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Producing morphologically complex words: An ERP study with children and adults

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ABSTRACT

A widely studied morphological phenomenon in psycholinguistic research is the *plurals-inside-compounds effect* in English, which is the avoidance of regular plural modifiers within compounds (e.g., **rats hunter*). The current study employs event-related brain potentials (ERPs) to investigate the production of plurals-inside-compounds in children and adults. We specifically examined the ERP correlates of producing morphologically complex words in 8-year-olds, 12-year-olds and adults, by recording ERPs during the silent production of compounds with plural or singular modifiers. Results for both children and adults revealed a negativity in response to compounds produced from regular plural forms when compared to compounds formed from irregular plurals, indicating a highly specific brain response to a subtle linguistic contrast. Although children performed behaviourally with an adult-like pattern in the task, we found a broader distribution and a considerably later latency in children's brain potentials than in adults', indicating that even in late childhood the brain networks involved in language processing are subject to subtle developmental changes.

1. Introduction

While language production in adult speakers has been studied extensively, relatively little is known about the processes involved in children's production of words and sentences. Models of the adult speaker posit a sequence of steps during production, from conceptual encoding via lemma selection, morphological and phonological encoding, and finally motor execution and articulation (e.g., Indefrey and Levelt, 2004). The temporal sequencing of these processes has been studied in detail using behavioural and neurophysiological measures leading to the proposal that morphological encoding occurs at about 250–330 ms after the stimulus, which is later than semantic encoding (175–250 ms) but earlier than phonological (330–455 ms) encoding (see e.g., Strijkers and Costa, 2011; Janssen et al., 2011). Neurophysiological studies of the time-course underlying language production processes in children are particularly rare (Budd et al., 2013), and the question of whether the temporal sequencing of language production processes posited for adults also holds for children remains largely unanswered. A number of previous brain-imaging studies have reported developmental changes of the brain networks involved in language production. For instance, it has been proposed that focused left-lateralized networks controlling, for example, silent naming, have emerged from bilateral networks during late childhood and adolescence (e.g., Lidzba et al., 2011; Everts et al., 2009), leading to speculations about how these changes in brain development can impact on language (and other higher cognitive) processes. Against this background, the question of whether adults and children make use of

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comparable mechanisms for language production becomes even more relevant. The present study contributes new findings to this under-researched issue by investigating processes involved in children's (in comparison to adults') production of morphologically complex words using ERPs.

The specific phenomenon we studied is the distribution of singular and plural modifiers inside compounds. In English, for example, compounds with singular modifiers are more acceptable than those with plural ones, and amongst those with plural modifiers, compounds with regular plural modifiers are less acceptable than those with irregular ones; compare *goose/duck feeder*,?*geese feeder*, **ducks feeder* (e.g., Haskell et al., 2003; Cunnings and Clahsen, 2007). The so-called plurals-in-compounds effect is subject to a number of subtle linguistic constraints (see below), which have been widely studied in the psycholinguistic literature, albeit mainly in behavioural experiments. Plurals-in-compounds have also played a prominent role in debates concerning the nature of children's language development and in the controversy between symbolic rule-based versus associative models of language (e.g., Pinker, 1999). Three-year-old children already demonstrated adult-like knowledge of this phenomenon (e.g., Gordon, 1985; Alegre and Gordon, 1996), which they could not have learnt from modelling the linguistic input, but instead may reflect properties of the innately specified architecture of the language system (Pinker, 1999: 208); see Haskell et al. (2003) and Ramscar and Dye (2010) for a different view. Although compounding has been examined previously in ERP studies (e.g., Koester and Schiller, 2008; MacGregor and Shtyrov, 2013), studies of the plurals-in-compounds effect using brain measures are not available. The neural correlates of the plurals-in-compounds effect and the question of whether there are any developmental changes in the brain's responses to contrasts such as *ducks feeder* vs. *geese feeder* have therefore remained unanswered. The present study addresses these questions by measuring ERPs from 8- to 12-year-old children as well as adults during their (silent) productions of English compounds containing (regular vs. irregular) plural modifiers.

1.1. Morphological encoding in (adults and) children

A number of previous experimental studies have compared processes involved in the production of morphologically complex words in children and adults; see Clahsen (2008) for a review. The most widely used technique is the speeded production paradigm in which participants read bare verb stimuli (e.g., "*collect*") and are asked to produce a corresponding inflected form (e.g., "collected"), as quickly and as accurately as possible. Studying adult speakers of English, Prasada et al. (1990) and Prado and Ullman (2009) found significantly longer production latencies for *irregular* past-tense forms with low than for high frequencies, but there was only a considerably weaker frequency effect for the production of regularly inflected (*-ed*) forms (Prasada et al., 1990; Prado and Ullman, 2009). This contrast suggests that irregular English past tense forms are accessed as full forms during production while regulars are composed from their component parts. The speeded production task has also been used to study morphological encoding in children (e.g., Clahsen et al., 2004; Fleischhauer and Clahsen, 2012). Testing 5- to 12-year-old children in different age groups on inflected verb forms of German, an advantage for high- over low-frequency irregular forms was found in all participant groups, parallel to the findings on the English past tense. Thus, a behavioural measure, namely speeded production latencies, yielded adult-like performance patterns in 5- to 12-year-old children.

The speeded production task has also been applied to examine the plurals-in-compounds effect in English, albeit only for adult speakers. (Buck-Gengler et al., 2004: 459) found that when participants were probed with an irregular plural form they took significantly longer to produce compounds containing singular non-heads than when they were probed with the corresponding singular form (e.g., *Tub holding mice is a* . . .. vs. *Crate for carrying a bead is a* . . .). Still, when probed with a regular plural form (e.g., *Box for transporting axes is an*. . .), there was no such contrast. These results indicate that singular forms are more easily accessible from a regular (than from an irregular) plural form during the encoding of the compound. Several other behavioural studies have used off-line elicitation tasks to examine children's sensitivity to modifier constraints for compounds in production (Gordon, 1985; Oetting and Rice, 1993; van der Lely and Christian, 2000; Clahsen and Almazan, 2001; Zukowski, 2005). A consistent finding from these studies was that children as young as three avoided regular plurals inside compounds (e.g., **rats eater*), but were very willing to produce irregular plurals inside compounds (e.g., *mice eater*). Despite the replicability of the plurals-in-compounds effect, the interpretation of these behavioural experiments has remained controversial; see, for example, Ramscar and Dye (2010) vs. Jaensch et al. (2014).

1.2. Neurophysiological markers of language production

As the review above illustrates, the majority of studies examining children's production of morphologically complex words have made use of behavioural tasks (e.g., elicited production, production latencies). While these are informative in their own right, they do not provide insight into the precise temporal unfolding of processes during language production. Thus, to get a better understanding of the temporal sequencing of processes underlying language production, some studies have started to apply more time-sensitive measuring techniques to investigate these processes; see Ganushchak et al. (2011) for a recent review. However, morphological encoding has (to our knowledge) only been examined in three previous studies, two using ERPs (Koester and Schiller, 2008; Budd et al., 2013) and one intracranial recording (Sahin et al., 2009), and a comparison between children and adults with respect to morphological encoding is only available from one study (Budd et al., 2013). Budd et al. (2013) used a silent-production-plus-delayed-vocalization-task to investigate the production of regular and irregular past-tense forms of English verbs by recording ERPs in 8- to 12-year-old children and in adults. Participants read infinitive forms (e.g., *to walk, to fall*) and were then prompted to silently produce either the past-tense form (e.g., *walked, fell*) or the third-person singular present-tense form (e.g., *walks, falls*). Finally they were cued to overtly produce the inflected word form. ERPs recorded from the cue to silently produce the inflected forms showed a negativity between 300 and 450 ms after cue onset for regular compared to irregular past-tense forms in adults. A similar but longer lasting negativity was found in 10- to 12-year-olds.; additionally, children showed a small positivity 650–800 ms after cue onset. These ERP responses were interpreted as signalling combinatorial processing required by regular but not irregular past-tense forms. As this is the only ERP study investigating morphological encoding in children, it remains to be seen whether the findings reported are replicable and generalizable to other morphological phenomena.

1.3. The present study

This study is the first to report results from brain measures during children's (and adults') production of compounds with plural and singular modifiers. In English, compounds are right-headed with the head noun denoting the kind of object the compound refers to. A *handgun*, for example, is a kind of gun, not a kind of hand. A compound's non-head (or modifier) is typically an uninflected stem, identical to the singular form of nouns (e.g., *hand* in *handgun*). If, however, the non-head appears in plural form, native English speakers rate compounds with regular plural modifiers (e.g., *ducks feeder*) as worse than those with irregular ones (e.g., *geese feeder*). This contrast has been explained in morphological terms. According to Kiparsky (1982) regular inflectional processes (e.g.,–*s* plurals in English) are formed at a later stage than compounding and are therefore unavailable as non-heads of compounds; see Berent and Pinker (2007), Cunnings and Clahsen (2007) and Silva et al. (2013) for experimental evidence and further linguistic background.

We adapted the silent-production-plus-delayed-vocalization task from Budd et al. (2013) to the current study. This task has a number of advantages over other ERP production designs. Firstly, it minimizes speech-muscle-related artefacts of the EEG signal, as ERPs are time-locked to the *silent* production of a given word form. Secondly, the delayed-vocalization part of the task requires participants to produce an *overt* spoken response of this word form, which maximizes the chance that the EEG recording does indeed reflect processes in producing this word form. We hypothesize that the constraint against regular plurals inside compounds is morphological in nature and engages the same combinatorial mechanism as –*ed* past-tense formation, namely stem + affix (de)composition. We therefore expect to find ERPs similar to those obtained by Budd et al. (2013), namely an enhanced negativity for compounds in the regular plural condition relative to the irregular one for both children and adults. In order to compare results to previously reported findings (Budd et al., 2013), we studied the same age groups of children, namely 8- to 12-year-olds.

2. Methods

2.1. Ethics statement

All participants gave informed written consent before completing the study, which was ethically approved by the University of Essex Ethical Review Board. In the case of the children, the parents of the children who participated gave informed consent.

2.2. Participants

Seventy-three right-handed native speakers of British English were tested, all with normal or corrected-to-normal vision, 20 adults (7 men, mean age 23.6 years, range 18–31 years) and 53 children. Thirteen children were excluded; two children could not perform the task, and 11 had high artefact rates (>70% trials lost) during EEG recording. Following Budd et al. (2013), the remaining 40 children were divided into two age groups, 11- to 12-year-old children '*Ch-12*' (*n* = 18, 12 boys, mean age: 11;07, range: 11;01–12;08) and '8- to 9-year-old children '*Ch-8*' (*n* = 22, 10 boys, mean age: 9;02, range: 8;08–9;07).

2.3. Materials

The experimental conditions and the critical nouns to be used as non-heads of compounds were the same as in Silva et al. (2013). Eight nouns that take irregular plural inflections were matched for frequency, length and meaning with eight nouns that take the regular plural. These items were: *man/men* vs. *boy/boys*, *woman/women* vs. *girl/girls*, *child/children* vs. *baby/babies*, *foot/feet* vs. *hand/hands*, *tooth/teeth* vs. *eye/eyes*, *goose/geese* vs. *duck/ducks*, *louse/lice* vs. *beetle/beetles*, *mouse/mice* vs. *rat/rats*. Participants were presented with these word forms as potential non-heads of noun-noun compounds; this yielded four conditions, irregular plural non-heads ('Pl-I'), regular plural non-heads ('Pl-R') and the corresponding uninflected 'singular' non-heads ('Sg-I', 'Sg-R'). Each non-head noun was presented with five different verbs (e.g., *bite, chase*) from which compounds containing deverbal -*er* agentive head nouns could be formed (e.g. *boy(s)/man(men) biter* and *boy(s)/man(men) chaser*). This yielded 160 experimental items (40 per condition). The 100 filler items consisted of head nouns that were 'occupations' (e.g., *vet, teacher, dentist*) paired with non-heads that were either adjectives (e.g., *red, green, wet, tall*) or pluralia tantum nouns (e.g., *maths, measles*).

2.4. Procedure

All participants were tested in quiet rooms either at the University of Essex (adult, older children) or at different schools (younger children) in the same area. Participants were first introduced to the task with six practice trials not used in the experiment. Each trial began with the presentation of a centred fixation-cross for 200 ms, followed by the visual presentation of two words placed one on top of the other in the centre of the screen for 1000 ms. The top word was always the unmarked verbal stem of the deverbal head noun to be produced (e.g., *feed* ->FEEDER) and the bottom word was the non-head (e.g., *duck*) either in its uninflected (singular) form or its inflected (plural) form. Presentation order of the two words was always different from their order in the compounds to be produced. This was also the case for the filler items. The stimulus was followed by a blank screen, which varied in duration (400, 600 or 800 ms). The presentation duration of the blank screen was counterbalanced across conditions. To cue the silent production of the compound, a picture of a cartoon figure was presented for 2000 ms.

Participants were instructed to first read the top and then the bottom word and only silently produce a 'good sounding' compound when the cue appeared (i.e. participants understood that they did not simply have to produce a compound from the exact words displayed on screen). If during the practice trials participants were, for example, presented with the words *socks* and *washer* and they produced *socks washer*, the experimenter would say to them: 'That doesn't sound quite right. Don't you think that *sock washer* sounds better?' This comment was then followed by a presentation screen on which the word *sock washer* was displayed. ERPs were time-locked to the onset of this silent production cue. The silent production cue was then followed by a 1000 ms long presentation of a loudspeaker picture to cue *overt* production of the compound. Finally, a blank screen was presented for 1500 ms. Trials were pseudo-randomized and distributed over ten blocks (26 items each). Participants only saw an item in either its uninflected (singular) or plural form in any one block. Blocks were divided by a short break and were counterbalanced amongst participants. Participants were asked to minimize eye and muscle movements during silent production. The run-time of the experiment was approximately 35 min. One experimental session (including EEG setup) lasted for approximately 105 min.

2.5. EEG recording and data analysis

The adult participants' EEGs were recorded using Neuroscan (version 4.5) acquisition software, from 64 electrode sites (see Fig. 1) according to the international 10–20 system using Ag/AgCl sintered electrodes embedded in an elastic cap (Quik-Cap, Neuromedical Supplies). Bipolar horizontal and vertical electro-oculograms (EOGs) were recorded for artefact rejection purposes. Epochs were extracted from 200ms before the onset of the silent production cue up to 1000 ms after cue onset. Recordings were referenced online to the left mastoid. Signals were recorded continuously with an on-line band-pass filter between 0.1 and 70 Hz and digitized at 500 Hz. Electrode impedances were kept below 5 KΩ. Recordings were re-referenced off-line to the average of the left and right mastoid electrodes,

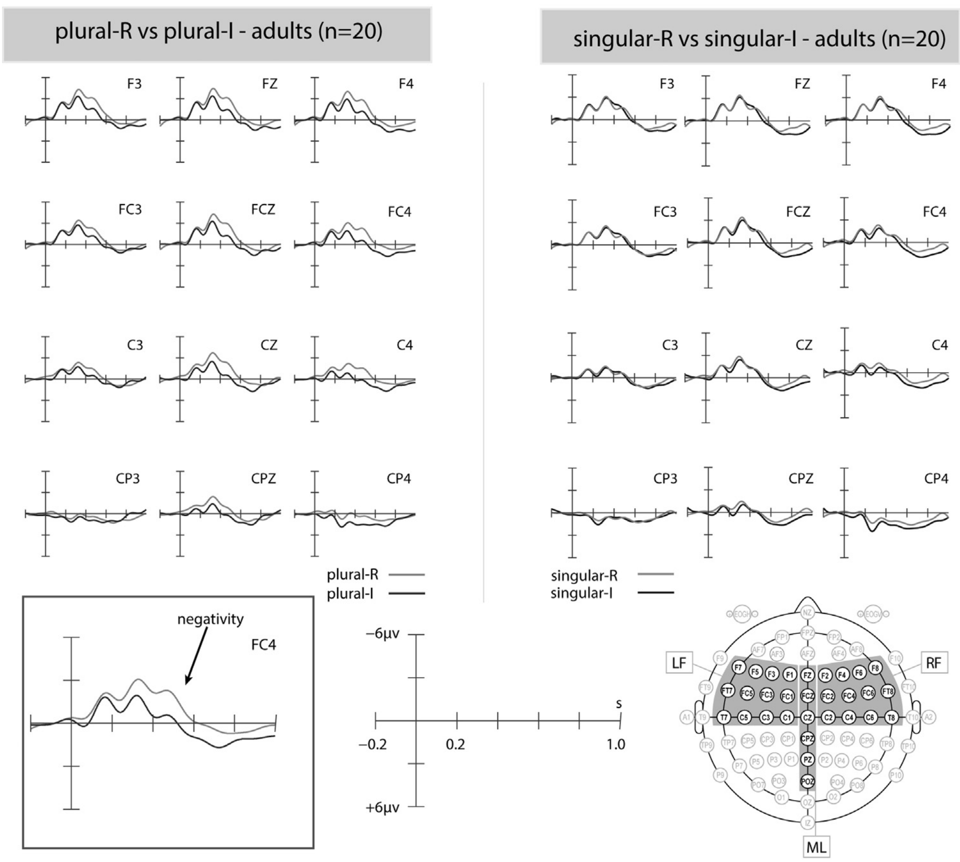

Fig. 1. Adult ERP effects at selected electrode sites. The head on the right shows ROIs used in the statistical analysis.

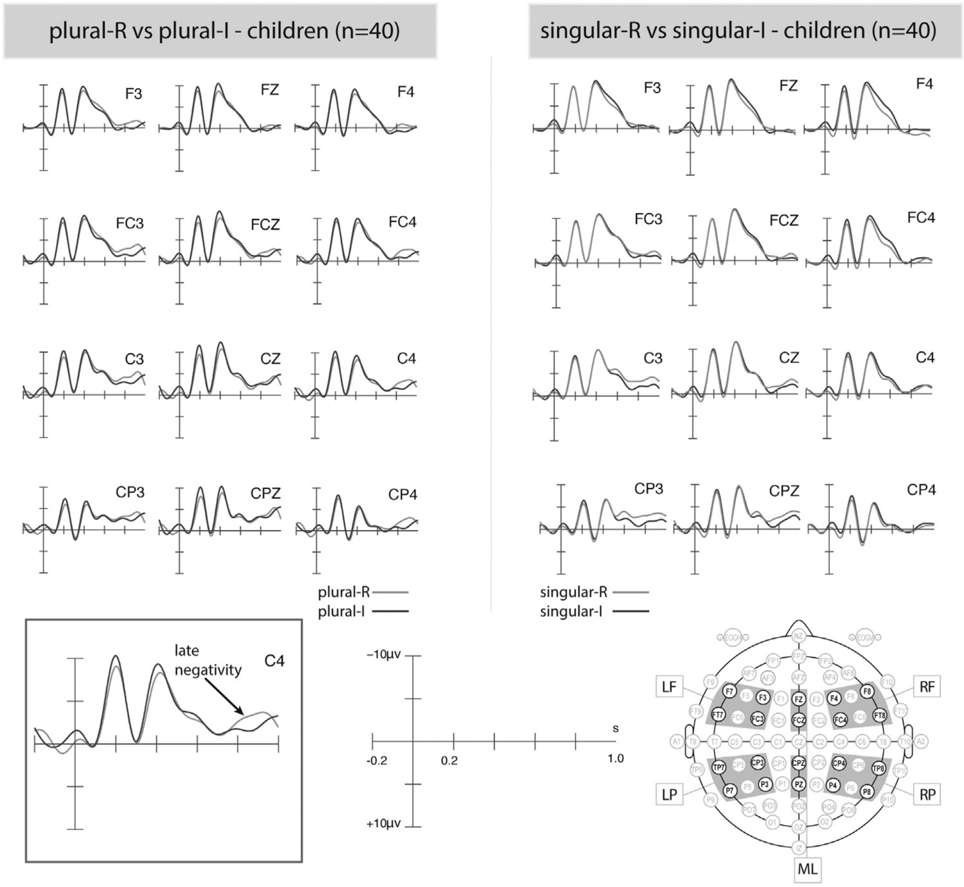

Fig. 2. ERP effects from children at selected electrode sites. The head on the right shows ROIs used in the statistical analysis.

band-pass filtered between 0.1 Hz and 30 Hz, and baseline corrected. For graphical illustration purposes only, grand average ERPs are smoothed with a 7 Hz low-pass filter. For the child participants, the EEG was recorded from only 32 electrode sites (see Fig. 2).

The EEG data was processed with EEGLAB (Delorme and Makeig, 2004). To remove typical muscle and eye movement artefacts, an independent component analysis (ICA) algorithm (Infomax) was applied to the data. Additionally, trials with artefacts were visually identified and removed. Trials for which a participant's overt production was inappropriate were not included in the ERP analysis; these included incorrect compounds with unreduced regular plural non-heads (e.g., *ducks feeder*), single-word responses (e.g., *feeder*) and responses containing a lexical item that was not available from the visual stimulus (e.g., *eater* instead of *feeder*).

Overt behavioural responses were analysed using generalized linear mixed models (lme4 function in R), with respect to whether the candidate non-head noun form was maintained or reduced inside the spoken compound. For the ERP data, time windows of interest for mean amplitude quantification were identified based on visual inspection and also based on previously reported findings (Budd et al., 2013). For the adult data, visual inspection revealed that effects between 300 and 450 ms were primarily visible at frontal electrode sites with a possible dominance in the right hemisphere. Thus, two ROIs were analysed which included electrodes from left and right frontal (LF/RF) electrode sites. Midline (ML) electrodes were analysed separately (see Fig. 1) to keep the number of electrodes constant in each ROI. For the two child age groups, visual inspection indicated contrasts most prominently between 800 and 900 ms, without any strong hemispheric or regional specialization. Thus, electrodes from left and right frontal sites (LF/RF), left and right parietal sites (LP/RP), as well as midline electrodes (ML) were analysed for this time window (See Fig. 2).

3. Results

3.1. Behavioural responses

Participants' overt responses indicated that both children and adults performed the compound-production task accurately, with few omissions or lexical errors (adults: 1.2%, older children 'Ch-12′': 3.3%, younger children 'Ch-8′': 6.5%). Because the focus of interest for the current study is the form of the compound-internal modifiers (rather than the overall accuracy), these omissions and lexical errors were excluded from any further analyses. For the remaining data, we calculated proportions of productions in which the form of the stimulus noun presented to participants as a candidate for a compound-internal modifier was maintained in their compound productions (against cases in which it was changed) for the three types of candidate noun forms (singular, irregular plural, regular plural) and the adult and the child groups.

The compound responses revealed that when presented with an uninflected singular form (e.g., *duck*/*goose*), this was almost always included as a compound-internal modifier, irrespective of whether the noun's corresponding plural form was regular or irregular (adults: 99.8%, Ch-12: 95.6%, Ch-8: 98.8%). When the noun to be included as a compound-internal modifier was an irregular plural form, it was still mostly maintained inside compounds, but less so than bare singular forms (adults: 91.1%; Ch-12: 85.2%; Ch-8: 82.3%). A clear contrast was found for nouns presented as regular plural forms which were rarely maintained in compounds but instead mostly reduced to bare singulars (adults: 12.5%; Ch-12: 4.3%; Ch-8: 5.7%). To examine these data statistically, we performed an ANOVA on the compound responses with the factors Condition (Singular, Irregular Plural, Regular Plural) and Group (Adults, Ch-12, Ch-8), which revealed main effects of Group ($F(2, 57) = 15.3$, $p < .001$) and Condition ($F(2, 114) = 814.6$, $p < .001$), but no reliable interaction of Condition by Group ($F(4,114) = 1.649$, $p = .167$). Subsequent pairwise contrasts showed that irregular plural forms were significantly less often maintained inside compounds than bare singular forms in both the adult and the child groups (adults: $\beta = 4.55$, SE = 1.05, $z = 4.34$; Ch-12: $\beta = 1.26$, SE = 0.21, $z = 5.98$; Ch-8: $\beta = 2.69$, SE = 0.31, $z = 8.72$). Furthermore, regular plural forms were significantly less often maintained in compounds than irregular plural forms (adults: $\beta = 5.75$, SE = 0.26, $z = 21.44$; Ch-12: $\beta = 4.99$, SE = 0.22, $z = 22.38$; Ch-8: $\beta = 4.44$, SE = 0.18, $z = 24.70$). These results suggest the same pattern of behavioural responses for adults and children, with irregular plurals less likely to be used than uninflected (singular) forms inside compounds, and regular –*s* plurals rarely occurring as a compound's non-head. It should be noted that these behavioural data should be interpreted with caution given the ceiling effects observed in the adult data.

3.2. ERP data

Mean amplitudes were extracted for each participant at each electrode site. After data cleaning, 81% of trials were included in the statistical analysis. On average, similar numbers of trials were included for the different types of non-head, bare singulars (adults: 84%, ch-12: 85%, ch-8: 79%), regular plurals (adults: 73%, ch-12: 76%, ch-8: 76%), and irregular plurals (adults: 85%, ch-12: 84%, ch-8: 81%). The grand-average ERP waveforms can be seen in Figs. 1 and 2.

3.2.1. Adults

Mean ERP amplitudes extracted from the 300–450 ms time-window were statistically analysed with a repeated measures ANOVA for Number (Plural vs. Singular), Regularity (Regular vs. Irregular), and 'Regions of Interest' (ROIs) as within-subjects factors. For the frontal electrode sites, this analysis revealed a significant main effect of Regularity ($F(1,19) = 7.26$, MSE = 1.56, $p < .05$) and a Number × Regularity interaction ($F(1,19) = 4.19$, MSE = 3.17, $p = .05$). Follow-up analyses by Number revealed a significant Regularity effect within the plurals ($F(1,19) = 7.06$, MSE = 3.48, $p < .05$), but not for the singulars ($F(1,19) = 0.03$, MSE = 1.25, $p = .86$). These results show that the source of the Number × Regularity interaction in the frontal electrode sites is due to more negative-going amplitudes for compounds produced from regular plural forms (as candidate compound-internal modifiers) relative to those produced from irregular plural forms, without any corresponding contrast in the singular condition. No significant effects were found at ML electrode-sites. These results show that adults show a bilateral, frontally distributed negativity when a regular (relative to an irregular) plural form was presented as a candidate non-head element for the (silent) production of a compound. This effect is visually illustrated in the left hand panel of Fig. 1. The right-hand panel of Fig. 1 compares the waveforms for the singular conditions, for nouns (e.g. *rat*) that have regular plurals ('singular-R') versus nouns (e.g. *mouse*) that have irregular plurals ('singular-I'), illustrating that this comparison indeed shows little difference between the two waveforms, in line with the statistical results.

3.2.2. Children

Regarding the child data, consider first the left side of Fig. 2 which shows that between 800 and 900 ms after the cue onset, ERPs for compounds produced from regular plural forms (as candidate compound-internal modifiers) indicate broadly distributed more negative-going amplitudes than ERPs to compounds produced from irregular plural forms. The right side of Fig. 2 compares waveforms in response to the singular-R and singular-I conditions; visual inspection does not indicate any clear contrast for this comparison. An ANOVA including Number, Regularity and ROI as within-subjects factors and Age Group ('Ch-8′, 'Ch-12′) as a between-participants factor was carried out for mean amplitudes extracted between 800 and 900 ms after cue onset. This analysis revealed an interaction of Number *x* Regularity that was approaching significance ($F(1,38) = 3.68$, MSE = 24.35, $p = .06$) and which was not qualified by ROI. Follow-up analyses by Number showed a significant Regularity effect within the plurals ($F(1,38) = 6.32$, MSE = 29.59, $p < .05$) but not within the singulars ($F(1,38) = 0.0$, MSE = 33.66, $p = .9$). This contrast is due to more negative-going amplitudes for compounds produced from regular plural forms relative to those produced from irregular plural forms, and no corresponding contrast for the singular forms of the nouns tested (e.g. *rat* vs. *mouse*). The effect of Regularity within the plural conditions was also not modulated by Age, which means that it applies to both age groups of children. Furthermore, this late negativity for compounds produced from regular plural non-head candidates was also seen in an additional analysis that only included trials in which the children's overt compound responses, both in the regular and the irregular plural condition, had an uninflected (i.e. reduced) non-head. No other effects were found significant. These results show a late globally distributed negativity for both age groups of children when a regular (relative to an irregular) plural form was presented as a candidate non-head element for the (silent) production of a compound.

4. Discussion

The plurals-in-compounds effect has received considerable attention in the psycholinguistic literature and has played a crucial role in more general debates in cognitive science concerning the role of grammar in language processing and development (e.g., McClelland and Patterson, 2002; Pinker and Ullman, 2002). The current study reports the first ERP production study of the plurals-in-compounds effect in 8- to 12-year-old children in comparison to adults. We found that the brains of both children and adults appear to honour the subtle linguistic constraints that govern the distribution of compound-internal modifiers. Specifically, the constraint against regular plurals inside lexical compounds was signalled by an enhanced negativity for the (silent) production of compounds from regular (compared to irregular) plural forms as non-heads. This negativity was found for both adults and for children across the age range tested. The behavioural results also seemed parallel for the two groups, indicating that 8- to 12-year-olds are sensitive to the constraint in the same way as adults, though interaction effects might have been masked by ceiling effects observed for adults. We also observed a number of developmental changes, particularly in the EEG data. Firstly, children's electrophysiological markers were considerably delayed (by ∼450 ms relative to adults). Secondly, the negativity was fronto-centrally distributed (and slightly more right-lateralized) for adults, but had a much broader distribution for children.

4.1. Temporal sequencing of morphological encoding

The adult ERP findings are broadly consistent with the temporal sequencing proposed in models of speech production (e.g., Indefrey and Levelt, 2004). Specifically, it is hypothesized that (in picture naming tasks) morphological encoding occurs around 250–330 ms after stimulus presentation with an assumed average naming latency of 600 ms. The nature of our silent production task is different from a standard word-naming experiment in that we presented participants with written word prompts for producing compounds, rather than with pictures. Furthermore, the compounds to be produced were relatively long words and thus likely to yield longer latencies. The timing of our adult ERP data is also in line with Koester and Schiller (2008), who reported morphological encoding to occur at around 350 ms after the start of conceptual processing, and with Budd et al. (2013), who reported morphological encoding effects in adults between 350 and 500 ms after the production cue. Moreover, intra-cranial EEG recordings (Sahin et al., 2009) also obtained neural signal modulation at around 320 ms after cue onset. Crucially, electrophysiological signals during (silent) language production appear to be reproducible for different morphological phenomena and across a variety of tasks and designs.

With respect to its functional significance, Budd et al. (2013) interpreted the negativity as signalling combinatorial processing required by regular (but not irregular) past-tense forms. We propose the same account for the types of compounds examined in the current study. Consider the two kinds of plural form presented as non-head elements, for example, *(feed) ducks/geese*. The morphological constraint bans regular plurals from appearing inside compounds. Consequently, the –*s* affix of a regular plural form such as *ducks* needs to be stripped off before being entered as a non-head into the formation of a compound. This process of affix stripping engages the same combinatorial mechanism as–*ed* past-tense formation, namely stem + affix (de)composition, hence eliciting similar brain responses.

The current ERP results are in line with findings from comprehension and offline judgment studies on plurals-inside-compounds in adult native speakers of English. Violations of the constraint against compound-internal regular plurals disrupt both written and spoken language comprehension. Compounds with regular plurals yielded the longest first fixation and gaze durations in an eye-movement during reading experiment (Cunnings and Clahsen, 2007), indicating that the –*s* plural constraint affects early stages of processing. Early effects of this constraint were also found in an eye-movement during listening experiment (Silva et al., 2013). Furthermore, findings from acceptability judgment tasks (Berent and Pinker, 2007; Jaensch et al., 2014) revealed that morphological plurals are disfavoured inside compounds, but not non-head elements with/s/or/z/sibilant-final codas that merely sound like regular plurals, indicating that the plurals-in-compounds effect is morphological in nature and cannot be accounted for by superficial phonological properties of the non-head nouns (contra Haskell et al., 2003; Ramscar and Dye, 2010). The proposed functional interpretation of the enhanced negativity as signalling morphological structure is consistent with these findings.

4.2. Developmental changes from child to adult

While the current ERP results for compounds from adults are in line with the assumed sequencing of language production (e.g., Indefrey and Levelt, 2004; Strijkers and Costa, 2011), our ERP results for children indicate a remarkable temporal delay. Specifically, the negativity in response to producing compounds from regular (as opposed to irregular) plural non-heads was found between 800 and 900 ms after cue onset in children. What could be the underlying reason for this temporal delay? First, production latencies in paradigms using picture naming have been shown to be 300–500 ms longer in children than adults (e.g., Jerger et al., 2002). Secondly, ERP studies of violation and discrimination have also shown that children's ERP components are sometimes delayed as compared to adults (Männel and Friederici, 2008). Thirdly, a study of morphological processing in language *comprehension* has also reported delayed ERP effects for children when compared to adults (Clahsen et al., 2007). If we assume a similar delay for our silent production task as for picture naming, a temporal adjustment of the observed ERPs for children is required, the result of which puts the negativity obtained for the production of compounds into roughly the same time-frame as for adults. That the ERPs have a delayed onset in children suggests that the compound encoding process is fairly established albeit slower in children. This interpretation is supported by the current behavioural data which showed that 8- to 12-year-olds produced adult-like compound forms. While a delayed vocalisation paradigm offers many advantages when working with children (by, for example, minimizing muscle movements and by allowing children to perform the task in their time), results from the delayed vocalisation task concerning time-course related information need to be interpreted with caution. Thus, future studies applying different paradigms (including immediate production) are required to further test the time-course of morphological processing in children.

However, the enhanced negativity we obtained was not only delayed, but also had a broader distribution in children than in adults. It was observed at both fronto-central and parietal electrode-sites bilaterally, whereas in adults the negativity was more localized, with the largest effect visible at fronto-central electrode sites. Clearly, ERPs have a rather low spatial resolution; however, topographical differences of ERP signatures are generally accepted to reflect neural source differences (c.f. Luck, 2014). In other words, if ERP patterns differ with regard to both temporal and spatial attributes, it is likely that the neural source(s) underlying the effects are at least partially different. The latter interpretation goes well with reports in the literature which suggest that the brain systems underlying higher cognitive functions including language are still fine-tuned even during adolescence (see Casey et al., 2005; Blakemore, 2012 for reviews). Specifically, both cross-sectional and longitudinal functional imaging studies have highlighted that the developing brain undergoes significant structural and functional changes of fronto-temporal cortices in children aged 8–12 years (i.e., the age groups investigated here) generated by a combination of neuron pruning, myelination, as well as vascular, neuronal and glial density changes. These developmental neuroanatomical changes are argued to be particularly important for growing and enhancing efficient neuronal communication (Casey et al., 2005). Hence, the observed delayed and differently distributed ERP effects may reflect slower and less efficient abilities in producing morphologically complex words in children than in adults.

It is noteworthy that despite the observed ERP differences, children seemed to produce the same overt behavioural responses as adults in our experiment. It is possible that group differences might not have been observed because of high response accuracy (i.e., ceiling effects can mask interactions). It could also be argued that this discrepancy is due to children sometimes self-correcting initially erroneous responses. This is unlikely, however, firstly because the experimenter encouraged participants not to change their initial response and secondly because the same pattern obtained in the current study, viz. adult-like offline performance paired with distinct ERP responses for children, has been reported in ERP *comprehension* studies testing morpho-syntactic and morphological phenomena (Hahne et al., 2004; Clahsen et al., 2007). The latter results have been taken to indicate that despite similar offline performance adult-like comprehension mechanisms take time to develop. Our results indicate that this also applies to processes involved in the production of morphologically complex words.

Finally, a similar pattern of ERP results to the one reported here was obtained by Budd et al. (2013), a study employing the silent production paradigm to examine past tense formation in children and adults. In both studies, children and adults responded with an enhanced negativity to regular (when compared to irregular) inflection, but with a later onset latency and a more broadly distributed effect for children than for adults. Taken together, these findings lend support to the assumption that the brain mechanisms underlying the production of morphologically complex words may not yet be fully adult-like in 8- to 12-year-old children. Specifically, it seems as if processing is slower and less efficient (delayed negativity) as well as possibly more resource-demanding in children than in adults.

4.3. Form priming in the silent production task?

An unexpected result from the current study warrants commenting. Several previous behavioural studies of plurals in compounds have found that irregular plurals are clearly dis-preferred as compound-internal modifiers relative to bare (singular) forms; see Jaensch et al. (2014) for a recent review. It is true that in the current study, singular modifiers were significantly more common than irregular plural ones in participants' overt productions, for both children and adults, but still irregular plural modifiers were most often not reduced to singular forms inside compounds. This admittedly unexpected finding could, however, be due to a form-priming effect (Ramscar and Dye, 2010). In our experiment, participants were confronted with a singular or plural form of a noun as a potential compound modifier immediately prior to the compound-production task. This recent presentation of a candidate modifier form could have biased participants to maintain the presented noun form inside the compound, *whenever possible*. This form-priming effect explains why participants commonly included not only singular but also (grammatically permissible) irregular plural forms into their compounds. Crucially, however, form priming only provides a partial account of the current findings, as form priming should have induced repetition of the primed form inside the compound *across the board*. This was not the case, however. Instead regular plural modifiers (compared to irregular ones) yielded an enhanced negativity during (silent) production in the EEG record and were reduced to singular forms in participants' spoken compounds, even though they were primed in the same way as irregular plurals (or singulars). This contrast strengthens the case for a morphological constraint against compound-internal *–s* plurals as the source for the reported ERP and behavioural responses.

5. Conclusion

This study illuminates the brain mechanisms involved in children's (as well adults') language production, by determining the brain responses obtained from the (silent) production of morphologically complex word forms. Although plurals in compounds have featured prominently in studies of child language development, the present study is the first to report results from children's brain measures for this phenomenon. Our main finding is an enhanced negativity for compounds produced from regular plural non-heads in 8- to 12-year-old children and in adults, which had a later onset latency and a broader scalp distribution for children than for adults. We interpret these ERPs effects as reflecting the combinatorial mechanisms involved in producing morphologically complex word forms. We conclude that the silent-production-plus-delayed-vocalization technique used here is a viable ERP paradigm to study brain processes involved in morphological processing in both children and adults.

Conflict of interest

The authors declare that they have no conflict of interest.

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