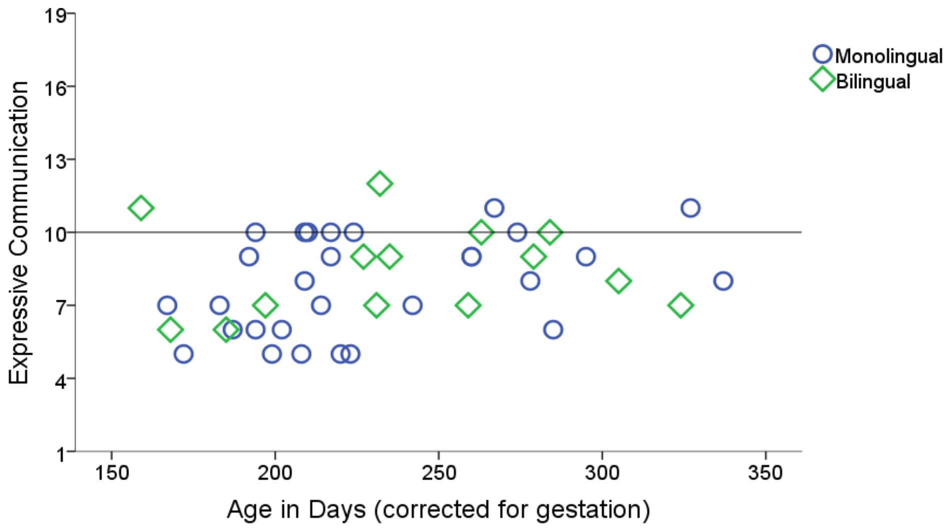

Figure E.2 Scatterplot illustrating the distribution of standardised scores on Bayley-III expressive communication subtest (Bayley, 2005) in infants. Both the scores and age were corrected for gestation. The shapes indicate monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis demonstrates the mean and 50th percentile as compared to the rest of the population.

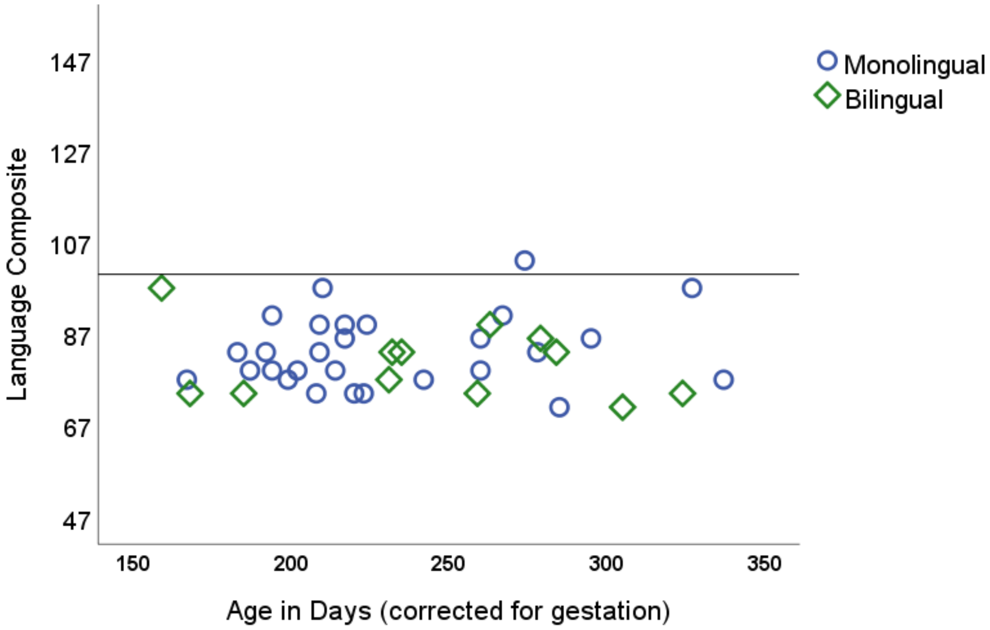

Figure E.3 Scatterplot illustrating the distribution of the language composite scores on Bayley-III (Bayley, 2005) in infants. Both the scores and age were corrected for gestation. The shapes indicate monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis demonstrates the mean and 50th percentile as compared to the rest of the population.

Appendix F. Language scores in Study 4 in 2-year-olds

RECEPTIVE COMMUNICATION AT 2 YEARS

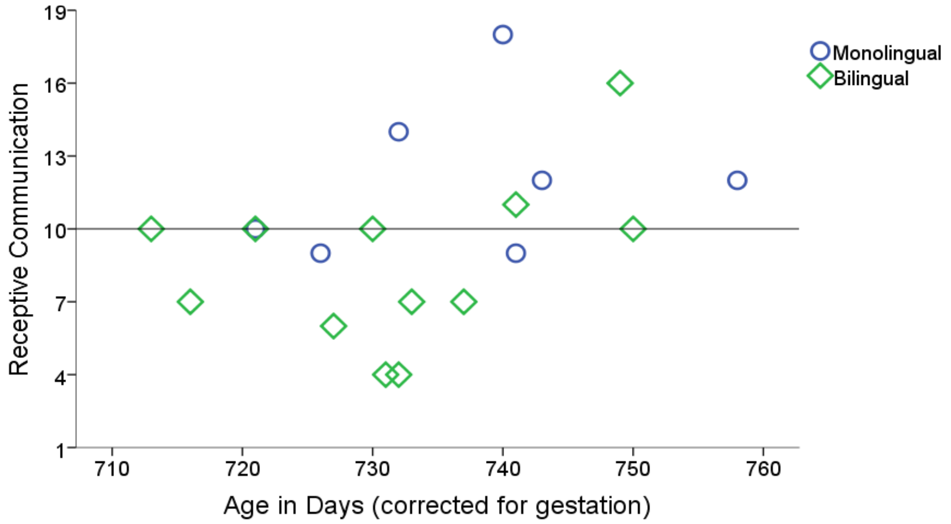

Figure F.1 Scatterplot demonstrating receptive communication scores on Bayley-III (Bayley, 2005) standardised to gestational age and as a function of age (corrected for gestation) in 2-year-olds. The shapes indicate monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis demonstrates the mean and 50th percentile as compared to the rest of the population.

EXPRESSIVE COMMUNICATION AT 2 YEARS

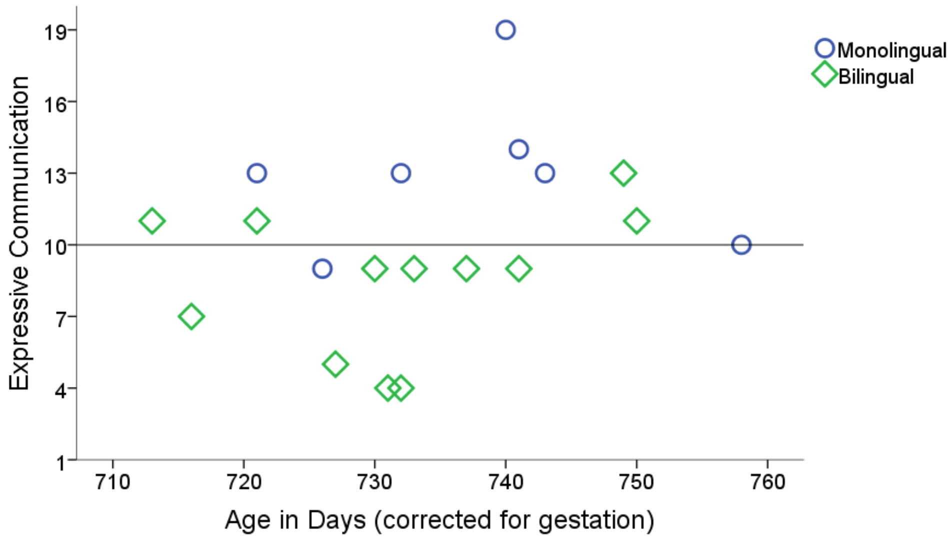

Figure F.2 Scatterplot demonstrating expressive communication scores on Bayley-III (Bayley, 2005) standardised to gestational age and as a function of age (corrected for gestation) in 2-year-olds. The shapes indicate monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis demonstrates the mean and 50th percentile as compared to the rest of the population.

LANGUAGE COMPOSITE AT 2 YEARS

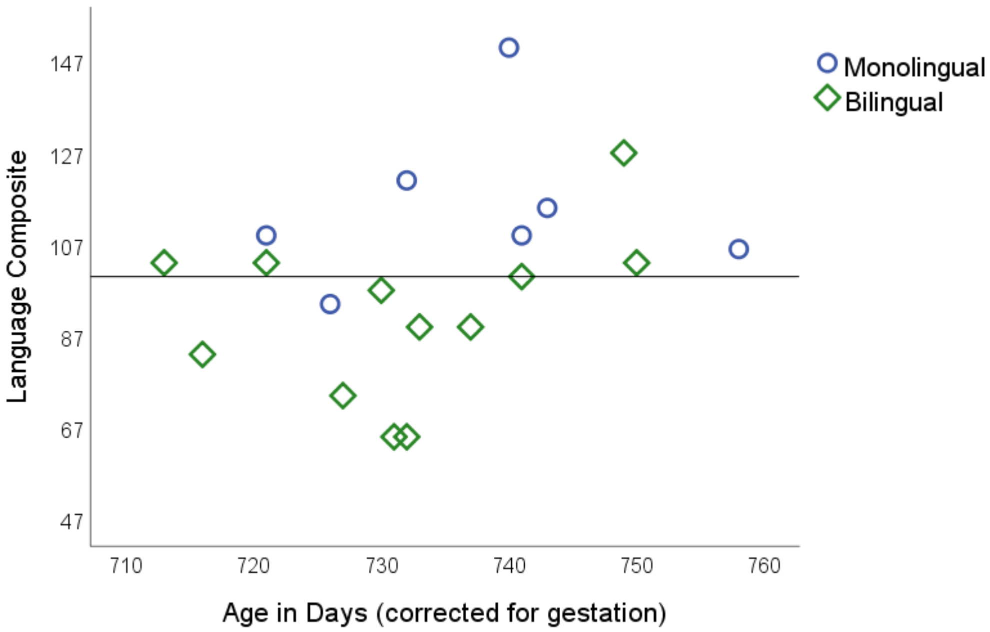

Figure F.3 Scatterplot demonstrating language composite scores on Bayley-III (Bayley, 2005) standardised to gestational age and as a function of age (corrected for gestation) in 2-year-olds. The shapes indicate monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis demonstrates the mean and 50th percentile as compared to the rest of the population.

Appendix G. MMR in Study 5 in children

Table G.1

T-test Results Demonstrating MMR Significance to Deviance in Phoneme Stream in the Streaming Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/ba/ - /da/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.167	1.752	.611	40	.545
		Right	-.068	1.425	-.308	40	.760
	Temporal	Left	-.020	1.405	-.092	40	.927
		Right	-.222	1.228	-1.157	40	.254
150-200	Frontal	Left	.278	1.936	.919	40	.364
		Right	-.044	1.650	-.171	40	.865
	Temporal	Left	.180	1.210	.953	40	.346
		Right	.143	1.366	.672	40	.505
200-250	Frontal	Left	.006	2.100	.018	40	.986
		Right	-.008	1.692	-.029	40	.977
	Temporal	Left	.050	1.497	.215	40	.831
		Right	.363	1.840	1.263	40	.214
250-300	Frontal	Left	-.346	1.889	-1.173	40	.248
		Right	-.274	2.098	-.836	40	.408
	Temporal	Left	-.044	1.877	-.149	40	.883
		Right	.404	2.197	1.178	40	.246
300-350	Frontal	Left	-.431	2.041	-1.353	40	.184
		Right	-.142	2.017	-.450	40	.655
	Temporal	Left	-.173	1.779	-.623	40	.537
		Right	.295	2.398	.787	40	.436
350-400	Frontal	Left	-.291	2.025	-.920	40	.363
		Right	-.200	1.825	-.703	40	.486
	Temporal	Left	.101	1.395	.464	40	.645
		Right	.131	2.369	.355	40	.725

Note. Paired t-tests between averaged ERPs to the /ba/ deviant and /da/ standard phonemes in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in phoneme stream in streaming paradigm in children (N=41).

Table G.2

T-test Results Demonstrating MMR Significance to Deviance in Tone Pair Stream in the Streaming Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/low-high/ - /low-low/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.396	1.891	1.340	40	.188
		Right	.305	1.643	1.190	40	.241
	Temporal	Left	-.185	1.335	-.886	40	.381
		Right	-.089	1.459	-.389	40	.700
150-200	Frontal	Left	.257	1.801	.914	40	.366
		Right	.026	1.833	.092	40	.927
	Temporal	Left	-.096	1.410	-.434	40	.666
		Right	-.241	1.592	-.970	40	.338
200-250	Frontal	Left	1.122	2.068	3.474	40	.001**
		Right	.912	2.052	2.846	40	.007**
	Temporal	Left	-.428	1.612	-1.701	40	.097
		Right	-.582	1.892	-1.970	40	.056
250-300	Frontal	Left	2.076	2.706	4.913	40	.000**
		Right	1.255	2.552	3.150	40	.003**
	Temporal	Left	-.661	1.971	-2.149	40	.038*
		Right	-.334	2.222	-.962	40	.342
300-350	Frontal	Left	-.001	2.864	-.002	40	.998
		Right	-.621	2.906	-1.369	40	.179
	Temporal	Left	-.330	1.986	-1.065	40	.293
		Right	-.067	2.352	-.183	40	.856
350-400	Frontal	Left	-2.197	2.068	-6.803	40	.000**
		Right	-2.192	2.701	-5.197	40	.000**
	Temporal	Left	.840	2.320	2.317	40	.026*
		Right	.928	2.173	2.734	40	.009**

Note. Paired t-tests (two-tailed) between averaged ERPs to /low-high/ deviant and /low-low/ standard tone pairs in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in tone pair stream in the streaming paradigm in children (N=41). Significance at $p<0.05$ is indicated with *, while $p<0.01$ with ** and highlighted in green. Only the higher significance level was used in analyses.

Table G.3

T-test Results Demonstrating MMR Significance to Deviance in the Phoneme Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/ba/ - /da/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	-.147	1.728	-.546	40	.588
		Right	-.047	1.594	-.191	40	.850
	Temporal	Left	-.274	1.389	-1.262	40	.214
		Right	.282	1.824	.990	40	.328
150-200	Frontal	Left	.193	2.197	.562	40	.577
		Right	.367	2.003	1.173	40	.248
	Temporal	Left	-.215	1.632	-.843	40	.404
		Right	.392	2.141	1.172	40	.248
200-250	Frontal	Left	.123	2.547	.308	40	.759
		Right	.228	1.788	.817	40	.419
	Temporal	Left	-.083	1.596	-.335	40	.739
		Right	.781	2.159	2.318	40	.026*
250-300	Frontal	Left	.150	2.622	.366	40	.716
		Right	.307	2.105	.935	40	.356
	Temporal	Left	.053	2.316	.147	40	.884
		Right	.807	2.126	2.431	40	.020*
300-350	Frontal	Left	.176	2.434	.464	40	.645
		Right	-.187	2.347	-.510	40	.613
	Temporal	Left	.072	1.879	.246	40	.807
		Right	.601	2.186	1.761	40	.086
350-400	Frontal	Left	-.142	2.353	-.385	40	.702
		Right	-.605	2.411	-1.606	40	.116
	Temporal	Left	.040	1.910	.136	40	.893
		Right	.471	2.142	1.409	40	.167
400-450	Frontal	Left	-.692	2.448	-1.810	40	.078
		Right	-1.127	2.314	-3.117	40	.003**
	Temporal	Left	.290	1.947	.953	40	.346
		Right	.681	2.369	1.841	40	.073
450-500	Frontal	Left	-.746	2.322	-2.058	40	.046*
		Right	-.968	2.414	-2.568	40	.014*
	Temporal	Left	.279	1.992	.896	40	.375

		Right	.521	2.610	1.278	40	.209
500-550	Frontal	Left	-.620	2.197	-1.808	40	.078
		Right	-.957	2.187	-2.802	40	.008**
	Temporal	Left	.239	2.016	.760	40	.452
		Right	.356	2.614	.871	40	.389
550-600	Frontal	Left	-.801	2.306	-2.225	40	.032*
		Right	-.987	1.986	-3.181	40	.003**
	Temporal	Left	.351	2.124	1.058	40	.296
		Right	.203	2.576	.504	40	.617
600-650	Frontal	Left	-.506	2.755	-1.177	40	.246
		Right	-.985	2.482	-2.542	40	.015*
	Temporal	Left	.026	2.166	.076	40	.940
		Right	.096	2.809	.218	40	.829

Note. Paired t-tests between grand-averaged ERPs to /ba/ deviant and /da/ standard phonemes in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in the phoneme paradigm in children (N=41). Significance at p<0.05 is indicated with *, while p<0.01 with ** and highlighted in green. Only the higher significance level was used in analyses.

Table G.3

T-test Results Demonstrating MMR Significance to Deviance in the Tone Pair Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/low-high/ - /low-low/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.048	1.823	.167	40	.868
		Right	-.106	1.850	-.367	40	.716
	Temporal	Left	-.053	1.186	-.288	40	.775
		Right	.119	1.651	.462	40	.647
150-200	Frontal	Left	-.106	2.097	-.325	40	.747
		Right	-.045	2.146	-.135	40	.893
	Temporal	Left	-.130	2.277	-.366	40	.716
		Right	.734	2.425	1.938	40	.060
200-250	Frontal	Left	1.510	2.114	4.574	40	.000**
		Right	1.166	2.000	3.731	40	.001**
	Temporal	Left	-.579	1.910	-1.941	40	.059
		Right	-.060	2.300	-.168	40	.867
250-300	Frontal	Left	2.478	2.607	6.087	40	.000**
		Right	1.849	2.218	5.337	40	.000**

	Temporal	Left	-.718	2.086	-2.205	40	.033*
		Right	-.137	2.487	-.354	40	.725
300-350	Frontal	Left	.167	2.652	.404	40	.688
		Right	-.229	2.651	-.552	40	.584
	Temporal	Left	-.034	2.230	-.098	40	.922
		Right	-.114	2.669	-.274	40	.786
350-400	Frontal	Left	-2.166	2.765	-5.016	40	.000**
		Right	-2.185	2.953	-4.739	40	.000**
	Temporal	Left	1.022	2.327	2.811	40	.008**
		Right	.691	2.649	1.670	40	.103
400-450	Frontal	Left	-1.364	2.874	-3.039	40	.004**
		Right	-1.489	2.919	-3.268	40	.002**
	Temporal	Left	.513	2.279	1.440	40	.158
		Right	.240	2.729	.562	40	.577
450-500	Frontal	Left	.778	3.678	1.905	80	.060
		Right	.374	3.585	.938	80	.351
	Temporal	Left	1.407	4.068	3.112	80	.003**
		Right	2.218	4.786	4.172	80	.000**
500-550	Frontal	Left	-.022	2.907	-.049	40	.961
		Right	-.642	2.482	-1.656	40	.106
	Temporal	Left	.647	2.171	1.908	40	.064
		Right	.432	3.096	.893	40	.377
550-600	Frontal	Left	-1.290	3.092	-2.672	40	.011*
		Right	-1.973	2.823	-4.475	40	.000**
	Temporal	Left	1.781	2.328	4.898	40	.000**
		Right	.713	2.941	1.551	40	.129
600-650	Frontal	Left	-2.353	2.930	-5.141	40	.000**
		Right	-2.561	3.057	-5.364	40	.000**
	Temporal	Left	1.744	2.668	4.184	40	.000**
		Right	.814	3.054	1.706	40	.096

Note. Paired t-tests (two-tailed) between averaged ERPs to /low-high/ deviant and /low-low/ standard tone pairs in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in the tone pair paradigm in children (N=41). Significance at p<0.05 is indicated with *, while p<0.01 with ** and highlighted in green. Only the higher significance level was used in analyses.

Appendix H. Scalp topopomaps in Study 5 in children

PHONEME STREAM IN STREAMING PARADIGM

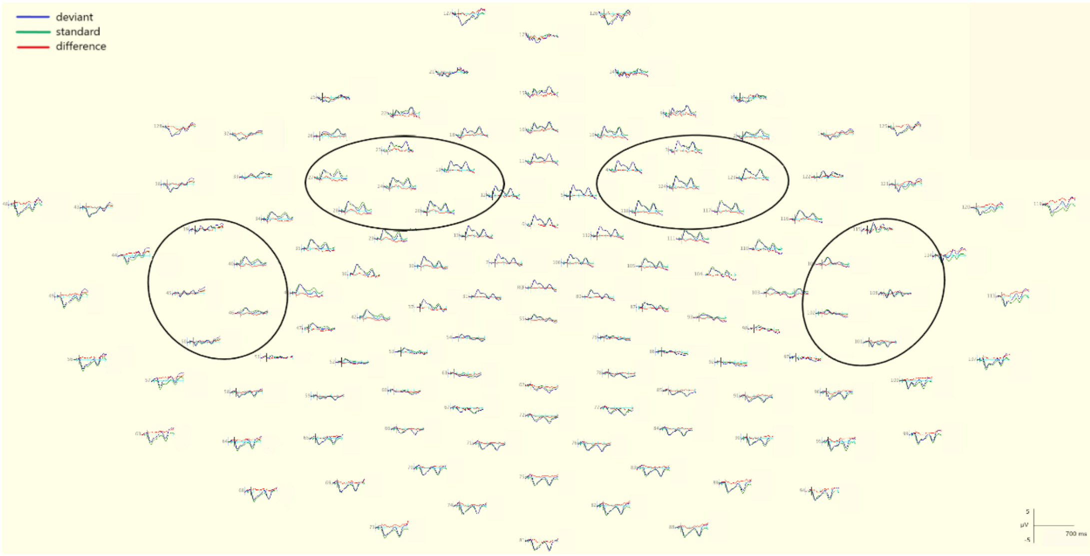

Figure H.1 Topomap of sample-averaged ERP to /ba/ deviant (blue line), /da/ standard (green line) and the MMR wave (red line) between them in phoneme stream in the streaming paradigm. The channels, which are circled around, were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal (101, 102, 108 and 115) clusters for statistical analysis.

TONE PAIR STREAM IN STREAMING PARADIGM

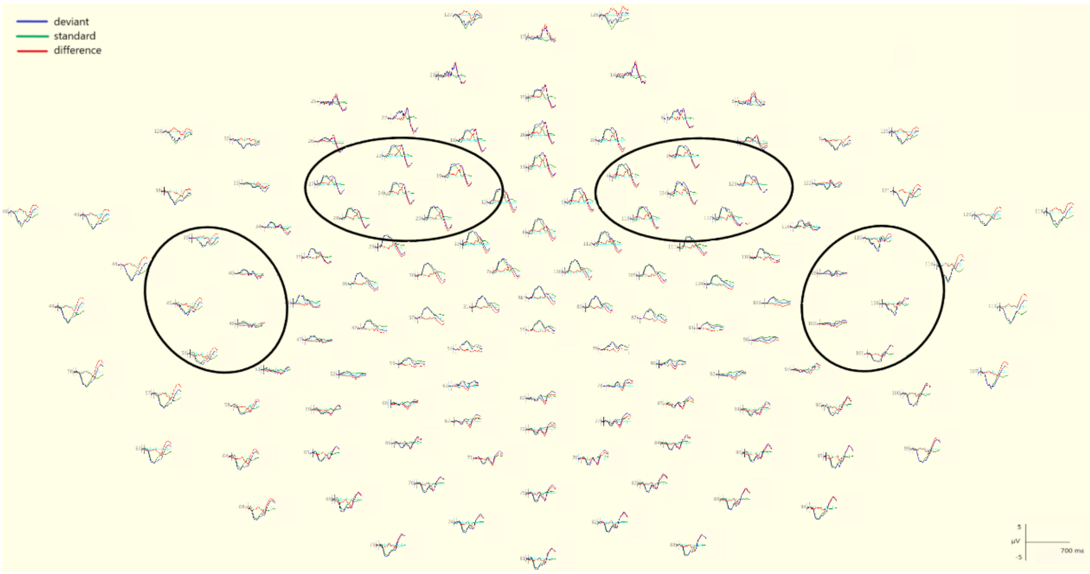

Figure H.2 Topomap of sample-averaged ERPs to /low-high/ deviant (blue line), /low-low/ standard (green line) tone pairs and the MMR wave (red line) between them in tone pair stream in the streaming paradigm. Channels averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal (101, 102, 108 and 115) for statistical analysis are circled around.

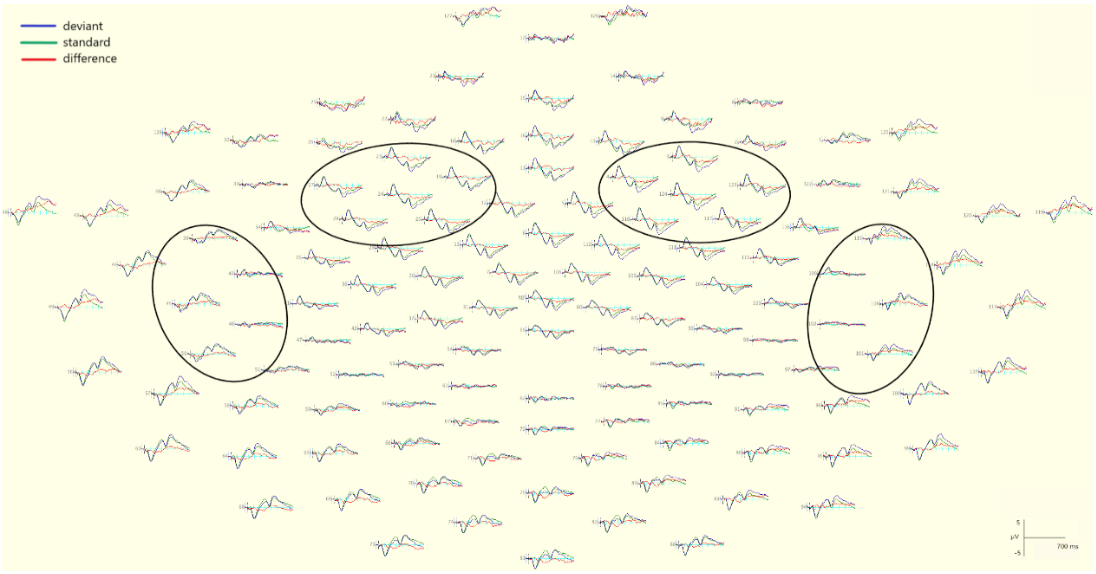

Figure H.3 Topomap of sample-averaged ERPs to /ba/ deviant (blue line), /da/ standard (green line) and the MMR waveform (red line) in the phoneme paradigm. Channels averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal (101, 102, 108 and 115) clusters for statistical analysis are circled around.

TONE PAIR PARADIGM

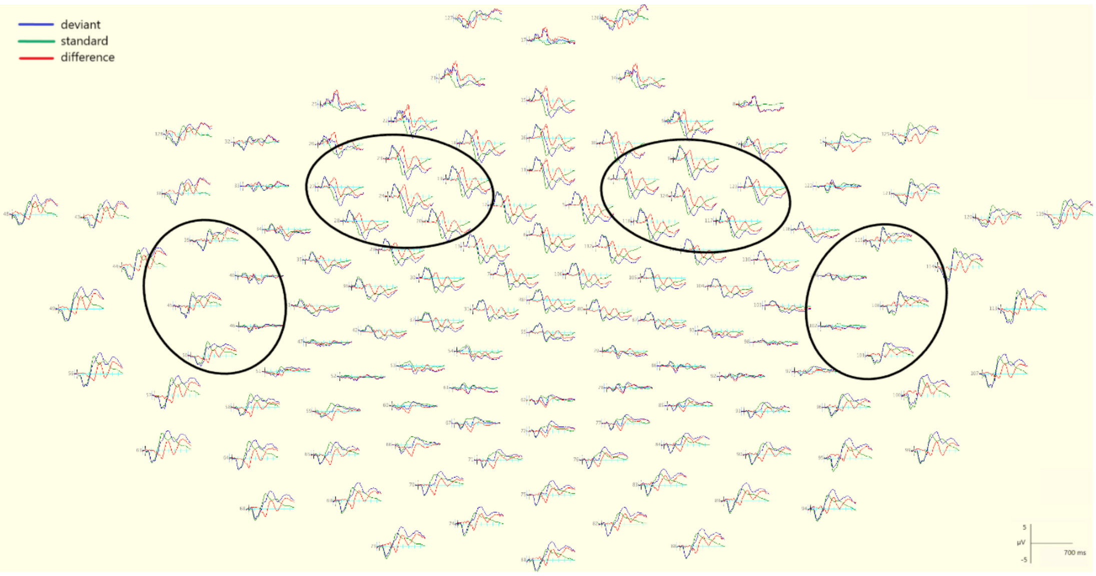

Figure H.4 Topomap of sample-average ERPs to /low-high/ deviant (blue line), /low-low/ standard (green line) tone pairs and the MMR wave (red line) in the tone pair paradigm. Channels averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50) and right temporal (101, 102, 108 and 115) for statistical analysis are circled around.

MMR DIFFERENCE: PHONEME STREAM VS PHONEME PARADIGM

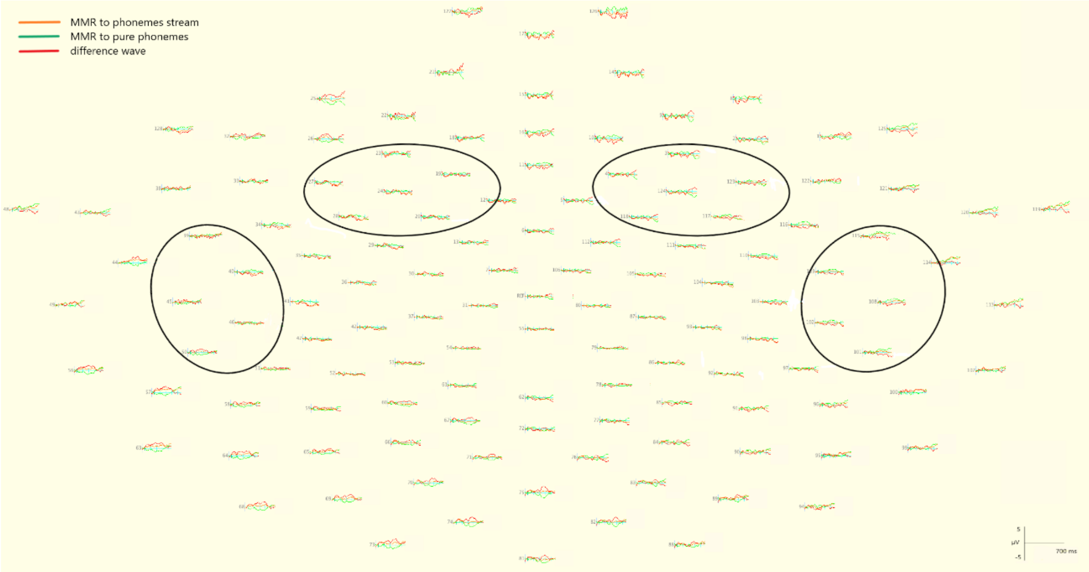

Figure H.5 Topomap sample-averaged MMR waveforms to deviance in phoneme stream in the streaming paradigm (orange line) and in the phoneme paradigm (emerald green line) and the difference wave (red line) between them. The channels circled around were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50), and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

MMR DIFFERENCE: TONE PAIR STREAM VS TONE PAIR PARADIGM

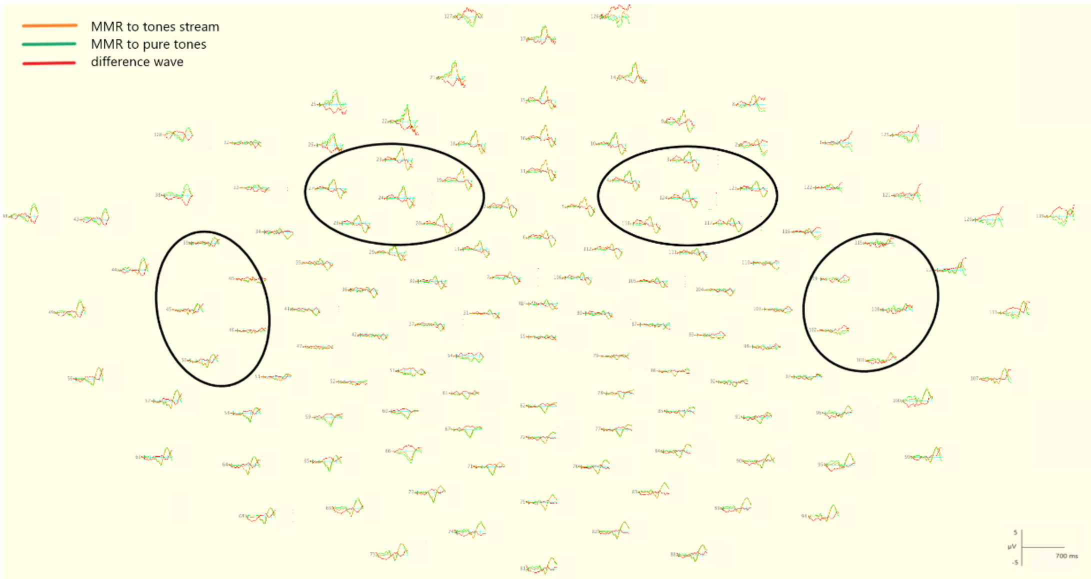

Figure H.6 Topomap of sample-averaged MMR waveforms to deviance in tone pair stream in the streaming paradigm (orange line) and in the tone pair paradigm (green line) and the difference wave (red line) between them. The channels circled around were averaged into the left (19, 20, 23, 24, 27 and 28) and right (3, 4, 117, 118, 123 and 124) frontal and temporal clusters (39, 45, 46 and 50 and 101, 102, 108 and 115 in the left and right temporal areas respectively) for statistical analysis.

MMR DIFFERENCE: PHONEME VERSUS TONE PAIR STREAM

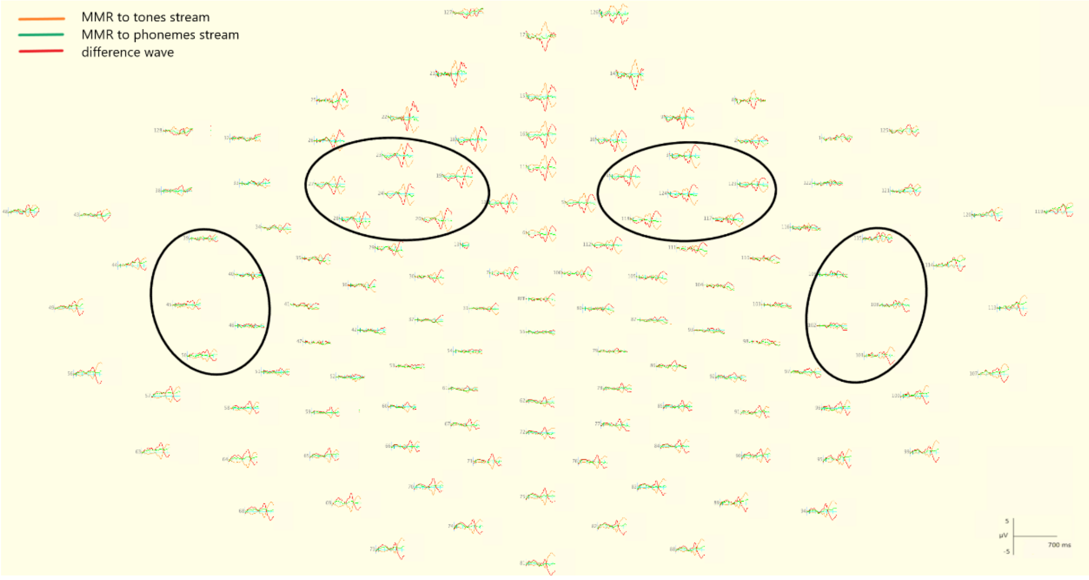

Figure H.7 Topomap of sample-averaged MMR waveforms to deviance in tone pair (orange line) and phoneme (emerald green line) streams in the streaming paradigm and the difference wave (red line) between them. The channels circled around were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50), and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

MMR DIFFERENCE: PHONEME VERSUS TONE PAIR PARADIGM

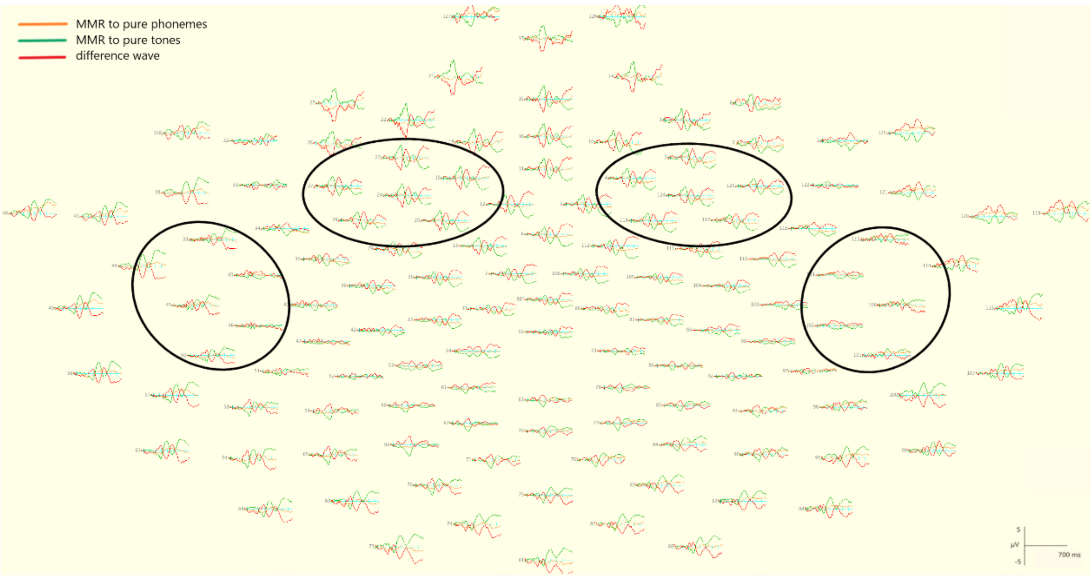

Figure H.8 Topomap of sample-averaged MMR waveforms to deviance in the phoneme (orange line) and tone pair (emerald green line) paradigms and the difference wave (red line) between them. The channels circled around were averaged into the left frontal (19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left temporal (39, 45, 46 and 50), and right temporal clusters (101, 102, 108 and 115) for statistical analysis.

Appendix I. Language scores in Study 6 in children

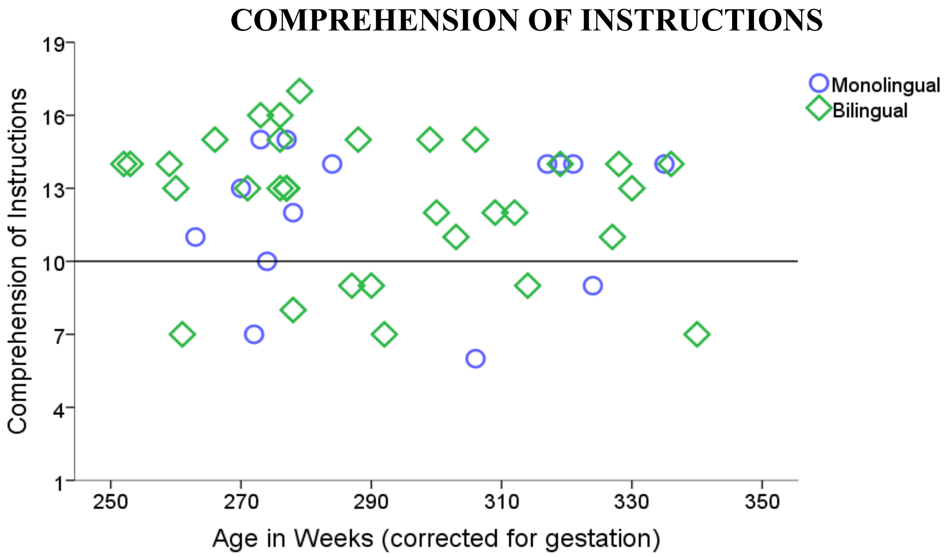

Figure I.1 Scatterplot demonstrating scaled scores on the NEPSY-II (Korkman et al., 2007c, 2007b) comprehension of instructions subtest (scale range on the y-axis) standardised to age (corrected for gestation) as presented on x-axis. The shapes indicate monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis demonstrates the expected mean in the assessment.

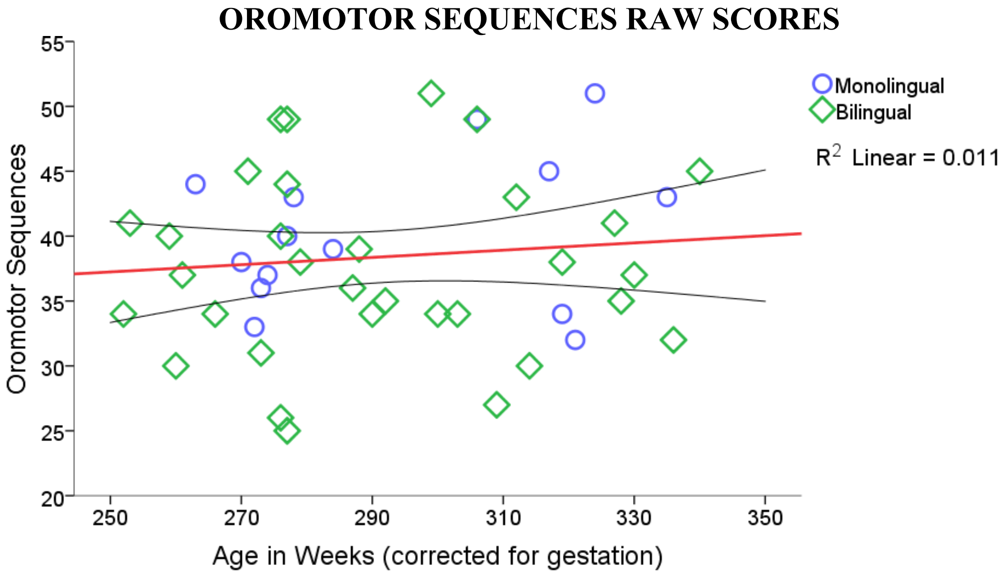

Figure I.2 Scatterplot demonstrating raw scores on the NEPSY-II (Korkman et al., 2007c, 2007b) oromotor sequences subtest as a function of age in weeks corrected for gestation. The shapes indicate children in monolingual (blue circles) and bilingual families (green diamonds). The red regression line represents the linear fit and the surrounding black lines confidence intervals at 95%.

OROMOTOR SEQUENCES SCALED SCORES

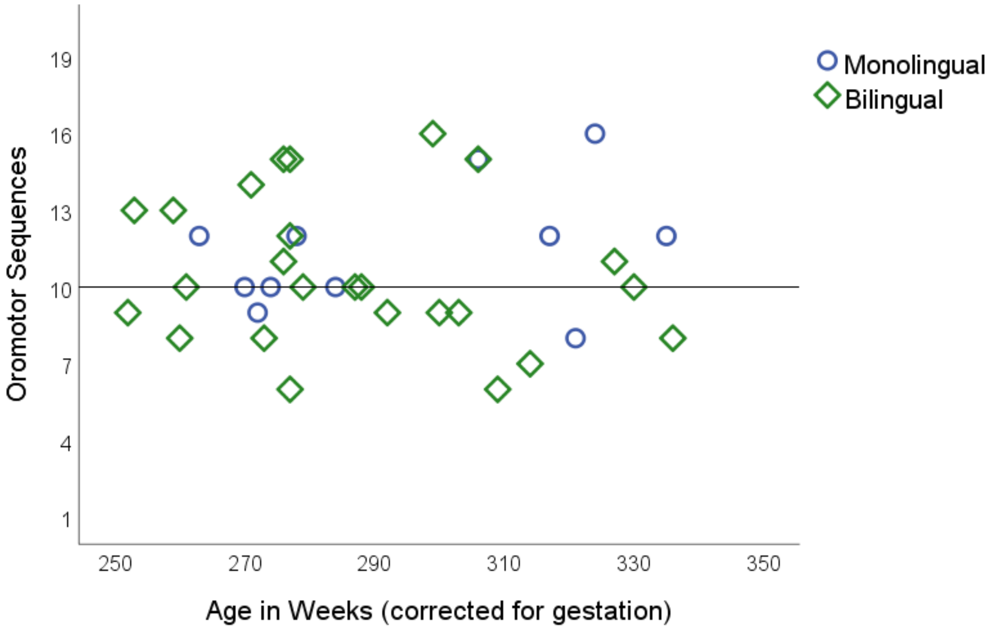

Figure I.3 Scatterplot demonstrating standardised scores (calculated manually) on the NEPSY-II (Korkman et al., 2007c, 2007b) oromotor sequences subtest as a function of age in weeks corrected for gestation. The shapes indicate children in monolingual (blue circles) and bilingual families (green diamonds). The line parallel to x-axis demonstrates the mean expected scores on the assessment.

PHONOLOGICAL PROCESSING

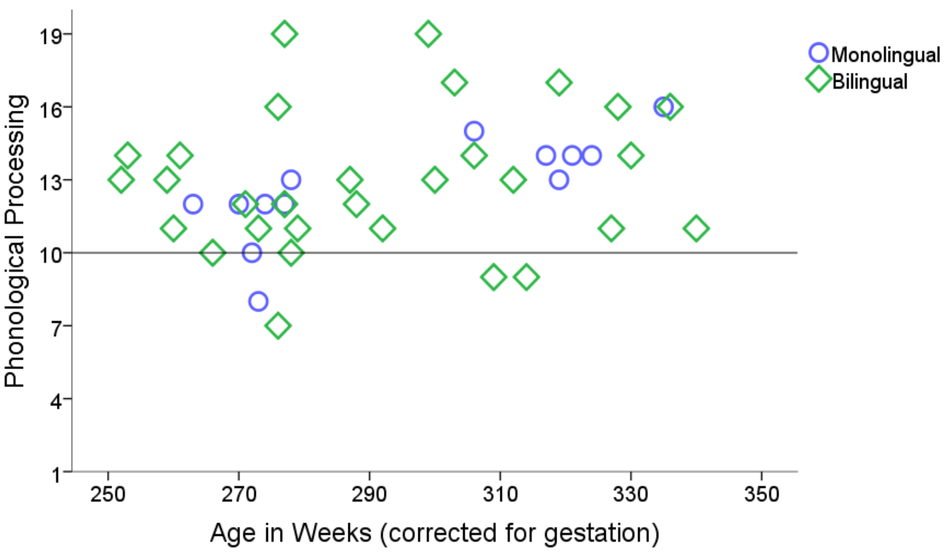

Figure I.4 Scatterplot demonstrating scaled scores on the NEPSY-II (Korkman et al., 2007c, 2007b) phonological processing subtest (scale range on the y-axis) standardised to age (corrected for gestation) as presented on x-axis. The shapes indicate monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis demonstrates the mean expected scores on the assessment.

REPETITION OF NONSENSE WORDS

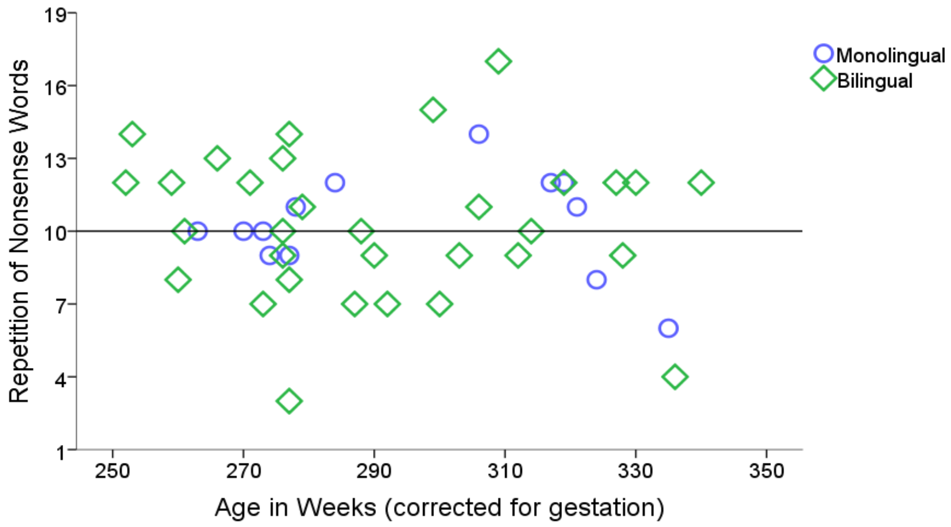

Figure I.5 Scatterplot demonstrating scaled scores on the NEPSY-II (Korkman et al., 2007c, 2007b) repetition of nonsense words subtest (scale range on the y-axis) standardised to age (corrected for gestation) as presented on x-axis. The shapes mark the monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis indicates the average expected scores on the assessment.

SPEEDED NAMING

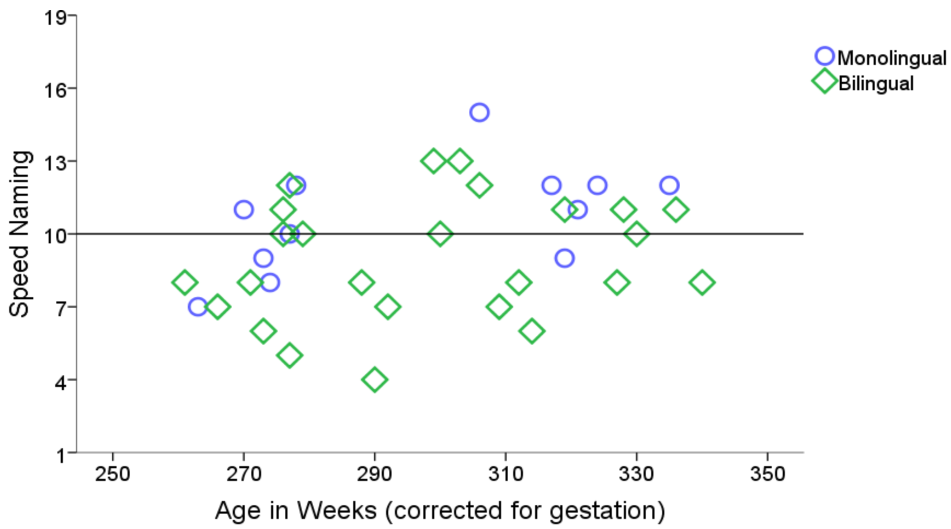

Figure I.6 Scatterplot demonstrating scaled scores on the NEPSY-II (Korkman et al., 2007c, 2007b) repetition of nonsense words subtest (scale range on the y-axis) standardised to age (corrected for gestation) as presented on x-axis. The shapes mark the monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis indicates the average expected scores on the assessment.

WORD GENERATION

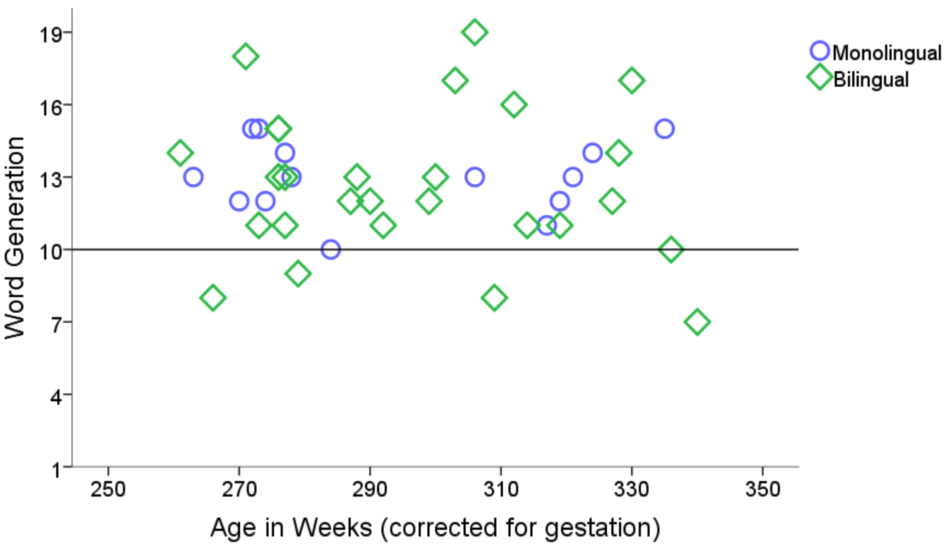

Figure I.7 Scatterplot demonstrating scaled scores on the NEPSY-II (Korkman et al., 2007c, 2007b) words generation subtest (scale range on the y-axis) standardised to age (corrected for gestation) as presented on x-axis. The shapes mark the monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis indicates the average expected scores on the assessment.

LANGUAGE COMPOSITE

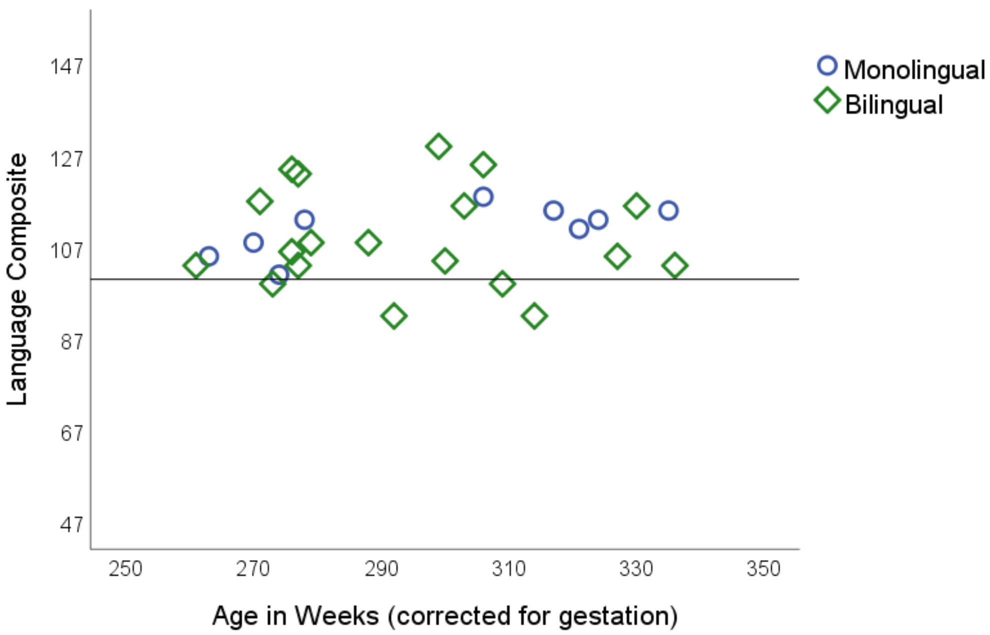

Figure I.8 Scatterplot demonstrating language composite scores which were computed by adding the standardised scores on NEPSY-II (Korkman et al., 2007c, 2007b) comprehension of instructions, oromotor sequences, phonological processing, repetition of nonsense words, speeded naming and words generation subtests and mapping the total value on a scale ranging 47-153 points and with a median of 100 (on the y-axis) standardised to age (corrected for gestation) as presented on x-axis. The shapes mark the monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis indicates the average expected scores on the assessment.

Appendix J. MMR across infants and children in Study 7

Table J.1

T-test Results Demonstrating MMR Significance to Deviance in Phoneme Stream in the Streaming Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/ba/ - /da/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.273	2.164	1.135	80	.260
		Right	.090	1.815	.444	80	.658
	Temporal	Left	.020	1.956	.092	80	.927
		Right	-.134	2.004	-.601	80	.549
150-200	Frontal	Left	.563	2.362	2.147	80	.035*
		Right	.195	1.946	.901	80	.370
	Temporal	Left	.222	2.039	.981	80	.329
		Right	.353	2.214	1.435	80	.155
200-250	Frontal	Left	.615	2.627	2.105	80	.038*
		Right	.399	2.191	1.638	80	.105
	Temporal	Left	.244	2.267	.968	80	.336
		Right	.691	2.464	2.522	80	.014*
250-300	Frontal	Left	.415	2.647	1.413	80	.162
		Right	.367	2.460	1.344	80	.183
	Temporal	Left	.365	2.447	1.343	80	.183
		Right	1.162	2.913	3.591	80	.001**

300-350	Frontal	Left	.137	2.582	.476	80	.635
		Right	.097	2.272	.386	80	.700
	Temporal	Left	.771	2.483	2.795	80	.006**
		Right	1.241	3.102	3.601	80	.001**
350-400	Frontal	Left	.120	2.703	.399	80	.691
		Right	-.078	2.225	-.318	80	.752
	Temporal	Left	1.002	2.408	3.746	80	.000**
		Right	1.124	3.169	3.193	80	.002**

Note. Paired t-tests between averaged ERPs to the /ba/ deviant and /da/ standard phonemes in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in phoneme stream in streaming paradigm in infants and children (N=81). Significance at $p<0.05$ is indicated with *, while $p<0.01$ with ** and highlighted in green. Only the higher significance level was used in analyses.

Table J.2

T-test Results Demonstrating MMR Significance to Deviance in Tone Pair Stream in the Streaming Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/low-high/ - /low-low/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.767	2.104	3.280	80	.002**
		Right	.497	2.010	2.227	80	.029*
	Temporal	Left	-.288	1.613	-1.605	80	.113
		Right	-.267	1.758	-1.365	80	.176
150-200	Frontal	Left	.658	2.184	2.712	80	.008**
		Right	.340	2.236	1.370	80	.174
	Temporal	Left	-.232	1.723	-1.211	80	.229
		Right	-.341	1.857	-1.651	80	.103
200-250	Frontal	Left	.978	2.156	4.084	80	.000**
		Right	.736	2.344	2.823	80	.006**
	Temporal	Left	-.555	1.974	-2.531	80	.013*
		Right	-.437	2.097	-1.877	80	.064
250-300	Frontal	Left	1.889	2.545	6.682	80	.000**
		Right	1.261	2.660	4.266	80	.000**
	Temporal	Left	-.667	2.433	-2.467	80	.016*
		Right	-.165	2.630	-.564	80	.574
300-350	Frontal	Left	1.085	3.075	3.177	80	.002**
		Right	.502	3.426	1.318	80	.191
	Temporal	Left	-.091	2.677	-.307	80	.760

		Right	.743	2.903	2.304	80	.024*
350-400	Frontal	Left	-.393	3.518	-1.006	80	.317
		Right	-.686	3.712	-1.662	80	.100
	Temporal	Left	1.358	3.357	3.641	80	.000**
		Right	1.309	2.643	4.456	80	.000**

Note. Paired t-tests (two-tailed) between averaged ERPs to /low-high/ deviant and /low-low/ standard tone pairs in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in tone pair stream in the streaming paradigm in infants and children (N=81). Significance at p<0.05 is indicated with *, while p<0.01 with ** and highlighted in green. Only the higher significance level was used in analyses.

Table J.3

T-test Results Demonstrating MMR Significance to Deviance in the Phoneme Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/ba/ - /da/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.046	2.096	.198	80	.843
		Right	-.092	1.788	-.461	80	.646
	Temporal	Left	-.234	1.657	-1.273	80	.207
		Right	.055	1.879	.263	80	.793
150-200	Frontal	Left	-.021	2.131	-.089	80	.929
		Right	.188	2.224	.761	80	.449
	Temporal	Left	.002	1.845	.011	80	.991
		Right	-.022	2.228	-.091	80	.928
200-250	Frontal	Left	.203	2.352	.776	80	.440
		Right	.306	2.076	1.326	80	.189
	Temporal	Left	-.039	2.137	-.163	80	.871
		Right	.278	2.183	1.146	80	.255
250-300	Frontal	Left	.314	2.513	1.125	80	.264
		Right	.330	2.071	1.432	80	.156
	Temporal	Left	-.014	2.252	-.055	80	.956
		Right	.934	2.655	3.165	80	.002**
300-350	Frontal	Left	.228	2.374	.866	80	.389
		Right	.007	2.304	.025	80	.980
	Temporal	Left	.155	2.307	.607	80	.546
		Right	.339	2.421	1.261	80	.211
350-400	Frontal	Left	-.045	2.329	-.176	80	.861
		Right	-.453	2.463	-1.655	80	.102

	Temporal	Left	.272	2.613	.935	80	.352
		Right	.262	2.491	.945	80	.347
400-450	Frontal	Left	-.373	2.406	-1.394	80	.167
		Right	-.869	2.644	-2.958	80	.004**
	Temporal	Left	.351	3.091	1.022	80	.310
		Right	.562	2.536	1.993	80	.050
450-500	Frontal	Left	-.538	2.191	-2.210	80	.030*
		Right	-.790	2.782	-2.554	80	.013*
	Temporal	Left	.119	2.988	.358	80	.722
		Right	.641	2.646	2.182	80	.032*
500-550	Frontal	Left	-.514	2.212	-2.093	80	.040*
		Right	-.764	2.686	-2.560	80	.012*
	Temporal	Left	.088	2.759	.288	80	.774
		Right	.520	2.583	1.812	80	.074
550-600	Frontal	Left	-.620	2.387	-2.339	80	.022*
		Right	-.928	2.520	-3.315	80	.001**
	Temporal	Left	.259	2.916	.801	80	.426
		Right	.336	2.575	1.174	80	.244
600-650	Frontal	Left	-.347	2.672	-1.170	80	.246
		Right	-.985	2.720	-3.258	80	.002**
	Temporal	Left	.190	2.991	.571	80	.569
		Right	.273	2.759	.889	80	.377

Note. Paired t-tests between grand-averaged ERPs to /ba/ deviant and /da/ standard phonemes in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in the phoneme paradigm in infants and children (N=81). Significance at $p<0.05$ is indicated with *, while $p<0.01$ with ** and highlighted in green. Only the higher significance level was used in analyses.

Table J.4

T-test Results Demonstrating MMR Significance to Deviance in the Tone Pair Paradigm

Bin (ms)	Region	Hemisphere	Mean / MMR (/low-high/ - /low-low/)	SD	t-test	df	Sig. (2-tailed)
100-150	Frontal	Left	.245	2.504	.879	80	.382
		Right	-.046	2.180	-.191	80	.849
	Temporal	Left	.163	1.788	.822	80	.413
		Right	.035	2.336	.134	80	.894
150-200	Frontal	Left	.161	2.457	.591	80	.556
		Right	-.029	2.527	-.104	80	.917
	Temporal	Left	.084	2.279	.333	80	.740
		Right	.118	2.706	.394	80	.695
200-250	Frontal	Left	.720	2.534	2.556	80	.012*
		Right	.618	2.543	2.187	80	.032*
	Temporal	Left	-.499	2.374	-1.893	80	.062
		Right	-.338	2.859	-1.066	80	.290
250-300	Frontal	Left	1.705	2.941	5.217	80	.000**
		Right	1.404	2.674	4.726	80	.000**
	Temporal	Left	-.698	2.591	-2.425	80	.018*
		Right	-.045	2.906	-.139	80	.890
300-350	Frontal	Left	.663	3.235	1.846	80	.069
		Right	.139	3.076	.408	80	.684
	Temporal	Left	.519	2.869	1.626	80	.108
		Right	.842	3.449	2.197	80	.031*
350-400	Frontal	Left	-.660	4.046	-1.469	80	.146
		Right	-.988	3.837	-2.316	80	.023*
	Temporal	Left	1.428	3.260	3.943	80	.000**
		Right	.670	3.246	1.857	80	.067
400-450	Frontal	Left	.141	4.145	.305	80	.761

		Right	-.135	3.787	-.322	80	.749
	Temporal	Left	1.313	3.487	3.389	80	.001**
		Right	1.227	3.553	3.108	80	.003**
450-500	Frontal	Left	.778	3.678	1.905	80	.060
		Right	.374	3.585	.938	80	.351
	Temporal	Left	1.407	4.068	3.112	80	.003**
		Right	2.218	4.786	4.172	80	.000**
500-550	Frontal	Left	.354	3.512	.908	80	.367
		Right	-.347	3.470	-.901	80	.370
	Temporal	Left	1.835	4.038	4.089	80	.000**
		Right	2.418	4.415	4.930	80	.000**
550-600	Frontal	Left	-.641	3.766	-1.531	80	.130
		Right	-1.419	3.443	-3.708	80	.000**
	Temporal	Left	2.165	4.325	4.506	80	.000**
		Right	1.979	3.859	4.616	80	.000**
600-650	Frontal	Left	-1.425	3.709	-3.459	80	.001**
		Right	-1.801	3.434	-4.719	80	.000**
	Temporal	Left	1.913	4.216	4.085	80	.000**
		Right	1.493	3.849	3.490	80	.001**

Note. Paired t-tests (two-tailed) between averaged ERPs to /low-high/ deviant and /low-low/ standard tone pairs in the clusters of channels in the left frontal (sensor numbers: 19, 20, 23, 24, 27 and 28), right frontal (3, 4, 117, 118, 123 and 124), left (39, 45, 46 and 50) and right (101, 102, 108, 115) temporal clusters in the tone pair paradigm in children (N=41). Significance at $p<0.05$ is indicated with *, while $p<0.01$ with ** and highlighted in green. Only the higher significance level was used in analyses.

Appendix K. Language composite in infants and children in Study 7

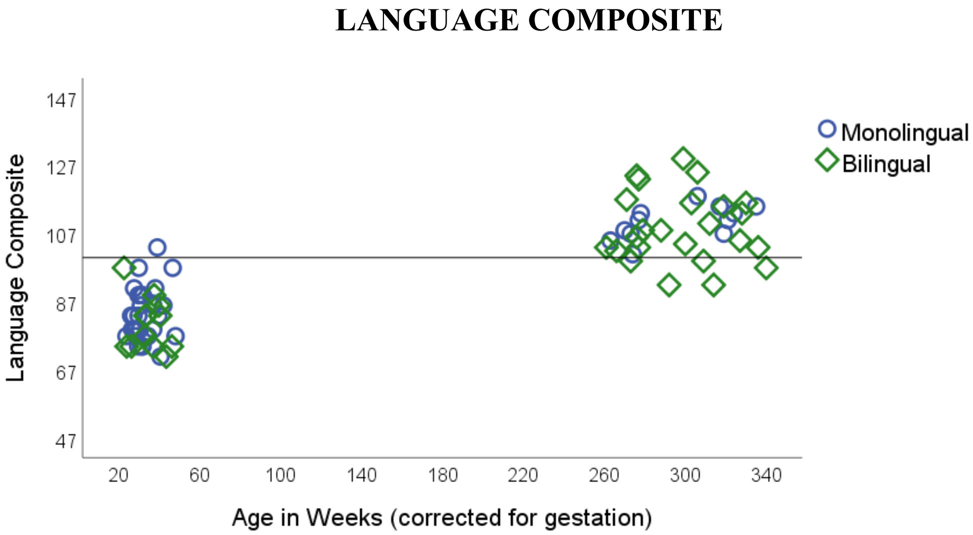

Figure K.1 Scatterplot demonstrating language composite variable consisting of standardised scores in Bayley-III (Bayley, 2005) in infants and in NEPSY-II (Korkman et al., 2007a, 2007b, 2007c) in children. Participants' age is corrected for gestation. The shapes mark the monolingual (blue circles) and bilingual children (green diamonds). The line parallel to x-axis indicates the average expected scores on the assessment.

Appendix L. Ethics documentation

L.1 Approval of PhD ethics application 1

18 August 2015

Dear Jolanta

Project Title:	**Early neural correlates of auditory processing: association between attention control and language in diverse socioeconomic backgrounds.**
Researcher(s):	**Jolanta Golan**
Principal Investigator:	**Dr Elena Kushnerenko**
Reference Number:	**UREC 1415 109**

I am writing to confirm the outcome of your application to the University Research Ethics Committee (UREC), which was considered at the meeting on **Wednesday 22nd July 2015**.

The decision made by members of the Committee is **Approved**. The Committee's response is based on the protocol described in the application form and supporting documentation. Your study has received ethical approval from the date of this letter.

Should any significant adverse events or considerable changes occur in connection with this research project that may consequently alter relevant ethical considerations, this must be reported immediately to UREC. Subsequent to such changes an Ethical Amendment Form should be completed and submitted to UREC.

Approved Research Site

I am pleased to confirm that the approval of the proposed research applies to the following research site.

Research Site	Principal Investigator / Local Collaborator
University of East London premises	Dr Elena Kushnerenko

Approved Documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*
UREC application form	1.0	25 June 2015
Participant information sheet	2.0	05 August 2015
Consent form	2.0	05 August 2015

Photo consent form	2.0	05 August 2015
Recruitment advertisement	2.0	18 August 2015
Invitation letters	1.0	25 June 2015
Session protocol	1.0	25 June 2015

Approval is given on the understanding that the UEL Code of Good Practice in Research is adhered to.

Please note, it is your responsibility to retain this letter for your records.

With the Committee's best wishes for the success of this project.

Yours sincerely,

Rosalind Eccles
University Research Ethics Committee (UREC)
UREC Servicing Officer
Email: researchethics@uel.ac.uk

L.2 Approval of amendment to PhD ethics application 1

15 April 2016

Dear Jolanta,

Project Title:	**Early neural correlates of auditory processing: association between attention control and language in diverse socioeconomic backgrounds.**
Researcher:	**Jolanta Golan**
Principal Investigator:	**Dr Elena Kushnerenko**
Amendment reference number:	**AMD 1516 10**
UREC reference no of original approved application:	**UREC 1415 109**

I am writing to confirm that the application for an amendment to the aforementioned research study has now received ethical approval on behalf of University Research Ethics Committee (UREC).

Should you wish to make any further changes in connection with your research project, this must be reported immediately to UREC. A Notification of Amendment form should be submitted for approval, accompanied by any additional or amended documents:
http://www.uel.ac.uk/wwwmedia/schools/graduate/documents/Notification-of-Amendment-to-Approved-Ethics-App-150115.doc

Approved Research Site

I am pleased to confirm that the approval of the proposed research applies to the following research site:

Research Site	Principal Investigator / Local Collaborator
University of East London premises	Dr Elena Kushnerenko

Approved additional/revised documents

Document	Date

ELAS2 Project Telephone Interview Protocol v2	13 April 2016

Summary of Amendments
Use of different version of Preschool Language Scales Inclusion of additional assessments of attentional control Inclusion of additional questionnaires for measuring socioeconomic risk factors Follow up of TALBY cohort by phone.

Ethical approval for the original study was granted on 18 August 2015.

Approval is given on the understanding that the UEL Code of Good Practice in Research is adhered to.

With the Committee's best wishes for the success of this project.

Please ensure you retain this letter, as in the future you may be asked to provide evidence of ethical approval for the changes made to your study.

Yours sincerely,

Rosalind Eccles
University Research Ethics Committee (UREC)
UREC Servicing Officer
Email: researchethics@uel.ac.uk

L.3 Certificate of passing Academic Integrity Quiz

CERTIFICATE of COMPLETION

This is to certify that

JOLANTA GOLAN

has completed the course

Academic Integrity Quiz

April 28, 2015

Academic Integrity Quiz Result - 100%

UEL
University of East London

oehKqish0I

L.4 Approval of PhD ethics application 2.

31 May 2016

Dear Jolanta,

Project Title:	**Early neural correlates of auditory processing: association between attention control and language in diverse socioeconomic backgrounds**
Principal Investigator:	**Dr Elena Kushnerenco**
Researcher:	**Jolanta Golan**
Reference Number:	**UREC 1516 105**

I am writing to confirm the outcome of your application to the University Research Ethics Committee (UREC), which was considered by UREC **on Wednesday 18 May 2016.**

The decision made by members of the Committee is **Approved**. The Committee's response is based on the protocol described in the application form and supporting documentation. Your study has received ethical approval from the date of this letter.

Please note the UREC Application Form for ethical approval has been revised. For future applications please use the revised application form which can be found on: https://uelac.sharepoint.com/ResearchInnovationandEnterprise/Pages/Ethics.aspx

The Committee would like to commend you on the presentation of this application for ethical approval.

Should you wish to make any changes in connection with your research project, this must be reported immediately to UREC. A Notification of Amendment form should be submitted for approval, accompanied by any additional or amended documents: http://www.uel.ac.uk/wwwmedia/schools/graduate/documents/Notification-of-Amendment-to-Approved-Ethics-App-150115.doc

Any adverse events that occur in connection with this research project must be reported immediately to UREC.

Approved Research Site

I am pleased to confirm that the approval of the proposed research applies to the following research site.

Research Site	Principal Investigator / Local Collaborator
University of East London	Dr Elena Kushnerenco

Approved Documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*
UREC application form	1.0	19 May 2016
Recruitment Advertisement	1.0	19 May 2016
Response and Invitation letter	1.0	19 May 2016
Project Information Sheet	1.0	19 May 2016
Project Location and Travel Sheet	1.0	19 May 2016
Consent Form	1.0	19 May 2016
Photo Consent Form	1.0	19 May 2016
Session Protocol: Baby form	1.0	19 May 2016
Session Protocol: Children form	1.0	19 May 2016
UEL Risk Assessment Form	1.0	19 May 2016
DBS for Jolanta Golan	1.0	19 May 2016
UEL Certificate of Completion: Academic Integrity Quiz, 28 April 2015	1.0	19 May 2016

Approval is given on the understanding that the UEL Code of Practice in Research is adhered to.

The University will periodically audit a random sample of applications for ethical approval, to ensure that the research study is conducted in compliance with the consent given by the ethics Committee and to the highest standards of rigour and integrity.

Please note, it is your responsibility to retain this letter for your records.

With the Committee's best wishes for the success of this project.

Yours sincerely,

Clare Redwood
UREC Servicing Officer
University Research Ethics Committee (UREC)
Email: **researchethics@uel.ac.uk**

University of East London

L.5 Approval of the title amendment request to PhD ethics application 2 (UREC 1516 105).

Dear Jolanta

Application ID: ETH1819-0215

Original application ID: UREC 1415 109

Project title: Neural and behavioural correlates of auditory discrimination and language processing in infants and children

Lead researcher: Ms Jolanta Golan

Your application to Psychology School Research Ethics Committee was considered on the 17th of September 2019.

The decision is: **Approved**

The Committee's response is based on the protocol described in the application form and supporting documentation.

Your project has received ethical approval for 2 years from the approval date.

If you have any questions regarding this application please contact your supervisor or the secretary for the Psychology School Research Ethics Committee.

Approval has been given for the submitted application only and the research must be conducted accordingly.

Should you wish to make any changes in connection with this research project you must complete 'An application for approval of an amendment to an existing application'.

Approval is given on the understanding that the UEL Code of Practice for Research and the Code of Practice for Research Ethics is adhered to.

Any adverse events or reactions that occur in connection with this research project should be reported using the University's form for Reporting an Adverse/Serious Adverse Event/Reaction.

The University will periodically audit a random sample of approved applications for ethical approval, to ensure that the research projects are conducted in compliance with the consent given by the Research Ethics Committee and to the highest standards of rigour and integrity.

Please note, it is your responsibility to retain this letter for your records.

With the Committee's best wishes for the success of the project

Yours sincerely

Fernanda Silva

L.6 Approval of PhD ethics application for Tower Hamlets Council

Law, Probity and Governance
Corporate Research Unit
6th Floor
Town Hall, Mulberry Place
5 Clove Crescent
London E14 2BG

Dr. Jolanta Golan
University of East London
School of Psychology
Arthur Edwards Building
Water Lane
E15 4L

Tel: 020 7364 4238
Email:rgf@towerhamlets.gov.uk

Our Ref: CERGF185

Date: 21st August 2015

Dear Dr. Golan

Research Title:
Early neural correlates of auditory processing: association between attention control and language in diverse socio-economic backgrounds

This is to confirm that your research proposal has been approved by the Research Governance Framework Panel.

Upon completion can you please submit a copy of your report or an extract from your conclusion to the above postal or email address. We may then publish details of your research on the National Social Care Research Register.

I would be grateful if you would complete a short questionnaire to provide feedback on the service that you have received. Please click on the link below.
https://www.surveymonkey.com/s/rgfsurvey We want to ensure that we offer the best quality service to our users and your feedback is essential in improving our services further.

Please do not hesitate to contact me should you need any further assistance.

I wish you well in your research study.

Yours sincerely,

Juanita Haynes
RGF Co-ordinator