

Environmental Sensitivity: A Multi-Domain Examination of its Development in Infancy

KATIE DAUBNEY

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**Environmental Sensitivity: A Multi-Domain
Examination of its Development in Infancy**

KATIE DAUBNEY

School of Psychology

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Abstract

Highly sensitive individuals are thought to be disproportionately susceptible to both the risk engendering and development enhancing elements of their environment. If this is so, it seems necessary to hold that sensitivity is a unitary construct, in which markers of sensitivity to stimuli at neural, autonomic, and behavioural levels of analysis moderate the relationship between early social environments and outcomes, for better as well as for worse. The trait of environmental sensitivity (ES) is theorised, through conditional adaptation to enable resource exploitation or risk survival in the developmental context. This thesis tests four main hypotheses: that measures of ES at different levels of analysis would covary at 6-months and would be evoked by positive and negative stimuli; whether associations between measures at 6-months would endure by 12-months; that indices of sensitivity at 12-months would associate with measures indexing the quality of the developmental environment; that measures indexing ES would moderate the relationship between the environment and outcomes. Neural, autonomic, and behavioural indices of ES were measured in N82 infants at 6-months and 12-months, while concurrently collecting data on the wellbeing and socioeconomic status (SES) of their parents. Levels of infant self-regulation and sustained attention were assessed at 12-months.

Associations between visual and auditory neural sensitivity were found at 6-months but not 12-months. Likewise, measures of positive and negative behavioural reactivity correlated at 6-months but not 12-months. Maternal SES moderated the relationship between negative reactivity at 6-months and positive reactivity at 12-months such that negatively reactive 6-months infants from high SES households were more positively reactive at 12-months. Baseline RSA at 6-months moderated the relationship between maternal anxiety and 12-months self-regulation but was marginally non-significant.

The results are interpreted from the perspective of theories and concepts that have been integrated into a single overarching meta framework of Environmental Sensitivity.

Declaration

I declare that this thesis is a presentation of original work. This work has not previously been presented for an award at this or any other university. The studies included in Chapters five and six have been submitted to journals and are currently under review. The titles and co-authors of these papers are presented below. Listed co-authors are Zeynep Suata, a Ph.D. student with whom I collected all data used in this thesis and with whom I collaborated on the coding scheme and pre-processing the coded data for the behavioural tasks in Chapter six. Ira Marriott-Haresign, a PhD student who produced the ERP plots used in Chapter five in Matlab from files that I had processed in Net Station. Senanur Sandikci and Louise Stubbs were interns at the UEL BabyLab who coded most of the video-recorded raw behavioural data. Elena Kushnerenko was consulted on issues regarding the EEG data. Sam Wass and Michael Thomas, my supervisors. I can confirm that I conducted all analyses and am the sole author. All sources are acknowledged as references.

Katie Daubney

The development of the relationship between auditory and visual neural sensitivity and autonomic arousal from 6-months to 12-months

Daubney, K.,¹ Suata, Z.,² Marriott Haresign,¹ I., Thomas, M.S.C.,³ Kushnerenko, E.,⁴ & Wass, S.V.¹

¹ BabyDevLab, University of East London

² Kings College London

³ Centre for Educational Neuroscience, BirkBeck University of London

⁴ University College London

Positive and negative emotional reactivity are initially associated during infancy, then diverge with increasing age

Daubney, K.,¹ Suata, Z.,² Sandikci, S.,¹ Stubbs, L,¹ Thomas, M.S.C.,³ & Wass, S.V.¹

¹ BabyDevLab, University of East London

² Kings College London

³ Centre for Educational Neuroscience, BirkBeck University of London

Table of contents

<i>Abstract</i>	<i>i</i>
<i>Declaration</i>	<i>ii</i>
<i>Table of contents</i>	<i>iii</i>
<i>List of figures</i>	<i>vi</i>
<i>List of tables</i>	<i>x</i>
<i>Definition of key terms</i>	<i>xii</i>
<i>List of abbreviations</i>	<i>xiii</i>
<i>Acknowledgements</i>	<i>xv</i>
<i>Dedication</i>	<i>xvii</i>
Chapter 1. Thesis Overview	1
Chapter 2. General Introduction	5
2. Introduction	5
2.1 Initial definition of Environmental Sensitivity	5
2.2 Developmental evolutionary theories of ES.....	7
2.3 Models and theories of ES.....	10
2.4 The distribution of ES in the population	22
2.5 The development of ES	26
2.6 Is ES a unitary construct?.....	27
2.7 The developmental environment	34
2.8 Chapter summary	37
Chapter 3. Literature Review	39
3. Introduction	39
3.1 Measures of Environmental Sensitivity.....	39
Chapter 4. Early Life Sensitivity and Adaptation (ELSA) study	63
4. Introduction	63
4.1 Study overview.....	63
4.2 Results	71
4.3 Chapter summary	84

<i>CHAPTER 5. The development of the relationship between auditory and visual neural sensitivity and autonomic arousal from 6-months to 12-months</i>	86
5.1 Introduction	87
5.2 Method	91
5.3 Results	98
5.4 Discussion	113
<i>Chapter 6. Positive and negative emotional reactivity are initially associated during infancy, then diverge with increasing age</i>	120
6.1 Introduction	121
6.2 Method	126
6.2.1 Participants	126
6.2.2 Equipment	127
6.2.3 Procedure.....	127
6.2.4 Data processing	129
6.2.5 Data preparation and reduction	130
6.2.6 Statistical Analysis	131
6.3 Results	133
6.3.1 Preliminary analyses – descriptive	133
6.3.2 Analysis 1	134
6.3.3 Analysis 2	136
6.4. Discussion	137
<i>Chapter 7. The moderating effect of RSA on positive developmental environments and developmental outcomes</i>	140
7.1 Introduction	142
7.2 Method	149
7.2.1 Participants	149
7.2.2 Measures	150
7.2.3 Statistical analyses.....	153
7.3 Results	155
7.4 Discussion	159
<i>Chapter 8. General Discussion</i>	165
8.1 Synopsis	165

8.2 Summary of findings.....	167
8.3 Methodological strengths	169
8.4 Methodological limitations.....	171
8.4.1 Sample size.....	171
8.4.2 Adequate measurement of the developmental environment.....	172
8.4.3 Fatigue effects	174
8.4.4 Ecological validity.....	174
8.4.5 Gold standard measure of infant sensitivity	175
8.5 Interpretation and integration of main findings	175
8.5.1 Hypothesis one – Sensitivity to immediate environmental effects is a domain-general unitary construct.	175
8.5.2 Hypothesis two – Measures of sensitivity to immediate environmental effects are stable across development.	179
8.5.3 Hypothesis three: Heightened sensitivity will associate with more highly positive or negative developmental environments.....	181
8.5.4. Hypothesis four: Highly sensitive individuals will benefit more from a positive developmental environment than less sensitive individuals.	183
8.6 How do the findings of this thesis inform our understanding of sensitivity and the measurement thereof?	184
8.7 Practical implications of study findings	186
8.9 Ethical considerations.....	190
Concluding comment.....	191
<i>References.....</i>	<i>192</i>
<i>Appendices.....</i>	<i>254</i>
Appendix A. Ethics documentation.....	254
Appendix B. Subscales included in the Negative affect and Surgency scales of the Infant Behaviour Questionnaire (IBQ).....	257
Appendix C. Information on the algorithms used to process the raw ECG data in Kubios	258
Appendix D. Coding manual for behavioural tasks.....	259

List of figures

Figure 2. 1 Diathesis Stress. Those high in ES (red) experience worse outcomes than those with low ES (black) in adverse environments. Shaded area represents the level of environmental quality at which the slopes for high and low sensitivity differ significantly (copied from (Jolicoeur-Martineau et al., 2019))	13
Figure 2. 2 Differential Susceptibility Theory (Belsky, 2007; Ellis et al., 2005). For better and for worse. Those low in ES (non-sensitive) are relatively unaffected by the quality of their developmental environment, those high in ES (sensitive) suffer the worse outcomes in poor developmental environments but can experience far better outcomes than those low in ES in supportive environments.	17
Figure 2. 3 Figure 2.3 Vantage Sensitivity. Those high in ES (green) experience better outcomes than those with low ES (black) in supportive, nurturing environments. Shaded area represents the level of environmental quality at which the slopes for high and low sensitivity differ significantly (copied from (Jolicoeur-Martineau et al., 2019))	19
Figure 2. 4 Figure 2.4. Conceptual models of heightened susceptibility to environmental effects as described in the theories of a) Differential Susceptibility, b) Sensory Processing Sensitivity and c) Biological sensitivity to context, which together constitute the meta-framework of Environmental Sensitivity (copied from (Greven et al., 2019))	21
Figure 3. 1 a) The QRS complex is the combination of three of the graphical deflections seen on a typical ECG with each letter corresponding to a different part of the heart’s action; b) The distance (in milliseconds) between each “R” is defined as the “RR interval”	49
Figure 4. 1 Distribution of the P3 component to standard, deviant and noise tones at 6-months (a) and 12-months (b); Grand Average waveforms to standard, deviant and noise tones at 6-months (c) and 12-months (d).	72
Figure 4. 2 Distribution of P1, N290 and P4 component neutral and fearful faces at 6-months (a) and 12-months (b); Grand Average waveforms to neutral and fearful faces at 6-months (c) and 12-months (d).	73

Figure 4. 3 Average RSA levels during three free play and three toy retraction trials at 6-
months (a) and 12-months (b); Average negative reactivity in response to free play
and toy retraction trials at 6-months (c) and 12-months (d). Time series indication
age-changes in negative reactivity at 6-months and 12-months (e). 74

Figure 4. 4 Average RSA levels during three preparation and three peekaboo trials at 6-
months (a) and 12-months (b); Average positive reactivity in response to preparation
and peekaboo trials at 6-months (c) and 12-months (d). Time series indication age-
changes in positive reactivity at 6-months and 12-months (e). 75

Figure 4. 5 plots of correlations between baseline RSA and RSA reactivity to peekaboo (a)
and toy retraction (b) at 6-months; and peekaboo (c) and toy retraction (d) at 12-
months. 76

Figure 4. 6. Distribution of demographic variables: ACE scores (a); maternal education (b);
household income (c); 6-months GAD-7 scores (d); 6-months CHAOS scores (e); 12-
months GAD-7 scores (f); 12-months CHAOS scores (g.) 80

Figure 5. 1 presentation sequence of stimuli for emotional face processing paradigm 94

Figure 5. 2 a) Grand average ERPs at 6-months to auditory oddball task. Shaded areas
represent the error bars, calculated as the Standard Error of the Mean b) Deviant-
Standard difference wave (grand average). Shaded areas represent the error bars,
calculated as the Standard Error of the Mean. c) Electrode locations used to calculate
all ERPs. The locations used are marked in green. d) and e) Topoplots showing
response to standard d) and deviant e) tones at 100ms intervals starting at 100ms pre-
stimulus onset and ending 500ms post stimulus onset. Each topoplot shows an average
of activity 50 ms around the given value (i.e. -100ms shows the average from -150ms
to -50ms). 99

Figure 5. 3 a) Grand average ERPs at 12-months to auditory oddball task b) Deviant -
Standard difference wave (grand average). Shaded areas represent the error bars,
calculated as the Standard Error of the Mean c) and d) Topomaps showing response to
standard c) and deviant d) tones at 100ms intervals starting at 100ms pre-stimulus
onset and ending 500ms post stimulus onset. Each topoplot shows an average of
activity 50 ms around the given value (i.e. -100ms shows the average from -150ms to -
50ms). 99

Figure 5. 4 a) grand average ERPS to emotional faces at 6-months. and b) 12-months.
Shaded areas represent the error bars, calculated as the Standard Error of the Mean c)

Electrode locations used to calculate all ERPs. The locations used are marked in green.

..... 100

Figure 5. 5 a) and b) topomaps showing 6-months response to neutral a) and fearful b) faces at 100ms intervals starting at 100ms before stimulus onset and ending 500ms post stimulus onset. c and d) topomaps showing 12-months response to neutral c) and fearful d) faces at 100ms intervals starting at 100ms before stimulus onset and ending 500ms post stimulus onset. Each topoplot shows an average of activity 50 ms around the given value (i.e. -100ms shows the average from -150ms to -50ms). Topomaps were produced on data that was subject to channel interpolation outside of the main preprocessing..... 101

Figure 5. 6 Correlations between measures of visual and auditory sensitivity at 6-months: Scatterplots showing strength and direction of the Bayesian Pearson correlation between the two variables analysed (Fig. 6.a, c, e); Plots showing the prior and posterior distributions of the true population correlation (Fig. 6. b, d, f). The BF is also presented graphically with the unit circle in the output. The shaded area corresponds to the evidence in favour of the alternative hypothesis (indicated in the graphic in Fig. 6 b) by “Data | H1”, and the unshaded area corresponds to evidence in favour of the null “Data \ H0”). The ratio of the shaded area to the unshaded area can be seen to be about 8:1 (6b), 12:1 (6d) 5:1 (6f), which is the value of BF10)..... 102

Figure 5. 7 Correlations between measures of visual and auditory sensitivity at 12-months: Bayesian correlation pairwise plots showing strength and direction of the Bayesian Pearson correlation between the two variables analysed (Figs. 7.a, c, e); Plots showing the prior and posterior distributions of the true population correlation (Figs. 7. b, d, f). 104

Figure 5. 8 Correlations between measures of HR and visual and auditory sensitivity at 6-months: Bayesian correlation pairwise plots showing strength and direction of the Bayesian Pearson correlation between the two variables analysed (Figs. 8. a, c, e); Plots showing the prior and posterior distributions of the true population correlation (Figs. 8. b, d, f). 107

Figure 5. 9. Correlations between measures of HR and visual N290 response to fearful faces at 6-months and 12-months: Bayesian correlation pairwise plots showing strength and direction of the Bayesian Pearson correlation between the amplitude of the 6-months N290 to fear and HR at 6-months (Fig. 5.9. a) and the amplitude of the

12-months N290 to fear and HR at 12-months (Fig. 5.9. b); Plots of prior and posterior distributions of the true population correlation (Figs.5.9. c, d).....	109
Figure 5. 10.....	Error! Bookmark not defined.
Figure 5. 11.....	Error! Bookmark not defined.
Figure 6. 1. a) Toys used in toy retraction task: at 6-months, a folded foil blanket was adopted. At 12-months, a toy that pops up and makes musical noise when its buttons are pushed was used. b) The structure of the toy retraction task. c) The structure of the peekaboo task:	129
Figure 6. 2 a) time series plot of grand average negative affect during all 90 seconds of the toy-retraction task b) time series plot of grand average positive affect during all 90 seconds of the peekaboo task windows in green show timing of the 15s trial c) group means of positive and negative affect in response to toy retraction and peekaboo at 6-months and 12-months.	134
Figure 6. 3 Scatterplot showing the relationship between positive and negative affect evoked: a) toy retraction at 6-months; b) peekaboo at 6-months; c) toy retraction at 12-months; d) peekaboo at 12-months.	134
Figure 6. 4 a) scatterplot of variables indexing positive reactivity to peekaboo and negative reactivity to toy retraction at 6-months. (b) bar chart of the observed and expected values of positive and negative reactivity from the chi-squared test.	135
Figure 6. 5 a) scatterplot of variables indexing positive affect to peekaboo and negative affect to toy retraction at 12-months. (b) bar chart of the observed and expected values from the chi-squared test.	135
Figure 6. 6. Plot of the interaction between 6-months negative reactivity and maternal SES predicting 12-months positive reactivity.....	137
Figure 7. 1. Regression lines of the interaction between maternal anxiety at 6-months, levels of RSA predicting infant duration of orienting at 12-months.....	156
Figure 7. 2. Regression lines of the interaction between maternal education and levels of baseline RSA on predicting infant sustained.....	158
Figure 7. 3. Regression lines of the interaction between maternal anxiety and levels of RSA predicting infant regulation.	159

List of tables

Table 4. 1 Demographic details of participants at 6-months (n = 82) and 12-months (n=68)	65
Table 4. 2 All measures collected at each visit for both infant and parent	70
Table 4. 3 Unadjusted bivariate Pearson’s correlations between ECG variables denoting RSA baseline and RSA reactivity at 6-months and 12-months (6-months N=56, 12- months N=48).....	77
Table 4. 4 Mean (SD) scores on IBQ subscales at 6-months and 12-months. Pearson’s correlations between the 6-months and 12-months measures.	77
Table 4. 5 Unadjusted bivariate Pearson’s correlations between IBQ scales at 6-months and 12-months (6-months N=80, 12-months N=48).....	78
Table 4. 6 Descriptive statistics and bivariate correlations between raw scores for demographic variables at 6-months (N =79) and 12-months (N =62)	81
Table 4. 7 Factor loadings based on Principal Components Analysis (PCA) with Direct Oblimin rotation for 14 subscales from the 6-months IBQ (N = 79).....	82
Table 4. 8 Descriptive statistics for the two 6-months IBQ factors (N = 79)	Error!
Bookmark not defined.	
Table 4. 9 Factor loadings based on Principal Components Analysis (PCA) with Direct Oblimin rotation for 14 subscales from the 12-months IBQ (N = 64).....	83
Table 5. 1 Bayesian Pearson Correlations for neural auditory and visual sensitivity measures at 6-months. Some of the Bayes Factors are exceptionally high: the BF for the association between visual diff P1 and visual diff P4 is 6.036×10^6 . This example shows how a Bayesian analysis allows researchers to report a useful estimate of the exceptionally high strength of evidence (6 million to 1 in favour of the alternative hypothesis) that would not be possible with a p value	103
Table 5. 2 Bayesian Pearson Correlations for neural auditory and visual sensitivity measures at 12-months	105
Table 5. 3 Bayesian Pearson Correlations for autonomic and neural measures at 6-months	107
Table 5. 4 Bayesian Pearson Correlations for measures of autonomic arousal and N290 response to fearful faces at 6-months and 12-months	109

Table 5. 5 Bayesian Pearson Correlations for autonomic and neural measures at 12-months
..... **Error! Bookmark not defined.**

Table 6. 1 Demographic details of participants at 6-months (n = 82) and 12-months (n=68)
..... 126

Table 6. 2 Summary of the interactions between variables predicting positive and negative
reactivity at 12-months..... 136

Table 7. 1 Demographic details of participants at 6-months (n = 82) and 12-months (n=68)
..... 149

Table 7. 2. Summary of regression analyses between interactions at 6-months predicting
infant developmental outcomes at 12-months * p < .1 **p< .05 155

Definition of key terms

Domain general

With regard to environmental sensitivity, domain general refers to a global, macro, trait like characteristic of individuals which functions across a wide range of phenomena and parallel responses are observed across domains of functioning. Environmental sensitivity is conceived as a trait which influences performance over a wide range of situations and tasks such that the same children are affected more than others by different experiences and exposures. It is thought to affect the perception and processing of and response to any type of environmental stimuli. The mechanisms driving individual differences in sensitivity at different levels of analysis such as endophenotypic (autonomic and neural) responses, and phenotypic (behavioural) responses are thought to covary within individuals such that the responses to stimuli at different levels of analysis are not independent of one another.

Environmental Sensitivity (ES)

Environmental Sensitivity describes an overarching meta framework which integrates concepts and theories contained in this thesis. However, within the body of the thesis the term environmental sensitivity (ES) most often refers to the individual trait of a heightened sensitivity to environmental stimuli which is thought to moderate the effects of the early environment on developmental outcomes.

Unitary Construct

A unitary construct describes a cluster or domain of covarying behaviours and the covariation that is attributed to the observed behaviours. A construct is a hypothesized cause for the observed behavioural covariations. If the phenomena that a construct encompasses are clearly defined, it can be universally understood, communicated, and become an object of conceptual scrutiny.

List of abbreviations

α	alpha
β	standardized beta coefficient
μV	microvolts
ACE	Adverse Childhood Experiences
AES	Aesthetic Sensitivity
ANS	Autonomic Nervous System
BAS	Behavioural Activation System
BIS	Behavioural Inhibition System
BPM	Beats per Minute
BSC	Biological Sensitivity to Context
CAN	Central Autonomic Network
CBQ	Child Behaviour Questionnaire
CHAOS	Confusion Hubbub and Order Scale
DofO	Duration of orienting
DR	Defence Response
DST	Differential Susceptibility Theory
ECG	Electrocardiogram
EEG	Electroencephalogram
EOE	Ease of Excitation
ERP	Event Related Potential
GAD -7	Generalised Anxiety Disorder 7- item screening tool
HGSN	HydroCel Geodesic Sensor Net
HPA	Hypothalamic Pituitary Adrenal
HRV	Heart Rate Variability
HSP	Highly Sensitive Person
IBQ	Infant Behaviour Questionnaire
Lab-TAB	Laboratory Temperament Assessment Battery
LST Low	Sensory Threshold
MCAR	Missing Completely at Random
OR	Orienting Response
PNS	Parasympathetic Nervous System

QRS complex	combination of three graphical deflections seen on a typical electrocardiogram
RMSSD	Root Mean Square of Successive Differences
RSA	Respiratory Sinus Arrhythmia
SES	Socioeconomic Status
SNS	Sympathetic Nervous System
SPS	Sensory Processing Sensitivity
SRS	Stress Response System

Acknowledgements

At the start of this endeavour, I used the analogy of climbing a mountain, the summit of which seemed out of sight. Now that the summit is in view, I must acknowledge all those who have helped me reach this point.

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and I could not have reached the summit of the mountain without his support. I look forward to all the adventures that await and reaching more summits together.

Dedication

For Matt, Manon, and Blythe. With love, always.

Chapter 1. Thesis Overview

Environmental Sensitivity describes the overarching meta-framework that integrates the evolutionary developmental theories of Biological Sensitivity to Context theory (BSC) (W. Boyce et al., 1995, 2005; B. Ellis et al., 2005) and Differential Susceptibility Theory (DST) (Belsky, 1997b; Belsky & Pluess, 2009b) with the theory of Sensory Processing Sensitivity (SPS) (Aron & Aron, 1997), as well as the concepts and models which they propose. Within this thesis, environmental sensitivity (ES) also refers to the individual trait of heightened sensitivity to stimuli in the environment which is thought to confer disproportionate susceptibility to the effects of that environment on developmental outcomes. This thesis contributes to further elucidation of the different mechanisms driving individual differences in sensitivity within individuals, and also whether these mechanisms - and the domains of functioning they affect - covary and in response to both positive and negative stimuli. For the remainder of this short chapter, I will provide an overview of the seven chapters which follow in order to clarify their contribution to the thesis as a whole.

Chapter two introduces the theories which constitute the framework within which this thesis tested its hypotheses. An evolutionary perspective is given as to why individuals should differ in their threshold of response to stimuli, whether they be stressors, challenges, or opportunities. The evolution of the main theories of BSC, DST and SPS are described and the preceding (diathesis stress) and resulting (differential susceptibility and vantage sensitivity) models of the potential developmental outcomes of highly environmentally sensitive individuals are summarized. Evidence is also presented to support the proposition within BSC of a curvilinear distribution of the trait of ES in more highly negative or positive developmental contexts. This is followed by posing two main questions. The first asks what determines levels of ES, and the second explores how ES moderates the relationship between the developmental environment and developmental outcomes. I then acknowledge considerations that need to be taken into account in order to address these questions. Finally, the concept of the environment that is envisaged for this study is presented.

Chapter three addresses the question of what determines ES by describing the way an individual responds to exogenous stimuli at a neural, autonomic, and behavioural level. For each level of analysis, the way responses are measured and the extent to which these measures are stable across infancy is detailed. For measures at each level of analysis,

evidence is provided for the extent to which they have been found to index sensitivity both to immediate environmental effects and to the effects of the environment on developmental outcomes. The chapter concludes with the four hypotheses that I tested. These are: 1) that measures of ES at different levels of analysis would covary at 6-months and would be evoked by positive and negative stimuli; 2) whether associations between measures at 6-months would endure by 12-months; 3) that indices of sensitivity at 12-months would associate with measures indexing the quality of the developmental environment; 4) that measures indexing ES would moderate the relationship between the environment and outcomes.

The studies which constitute chapters five and six have been submitted to scientific journals. At the time of writing, Chapter five is published and Chapter six is under review. Therefore, each chapter is presented as a self-contained study. As such, details of the participants, equipment, procedures, measures, and analyses are contained in the methods sections of each individual study. However, all three empirical studies- including a third in Chapter seven - used data collected from the same participants at two testing sessions held at the BabyLab in the University of East London (UEL) when the infants were 6-months and 12-months old. In Chapter four, I present an overview of the study as a whole, which was conducted in collaboration with another Ph.D. student investigating different research questions. Due to instances of non-compliance, technical issues or low-quality data, the N for each individual study is variable. Therefore, I present an overview of the whole sample. This is followed by summarizing the measures used to operationalise ES, the developmental environment, and developmental outcomes before describing the overall process including recruitment and the procedure followed during the testing sessions.

In the second section of Chapter four, I provide descriptive statistics and preliminary analyses of the variables used to operationalise sensitivity at the neural, autonomic, temperament and behavioural levels of analysis. The prediction that ES is a unitary construct in infants was tested by looking at the covariance between the measures indexing heightened sensitivity to environmental effects at different levels of analysis. Evidence was found for associations within different levels of analysis. Scores on parent-reported measures of negative and positive temperament did not correlate with lab-induced measures of behavioural reactivity. Therefore, an exploratory factor analysis on the subcomponents of the composites of positive and negative affect and regulation was carried out to determine the factor structure of temperament for this sample. The results of this factor analysis are included for interest.

The study contained in Chapter five builds on previous work to which this author contributed, looking at the relationship between neural auditory sensitivity and autonomic arousal in children. The same auditory paradigm as used in previous studies was used with the infants in this study when they were 6-months and 12-months old. Sensitivity was operationalized as the automatic detection of difference between two conditions of auditory and visual stimuli. No differences were found between conditions at a group level. However, fundamental to the theory of differential susceptibility is the notion that individuals differ with regard to both the threshold at which reactions to stimuli are provoked and the intensity of these reactions. Therefore, we found that measures indexing heightened sensitivity in the visual and auditory domains correlated within individuals at six-months. This provided some support for the first hypothesis of this study that measures of sensitivity would covary by suggesting that involuntary neural sensitivity was domain general in early development. Hypothesis two was exploratory as, based on the literature, we were agnostic as to whether associations found at 6-months would endure by 12-months. The disappearance of this covariance by 12-months was interpreted from a neuroconstructivist perspective of ‘domain relevant’ mechanisms becoming increasingly ‘domain specific’ with experience across development (Karmiloff-Smith, 1998). This finding contributed to answering the question of what determines ES by suggesting that initially, in early development, the sensitivity of neural domains of perception is equally calibrated.

The second finding of this study was that autonomic arousal was negatively correlated with some components indexing automatic detection of difference, but positively correlated with neural responses to fearful faces. This could be interpreted as more neural vigilance to threat at heightened levels of autonomic arousal.

The second study, contained in Chapter six provides support for hypotheses one and three of this study and contributes to answering the overarching questions of a) what determines ES, and b) how ES moderates the relationship between the developmental environment and developmental outcomes. To test the hypothesis that indices of sensitivity to both positive and negative stimuli would covary, I predicted that positive behavioural responses to a standardised positive-behaviour eliciting task would correlate with negative responses to a standardised negative-behaviour eliciting task and that the developmental environment would moderate the development of reactivity from 6-months to 12-months. Positive and negative reactivity correlated at 6-months but not 12-months. This supported the hypothesis that heightened sensitivity confers reactivity to both positive and negative

stimuli. The second finding was that negative reactivity at 6-months predicted more positive reactivity at 12-months at higher maternal SES - indexed by level of education. This suggests that heightened negative reactivity in early development is one determinant of the extent to which the developmental environment associates with outcomes.

The third study, contained in Chapter seven, tested hypothesis four, that infants' autonomic activity, indexed using a measure of baseline respiratory sinus arrhythmia (RSA), would moderate the relationship between the developmental environment and developmental outcomes. This study was significantly underpowered but was undertaken to provide an example of a more conventional test of the extent to which specific measures index environmental sensitivity. In addition, I wanted to test whether the data was more aligned with either of the models of differential susceptibility or vantage sensitivity. Descriptive statistics of the variables indexing the developmental environment (described in section four of Chapter four) revealed that the sample was characterised by high levels of SES, indexed by levels of education and household income, and high maternal wellbeing, indexed by questionnaire data. As a result, the opportunity was taken to address the question raised by the model of vantage sensitivity, of whether heightened ES enables individuals to be disproportionately susceptible to the benefits of an advantaged developmental environment, leading to better developmental outcomes.

Chapter eight comprises a general discussion which provides a synopsis of the whole thesis and summarizes and integrates the main findings contained in Chapters five, six and seven. Overall strengths and limitations are outlined. The results are interpreted with regard to the wider literature to clarify how the findings inform our understanding of sensitivity and measurement thereof. This leads to a discussion of the practical implications of the findings. Finally future directions for research are suggested and ethical considerations acknowledged.

Chapter 2. General Introduction

2. Introduction

This thesis formed and tested hypotheses resulting from the theoretical perspective of Environmental Sensitivity (ES). ES constitutes a single over-arching meta-framework which unites the theories of Biological Sensitivity to Context theory (BSC) (W. Boyce et al., 1995, 2005; B. Ellis et al., 2005); Differential Susceptibility Theory (DST) (Belsky, 1997b; Belsky & Pluess, 2009b) and Sensory Processing Sensitivity (SPS) (E. N. Aron & Aron, 1997).

BSC and DST are both evolutionary developmental theories whereas SPS had no initial developmental focus but shares core notions about the nature of sensitivity and has contributed key tools and concepts that complement the theoretical and empirical applications of ES research. All share the notion that ES can confer disproportionate susceptibility to being affected by both adverse and supportive environments and thereby constitutes increased potential for better and for worse outcomes.

This chapter will present the theories, perspectives and concepts which informed the studies which follow in the empirical chapters. In this way, two fundamental questions will be raised. The first seeks to examine what determines ES and the second explores how ES moderates the relationship between the developmental environment and developmental outcomes. I will examine the extent to which extant theories and models have addressed these questions and the areas in which further research is needed. I will start by introducing the concept of ES.

2.1 Initial definition of Environmental Sensitivity

To survive and thrive on this planet it is essential to be able to draw on environmental resources, such as protection from predators, food, and social support. Both humans and animals are programmed to perceive, process, react and adapt to specific social and physical elements of the environment (Ellis & Boyce, 2008). Human development across the lifespan is fundamentally contextual. Without the specific and active support of a nurturing environment, no child would even survive, let alone thrive. Because of this profound dependence on external environmental resources, a defining characteristic of humans is a remarkable aptitude to register, process, and respond on multiple levels to many different aspects of our social and physical environment, whether these are physical

or psychosocial in nature, and whether they are negative or positive (i.e., whether they threaten or promote the development, survival, and reproductive success of the individual) (Pluess, 2015a). Environmental Sensitivity (ES), defined as the ability to register and process external stimuli (Pluess, 2015a), is one of the most basic individual characteristics and as well as humans, it is observable across most species.

Neuroception is a subconscious system for detecting threats and safety (Porges, 2004). Individuals are constantly scanning environments and situations to assess whether they are safe or contain threatening elements. When challenges or threats arise, whether actual/real or perceived/imagined, it leads to a disturbance in an individual's internal milieu (Bernard, 1859). The stimulus (input) leads to an evaluative process followed by a response (output) (Kollack-Walker et al., 2000). During aversive or stressful events, subcortical networks link the amygdala to the hypothalamus, midbrain and brainstem. These subcortical networks convey information on visceral (pain and bloating), humoral (antigens in the blood) and nociceptive (physical damage), as well as processive (psychological) stressors to the amygdala and mediate its effects on the hypothalamic-pituitary-adrenal (HPA) axis (Berretta, 2005), which produces glucocorticoids from the cortex of the adrenal glands (adrenocortical activity) (Gunnar & Cheatham, 2003). This leads to activation of a complex, integrated system. Physiological resources are mobilised. The autonomic nervous system (ANS), specifically the sympathetic nervous system (SNS) - involved in the "fight or flight" response to threat or challenge (Canon, 1915) - prepares the organism for an immediate response in the face of threat and to allow adaptation to changing environments and situations (Selye, 1950; Ellis & Boyce, 2008). Once a threat has passed, autonomic arousal levels decrease due to activation of regulatory mechanisms such as the parasympathetic nervous system (PNS), the branch of the ANS which decreases arousal levels and serves to restore homeostasis (Selye, 1951). This activation of multiple systems working in concert has been called "allostasis" or "stability through change" (Sterling & Eyer, 1988) and is an essential component of maintaining homeostasis or a constant internal milieu (Gunnar & Cheatham, 2003).

This complex system of response to a stressor has a core structure that all humans share. However, while the body's physiological response is universal, the threshold at which it is provoked is not. There is a wide range of individual variation in neural sensitivity and autonomic and adrenocortical reactivity to challenge, which has been interpreted as indicating different stress response phenotypes (Ellis, Jackson and Boyce, 2006), and therefore how efficiently and effectively the body responds to stress (Ellis &

Boyce, 2011; Ellis, Del Giudice & Shirtcliff, 2016; Pluess, 2015). Research looking at the reliability of children's neuroendocrine responses to stress found important cross-system regularities that are linked to development and prior experiences suggesting that individual differences in sensitivity are stable and reliable as measures of individual differences (Quas 2014). This substantial inter-individual variability of response to the same environmental conditions represents different degrees of ES (Pluess, 2015). Some individuals incur powerful biological responses to relatively minor stressors, while others experience little change from baseline in response to even major, life-altering events (Ellis et al., 2006). Thus, heightened sensitivity was framed as a weakness or vulnerability with low sensitivity indexing resilience in the face of any form of environmental perturbation by models explaining the development of (psycho)pathology (Zuckerman, 2004). The continuing coexistence of more and less sensitive types in the population (Wolf et al., 2008) has led to the development of models and theories concerning the evolution and effect of such differences.

2.2 Developmental evolutionary theories of ES

The question of why children should differ in their levels of susceptibility to environmental effects was examined by two research teams from an evolutionary developmental perspective. The resultant theories addressing that question will be outlined below and lay the groundwork for one of the core notions to be examined in this thesis – that sensitive individuals differ not only in their response to environmental adversity but also in response to positive, supportive aspects of the environment (Pluess, 2015).

2.2.1 *Conditional Adaptation*

From a developmental psychopathology perspective, sensitivity to stressors in the environment has long been regarded as a vulnerability - leading inevitably to poorer long-term mental and physical-health outcomes (R. Juster et al., 2010.; Lazarus, 1993; Mead et al., 2010). Central to this view is the assumption that vulnerable individuals have a far greater risk of worse developmental outcomes than their more resilient counterparts. However, this is inconsistent with an evolutionary perspective in which developmental adaptations are thought to be made to best prepare an individual for the ecological conditions into which they are likely to mature. Animal studies prompted a review of the developmental-psychopathology analysis of maladaptive outcomes in adverse

environments. Rat studies showed that low quality maternal care (less licking) alters pups' brain morphology such that there were more CRH1 receptors which process events as threatening, leading to a greater cortisol response to stressors. At the same time receptors in the hippocampus were down-regulated, which decreased the pups' ability to self-regulate. While seeming disadvantageous, these changes enhanced memory and learning processes under stressful conditions (Meaney, 2001; Champagne et al., 2008; Hartman & Belsky, 2018b). Therefore, the "care" provided by the putatively neglectful mothers may have induced the most appropriate adaptations in their offspring for surviving their particular developmental environment. This evolutionary developmental perspective emphasises conditional adaptation over the so-called dysfunctional or maladaptive outcomes viewed from a developmental-psychopathology framework.

The models of adaptive calibration (del Giudice et al., 2011) and conditional adaptation (Ellis et al., 2011) advance the notion that those who are more susceptible (responsive) to context are more likely to experience sustained developmental changes in reaction to contextual factors. Thus, when stressful environments are encountered, this does not so much *disturb* development as *direct or regulate* it toward strategies and patterns of functioning that are *adaptive* under stressful conditions such as by augmenting vigilance to threats and dangers even if costly in the long term (W. T. Boyce & Ellis, 2005a; Ellis & Del Giudice, 2019; Frankenhuis & Amir, 2022). From an evolutionary perspective, where the goal is to maximise reproductive fitness, development directs individuals to act in ways that promote or once promoted status and reproductive success in dangerous environments such as aggressive behaviour to control resources, (i.e., to get what they want, get attention from others, overcome social obstacles) or sexual promiscuity. From a developmental psychopathology perspective these behaviours constitute a high-risk strategy that jeopardises the person's health and survival (Mulvihill, 2005; Shonkoff et al., 2009) or are harmful in terms of the long-term welfare of the individual or society as a whole (Main, 1990; Hinde et al., 1990) and are therefore not adaptive in terms of achieving the outcomes defined as desirable by dominant Western values; e.g., secure attachment, happiness, high self-esteem, emotion regulation, educational and professional success, and stable relationships (B. J. Ellis et al., 2007a; Ellis et al., 2022).

However, this same capacity for sustained developmental changes in reaction to contextual factors could also condition or moderate the effects of supportive or enriched environmental contexts on functioning and well-being (Belsky et al., 1991; Chisholm, 1999). In contrast to dangerous environments, supportive environments direct susceptible

children to act in ways that are cooperative, positive, and garner support and social resources from others, including enacting less aggression (Eisenberg et al., 2012), all behaviours which are highly valued by dominant Western cultures.

However, conditional strategies to best adapt an organism to its environment are only adaptive if the future environment is similar to the past. This challenge to conditional adaptation was being advanced by the research team responsible for another theory under the umbrella of ES, Differential Susceptibility Theory (DST) (Belsky, 1997b; Belsky & Pluess, 2009b).

2.2.2 Evolutionary insurance

The adaptive need for variation in susceptibility to environmental influences has been documented for decades. The person-process-context model of development specifically addresses the prospect that as well as processes of development operating differently in different ecological niches, different individuals may be differentially affected by the same rearing practices (Bronfenbrenner & Crouter, 1983). However, Jay Belsky (1997) felt it necessary to broaden the ecological perspective by incorporating evolutionary considerations to address questions of ultimate causation. Thus, the questions “why are some children are more environmentally sensitive than others?” and “why should childhood experience influence development?” were the origin of DST.

From an evolutionary perspective, developmental mechanisms that use earlier experiences to guide later development should only evolve in environments with recurring conditions in which the future (within generations) is tolerably related to the past (Pigliucci, 2003). Only then could the model of conditional adaptation - using childhood experiences to regulate adolescent and adult development – produce reliable fitness payoffs. The fact that the future is inherently uncertain, however, renders conditional adaptation theoretically problematic. To address this challenge, Belsky (1997a, 1997b, 2000, 2005) proposed that, as a form of bet-hedging against an uncertain future, natural selection has maintained genes for both “conditional” and “alternative” developmental strategies. Whereas those who have a genetic predisposition for conditional strategies are shaped by environmental factors to better fit the organism to the future environment (assuming consistency of environmental conditions), those with a genetic predisposition for alternative strategies are largely fixed and less susceptible to environmental influence (Rowe et al., 1997).

This differing susceptibility between individuals is *adaptive* in the evolutionary sense as dispersion of genes into future generations depends on varying the sensitivity of the offspring. Therefore, individual differences in sensitivity are conserved by fluctuating selective pressures that generate different fitness payoffs across different social, physical, and historical contexts (or at least did so during human evolution). For this reason, DST stipulated that children should vary in their susceptibility to environmental influence. The fact that as a species, humans are highly susceptible to learning and evince much less instinctual behaviour than do other species does not necessarily mean that all individuals are equally responsive to environmental inputs (Belsky, 1997).

In summary, common to both theories is that they challenge the prevailing developmental psychopathology model of ‘worse’ developmental outcomes for those with high ES in adverse environments. According to both theories individuals with heightened sensitivity are better able to adapt their phenotype to ‘make the best’ of their environment. Those who are more reactive at lower levels of provocation are more susceptible to the effects of the environment on developmental outcomes, be they adaptive in terms of evolutionary models or either adaptive or maladaptive in terms of developmental-pathology models. However, as futures are uncertain, this responsive phenotype is not uniform across the population, but varies between individuals in the manner of hedging bets to cover all eventualities. In the following section I shall turn to the evidence for what determines levels of sensitivity and how this has led to different developmental models which have influenced the perception of ES.

2.3 Models and theories of ES

In this section, attention will be given to ideas exploring how ES is determined. First, the concept of allostatic load will be used to explain how heightened sensitivity is viewed as a vulnerability in the diathesis-stress models of heightened sensitivity outcomes. I will briefly look at the direct and indirect impact of sensory sensitivity in atypical development. This will be followed by focusing on the theories and models which challenge this portrayal of heightened sensitivity as a weakness. BSC, the differential susceptibility hypothesis, and DST followed by vantage sensitivity and SPS all build on evidence that the same heightened sensitivity to the environment that constitutes a vulnerability in adverse environments can also confer the likelihood of disproportionately positive developmental outcomes in supportive environments.

2.3.1 Allostatic load and diathesis stress

Even though theories comprising the ES framework highlight the ‘bright side’ of heightened sensitivity (Bakermans-Kranenburg & van Ijzendoorn, 2011), it is important to acknowledge the well evidenced ‘dark side’. Most theorists have argued that highly reactive children are more liable than less reactive children to do especially poorly in high-risk settings (Eisenberg et al., 2012). This has led to the development of models and theories such as the allostatic load model (R. P. Juster et al., 2010; Lupien et al., 2009; McEwen et al., 1993) and diathesis stress (Gottesman & Shields, 1976; Monroe & Simons, 1991a; Zuckerman, 2004). The latter posits that an individual’s trajectory will deviate significantly for the worse from those who are less sensitive once conditions become adverse but will function similarly in good conditions (see fig. 2.1). Allostatic load refers to the cumulative cost of frequent activation of the body’s stress response system (SRS) and repeated physiological arousal (Guidi et al., 2020). The short-term activation of the SRS can be essential to survival, as noted in the first section of this chapter. However, repeated evocation of a stress response leads to not only increased levels of long-term physiological stress but can also cause hypersensitization of the stress response (Beauchaine & Thayer, 2015; Ulrich-Lai et al., 2009), sympathetic hyper-reactivity (Uchino et al., 1996) and elevated HPA activation (Cacioppo, Ernst, et al., 2000).

The amygdala is a subcortical structure central to interpreting and responding to perceived threats (LeDoux, 2003). The maturation of the amygdala and emotion circuits in the brain is thought to be influenced by infant stress responsivity (Schwartz et al., 2012). This may be because in response to even quite mild acute uncontrollable stress, activation of the HPA axis prompts glucocorticoids to be released, which can cause a rapid and dramatic loss of prefrontal cognitive abilities. But while stress downregulates the frontal lobes, it simultaneously enhances processes dependent on subcortical structures (Luethi et al., 2009), increases signal-to-noise ratios within primary sensory cortices (Foote et al., 1975) and leads to more vigilant bottom-up, stimulus-driven, attention (Buschman & Miller, 2007). Through development, the frontal lobe exerts increasing control over emotions, modulating the degree to which the amygdala’s output produces emotional responses in different contexts (Kolb & Taylor, 1990). However, prolonged exposure to glucocorticoids causes architectural changes in prefrontal dendrites, which impair working

memory abilities. These same neurochemical events strengthen the emotional operations of the amygdala. In this way, in the face of uncontrollable stress, heightened sensitivity switches control of behaviour from the thoughtful prefrontal cortex to the more primitive conditioned emotional responses of the amygdala (Arnsten, 2009), causing heightened fear responses. This causes a threat bias in the brain, which means more events are interpreted as threatening, leading to more frequent activation of the SRS. In this way, prolonged, and repeated activation contributes to increasing an individual's allostatic load (McEwen, 1998). Biomarkers including cortisol, Heart Rate Variability (HRV) have been included in a cumulative index of allostatic load (McEwen, 2015), which has proved better than individual markers for predicting declining physical functioning (Edes & Crews, 2017). Recent studies in both adults (Chasiropoulou et al., 2019) adolescents (Li et al., 2022), and children (van Eldik et al., 2021; Li et al., 2023) still support the diathesis-stress model by finding that stress intolerance, neuroticism, low levels of emotional stability and physiological reactivity respectively were vulnerabilities for developing disorders in the face of stressors.

In addition to being the neural substrate of the body's stress response (Cacioppo, Berntson, et al., 2000; Ulrich-Lai et al., 2009), the ANS also performs self-regulatory functions, and is one of the earliest systems to become functionally mature (Geva et al., 2000; Paus et al., 2001). Early impairments in aspects of regulatory stress-responses can lead to disrupted performance and sub-optimal cognitive outcomes. As such, early heightened sensitivity in adverse environments can lead, cascade-like, to deficits that become progressively more severe over time (Karmiloff-Smith, 1998; Johnson, 2012). Thus, heightened sensitivity reflected in variation in the threshold for the activation of the SRS, is thought to strengthen the positive association between, adverse developmental environments, social disruptions, and the level of adverse developmental outcomes (W. T. Boyce et al., 1995) and disease (Cacioppo, Berntson, et al., 2000).

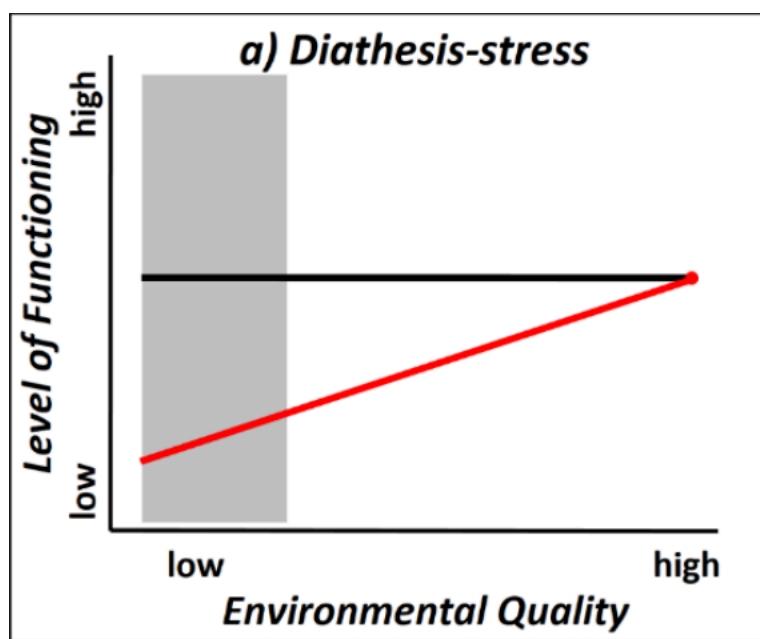


Figure 2. 1 Diathesis Stress. Those high in ES (red) experience worse outcomes than those with low ES (black) in adverse environments. Shaded area represents the level of environmental quality at which the slopes for high and low sensitivity differ significantly (copied from (Jolicoeur-Martineau et al., 2019))

2.3.2.i Atypical sensory development

The above evidence describes heightened sensitivity in typically developing populations. I will now briefly present evidence from atypically developing populations such as those with autism spectrum disorder (ASD) or attention deficit hyperactivity disorder (ADHD) which also highlights how heightened sensitivity can have both direct and indirect cascading effects on development. Atypical sensory responsiveness can be characterised as three separate empirically derived constructs: hyper-responsivity, hypo-responsivity, and sensory seeking - the latter being behaviours such as repetitive banging or stroking enhance or prolong a non-social sensory experience (Ben-Sasson et al., 2009; Boyd et al., 2010). Such sensory atypicalities may associate with atypicalities in the development of motor skills (Ting, 2013) and later social and adaptive functioning (Jasmin et al., 2009; Mattard-Labrecque et al., 2013). For example, a child who is hypersensitive to tactile stimulation may refrain from seeking contact with caregivers, limiting early opportunities for socialisation. Similarly, a child who is hypersensitive to bright lights or noises may refrain from everyday activities, limiting opportunities for motor exploration of the environment and interacting with peers (Piccardi et al., 2021). To the best of our knowledge no such similar studies have been carried out with typically developing

populations. However, individual differences in patterns of sensitivity of response to environmental stimuli are thought to cause variation between typically developing individuals in a wide range of adaptive processes of which learning is just one among many (del Giudice et al., 2011a) and therefore a better understanding of these differences is a worthy cause for investigation.

There are shared behavioural characteristics between those with high ES and those with ASD, Sensory Processing Disorder (SPD) or attention deficit hyperactivity disorder (ADHD). A positive correlation was found between scores on the Highly Sensitive Person Scale (HSPS) and the adult ADHD Self-Report Scale (ASRS) for ADHD traits in a non-clinical sample (Panagiotidi, 2020). However, neuroimaging studies of individuals within typically developing populations, who score high on a Sensory Processing Sensitivity (SPS) scale show that emotional and social cues and stimuli are processed very differently (Acevedo et al., 2014, 2018, 2021) to those who have reached the threshold for a clinical diagnosis of atypical development. In ASD, studies have shown deficient responsivity of neural structures involved in facial processing, empathy emotion, and reflective thinking (Kim S-Y et al. 2015; Di Martino et al., 2009). In contrast, fMRI research on SPS has tended to show prominent brain activation of regions that are implicated in empathy, social processing, and reflective thinking (Acevedo et al., 2014; Acevedo et al., 2017).

Furthermore, individuals with high SPS can also become over aroused by their environments, which may result in cognitive depletion, and fatigue. However, this may be due to greater depth of processing of the complexities and details of the environment (Jagiellowicz et al., 2011). In support of this, a recent study of resting state brain connectivity showed greater connectivity between structures implicated in depth of processing involving attentional control, consolidation of memory, physiological homeostasis, and deliberative cognition (Acevedo et al., 2021).

Understanding the mechanisms involved in individual differences in context sensitivity will not only improve our ability to identify high-risk individuals early in development but will also enable the formulation of effective and better-targeted interventions both to mitigate the risk-engendering ‘downside’ of differential susceptibility and to catalyse its benefits (Belsky & Pluess, 2013; Wass, 2018b). Such benefits are outlined in the following theories and models.

2.3.3 Biological Sensitivity to Context theory and the differential susceptibility hypothesis

A large body of evidence supports the hypothesis that the cumulative effects of adverse childhood experiences reliably associate with poorer long-term outcomes. This can be in terms of developmental delays (Sameroff et al., 1987), worse mental health and poor socioemotional adjustment (G. W. Evans & English, 2002), or poor physical health in adulthood (Dong et al., 2004). However, despite a trend for worse outcomes in adverse environments, there exists huge variation in data points. This prompted Thomas Boyce to explore whether the ‘noise’ inherent in such associations might, in reality, be the ‘music’ to which research efforts should be attuned (Boyce, 2019, p30). In part, this perspective was informed by the realisation that noisy variability in the data persisted despite strong methodological efforts to sharpen the validity of the measurement instruments employed (Boyce, 2019; Boyce, 2014.; Boyce 2016), suggesting that the developmental environment was not the only factor which predicted outcomes. Instead, attention might be better directed to understanding why the outcomes of children from the same developmental context are so extraordinarily varied (Greven, et al., 2020; Boyce, 2016).

Research into individual differences in reactivity to lab-based stressors, found that in line with prevailing diathesis-stress developmental psychopathological theories, physiological markers of sensitivity associated with higher rates of respiratory illness in high adversity settings than those with low reactivity (W. Boyce et al., 1995). Models such as diathesis stress and allostatic load coming, as they do, from a developmental psychopathology perspective, look at the consequences of adverse environments on developmental outcomes. One consequence is that many studies do not measure either the full range of environments (just adversity and its absence, e.g., maltreatment vs. no maltreatment) or a full range of psychological/behavioural functioning (just dysfunction and its absence, e.g., depressed vs. not depressed). The inclusion of an analysis of the outcomes in *low* adversity (supportive) settings led to an unexpected finding from the work of Boyce and colleagues (1995). Children showing low physiological reactivity to stressors had approximately equal rates of respiratory illnesses in both low and high adversity settings, but highly reactive children living in lower adversity conditions (i.e., more supportive childcare or family settings) had the *lowest* illness rates, which were significantly lower than low-reactivity children in comparable settings (W. Boyce et al., 1995). Therefore, by including a measurement of the outcomes of highly sensitive children in supportive environments (as well as adverse environments), it was possible to see that developmental trajectories departed from those who are less sensitive at *both* the better and worse ends of the scale of quality of developmental environment (see fig. 2.2). Thus, a

hypothesis which predicted an association between differential sensitivity and differential susceptibility to the environment was supported. The differential susceptibility hypothesis provided an interpretation of the physiological mechanism of environmental susceptibility, which was consistent with the evolutionary developmental theory on conditional adaptation described in section 2.2.1 of this chapter. The shorthand designation of ‘orchid children’ was given to those whose high physiological reactivity made them especially susceptible to both the advantages of nurturing environments but also the risks associated with adverse environments. The designation ‘dandelion children’ referred to the relative imperviousness against environmental vagaries of children with low physiological stress reactivity.

Subsequent studies have found evidence for the moderating effect of greater physiological reactivity (vagal tone (Skibo et al., 2020); cortisol reactivity (Pearson et al., 2022); and autonomic function (Salisbury, 2021)) in the association between environment and outcomes which supports the differential susceptibility hypothesis as opposed to the diathesis-stress model.

2.3.4 Differential Susceptibility Theory

The evolutionary developmental Differential Susceptibility Theory (DST) differs from BSC, which originated in empirical observations of differences in children’s autonomic and adrenocortical reactivity to challenge, in that it initially advanced no mechanistic hypotheses about how individual differences in susceptibility operated. Early attempts to identify potential susceptibility factors or markers that might distinguish context sensitive children who were more susceptible from those who were less so focused on phenotypic descriptors of children such as negative emotionality or difficult temperament (Belsky 2005; Belsky, 1997a; Belsky et al., 1998). Evidence for autonomic measures as well as temperament as indicators of ES has since been substantiated at multiple levels of analysis, ranging from peripheral neuroendocrine pathways and brain circuitry to behavioural indicators. The evidence for measures used as indices of sensitivity to environmental effects will be presented in the following Chapter. Thus, theory and data suggest that a common, context-sensitive endophenotype may plausibly underlie differential susceptibility. Common to each level of analysis is a bio behavioural process involving heightened susceptibility.

BSC and DST highlight the extent to which personal characteristics condition or moderate the effects of not only risk-promoting but also development-enhancing

environmental contexts on both negative and positive outcomes (Belsky et al., 1991; Chisholm, 1999).

In this way, both theories so far described, which underpin ES propose that sensitivity may have a bivalent effect in that it can be less of a ‘vulnerability factor’ and more of a ‘malleability factor’ and thereby render some individuals more susceptible than others to both positive *and* negative environmental influences (see fig. 2.2). However, BSC proposes the within-individual developmental trajectory of ES through conditional adaptation - with those high in ES better able to exploit the advantages of well-resourced, nurturing environments or “make the best” of adverse environments despite fitness costs (B. J. Ellis, Belsky, et al., 2011), whereas DST proposes the maintenance of between-individual differences in differential susceptibility, represented by high and low levels of ES in the population, as a form of diversified ‘bet-hedging’ to ensure dispersion of genes in a future environment for which conditional adaptation may or may not represent the best strategy (B. J. Ellis, Belsky, et al., 2011).

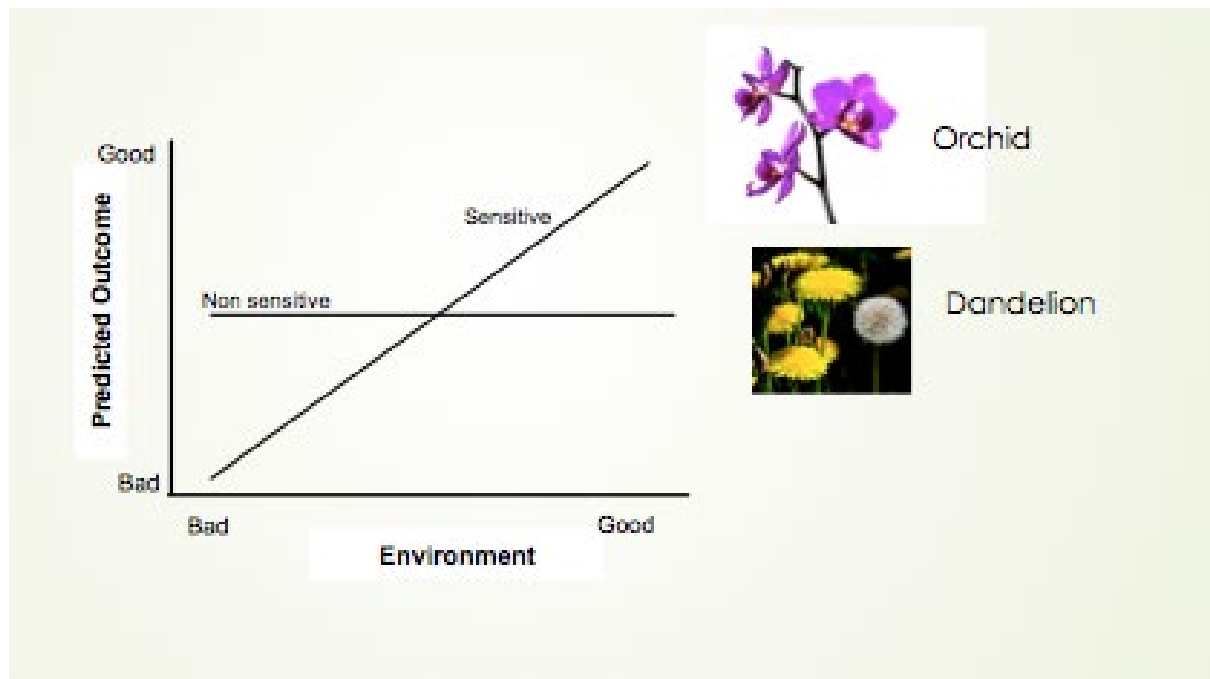


Figure 2. 2 Differential Susceptibility Theory (Belsky, 2007; Ellis et al., 2005). For better and for worse. Those low in ES (non-sensitive) are relatively unaffected by the quality of their developmental environment, those high in ES (sensitive) suffer the worse outcomes in poor developmental environments but can experience far better outcomes than those low in ES in supportive environments.

2.3.5 *Vantage Sensitivity*

The notion that some people are more vulnerable in the face of adversity has been well covered. Furthermore, the theory that the same factors reflecting susceptibility to adverse environments, also confer heightened susceptibility to the benefits of supportive environments has been established. However, the lack of a term to characterise this disproportionate likelihood to benefit from positive experiences makes it difficult to direct attention to it and possibly explains the underrepresentation of research into variability in response to positive—as opposed to negative—experiences (Pluess & Belsky, 2013). It is difficult to identify the linguistic converse of “vulnerability” (Belsky & Pluess, 2009a). A search of several languages revealed no word that captures the notion that some are more likely than others to benefit from environmental support and enrichment. The term *Vantage Sensitivity* was introduced to describe a predisposition to benefit from a supportive environment (Sweitzer et al., 2013). *Vantage Sensitivity* theory concerns individual differences in response to positive stimuli, such as supportive psychological interventions without making claims about the potential response to adverse experiences (de Villiers et al., 2018; Pluess & Belsky 2015). *Vantage* is short for advantage, but in addition to implying benefit, it is also defined as “a position, condition, or opportunity that is likely to provide superiority or an advantage” (Watkins, 2000).

Evidence for *vantage sensitivity* is growing: Japanese girls reporting high on SPS were more responsive to an intervention designed to enhance their self-efficacy than those low on SPS (Kibe et al., 2020). Furthermore, in week one of a longitudinal study, highly sensitive adolescents reported better socioemotional wellbeing associated with positive life events than their less sensitive counterparts (Iimura 2021). However, it should be noted that the HSPS and the HSCS both contain fewer items that reflect the positive aspects of sensitivity (i.e., AES subscale) than those that reflect the negative aspects (i.e., EOE and LST subscales). Improvements in the scale may increase evidence supporting *vantage sensitivity* (Greven et al., 2019; Iimura et al., 2021)

Vantage is the opposite characteristic to vulnerability. *Vantage resistance* describes low sensitive individuals remaining stable under supportive environments while only highly sensitive individuals benefit from positive life events (Pluess & Belsky, 2013; Pluess, 2017). In this way *vantage resistance* describes the failure to benefit from positive influences, just as resilience characterizes resistance to negative effects of adversity in the diathesis-stress framework. Figure 2.3 illustrates the concept of *vantage sensitivity*.

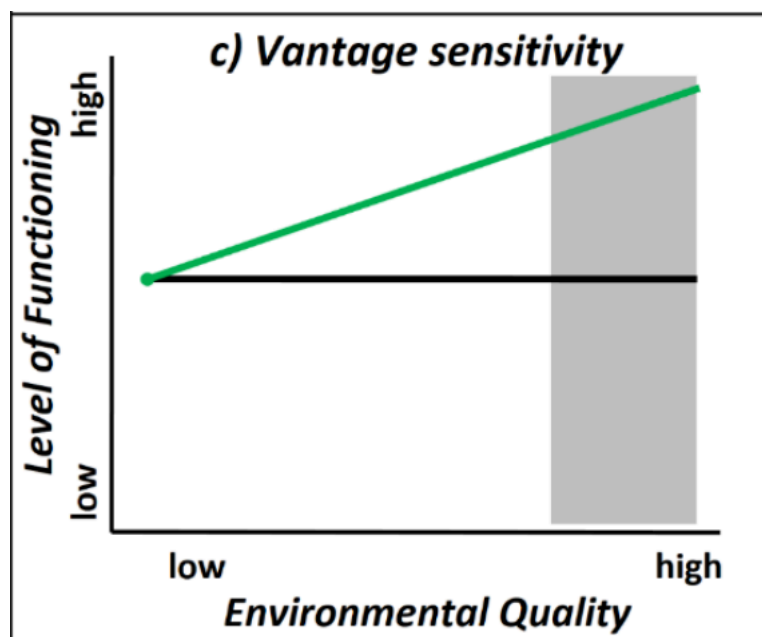


Figure 2. 3 Vantage Sensitivity. Those high in ES (green) experience better outcomes than those with low ES (black) in supportive, nurturing environments. Shaded area represents the level of environmental quality at which the slopes for high and low sensitivity differ significantly (copied from (Jolicoeur-Martineau et al., 2019))

2.3.5 Sensory Processing Sensitivity

The third theory included here – Sensory Processing Sensitivity (SPS) (E. N. Aron & Aron, 1997) did not originate from a developmental perspective, rather from a desire to obtain distinct recognition for sensitivity in psychological research. However, it is included here as it has made important contributions which are relevant to a developmental analysis of ES.

Over a series of seven studies a new 27-item Highly Sensitive Person (HSP) scale was developed. The first study used qualitative interviews with those who self-identified as highly sensitive to induce the phenomenon of high sensitivity which could then be tested quantitatively. Quantitative studies on diverse student and community samples revealed that the 27-item HSP Scale appeared to be one-dimensional and to have levels of reliability and content, convergent, and discriminant validity that made it adequate for use in future research.

Building on the HSP scale for adults, the Highly Sensitive Child (HSC) Scale was developed to measure SPS in children as young as 8 years of age with a 12-item self-report questionnaire (Pluess et al., 2018a). The HSC scale has also rephrased the same items to be used in a parent-report format (Slagt et al., 2017). Factorial analyses of the scale structure have found it to show adequate internal consistency and good psychometric properties

across independent samples (Pluess et al., 2018a). The HSC scale was also found to be partially measurement invariant across developmental stage, gender, and country (Weyn et al., 2021).

Unique to SPS is that it is the first framework to propose and develop a psychometric tool that captures sensitivity to environments directly as a phenotypic (temperament) trait in adults and children, with important theoretical and applied implications for the study of individual differences in response to the environment. Initial factor analyses on the HSP scale suggested a relatively stable unitary psychological construct that reflected an individual's sensitivity to environmental influences captured by a variety of items (Aron & Aron, 1997). More recently, evidence has been provided in support of a bifactor solution. This solution includes a general SPS factor and three sub components: 1) Low Sensory Threshold (LST, i.e. sensitivity to subtle external stimuli), 2) Ease of Excitation (EOE, i.e. being easily overwhelmed by internal and external stimuli), and 3) Aesthetic Sensitivity (AES, i.e. openness for, and pleasure of, aesthetic experiences and positive stimuli) (Pluess et al., 2017; Smolewska et al., 2006).

Of the three sensitivity components of LST, EOE and AES, only AES was reported to be associated with positive emotionality such as positive affect and self-esteem, but not with negative emotions, both in adulthood and childhood (Pluess et al., 2018a; Sobocko et al., 2015). Both LST and EOE have been associated with negative emotionality, anxiety, and depression in young adults (Liss et al., 2005). These results are consistent with findings identifying the summary score of the HSP and HSC scales capturing an increased sensitivity to positive and negative stimuli (Slagt et al., 2018).

Children scoring high on the HSC scale were more sensitive and responsive to the positive influence of psychological interventions (Nocentini et al., 2018; Pluess et al., 2015) as well as to both positive and negative parenting quality (Slagt et al., 2018) confirming the scale's criterion validity.

While biological research on the aetiology and mechanisms underlying SPS is still in its infancy, and how neural processes interact and shape sensitivity to the environment is not well understood yet (Greven et al., 2019), support has been found for the overall SPS model corresponding to biological responsiveness from neuroimaging (Acevedo et al., 2018; Acevedo et al., 2014; Jagiellowicz et al., 2011) and genetic (Homberg et al., 2016) studies.

SPS is conceptualised as a temperament trait, and not a disorder despite having overlapping symptoms such as hyper-responsiveness to incoming stimuli common to seemingly related clinical disorders such as autism spectrum disorder (ASD). Evidence for

this differentiation comes from fMRI studies showing that in response to stimuli, different brain regions become engaged for SPS and ASD (see section 2.3.2. i). Therefore, SPS advances theoretical explanations for sensory sensitivity in typically developing populations. However, it is possible that for individuals with high SPS scores exposure to adverse childhood environments may shift development from typical to atypical, with an attendant impact on well-being, and higher risk for behavioural problems and psychopathologies in childhood and adulthood (E. Aron et al., 2005; Booth et al., 2015; Liss et al., 2005). That said, when exposed to positive life events individuals high on SPS may flourish and perform exceptionally well, for example showing more positive mood and intervention responsiveness (Pluess, et al., 2018; Slagt et al., 2018). Adults high in SPS who were exposed to a positive mood induction video-clip, were shown to be more positively emotionally reactive to positive exposures compared to those reporting low sensitivity (Lionetti et al., 2018).

Figure 2.4 is a model encapsulating the concepts as have been described above that are contained within the three theoretical frameworks of BSC, DST and SPS (copied from Greven et al., 2019).

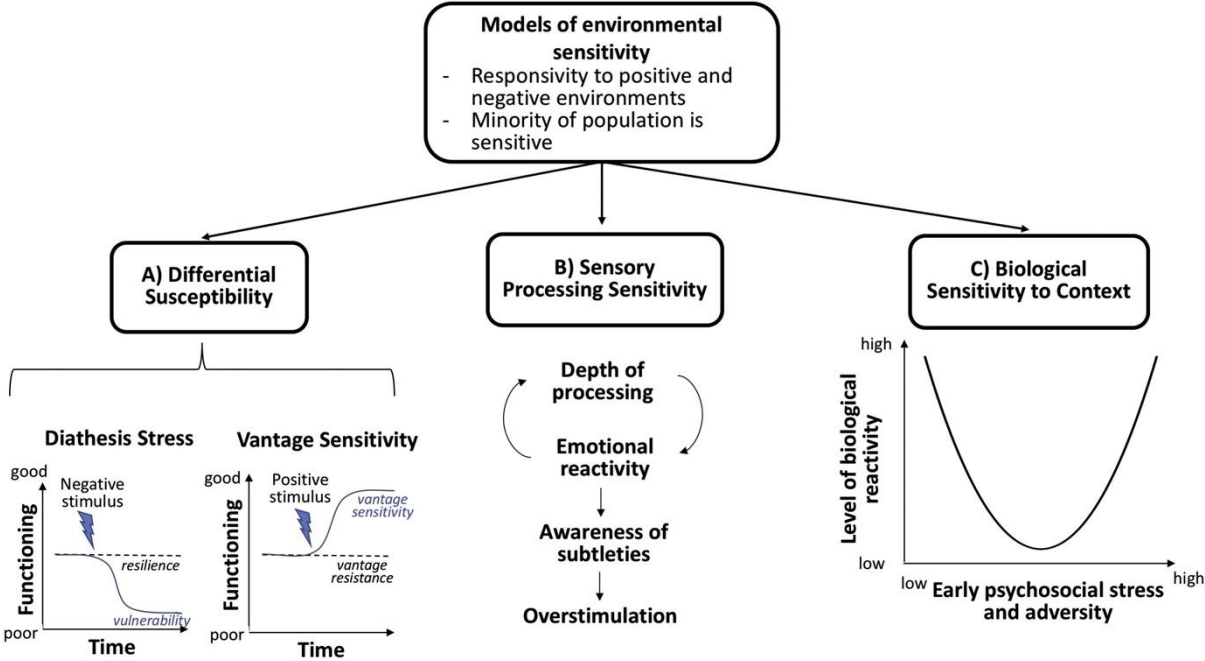


Figure 2. 4. Conceptual models of heightened susceptibility to environmental effects as described in the theories of a) Differential Susceptibility, b) Sensory Processing Sensitivity and c) Biological Sensitivity to Context, which together constitute the meta-framework of Environmental Sensitivity (copied from (Greven et al., 2019))

2.3.6 Section summary

In summary, BSC and DST both originated from an evolutionary developmental perspective and attempt to explain why children should differ in their levels of sensitivity to the effects of the environment on development. SPS did not originate from a developmental perspective rather from a desire to obtain distinct recognition for sensitivity in psychological research. However, it is included here as it has made important contributions which are relevant to a developmental analysis of ES.

Despite evolving from different perspectives (theoretical, empirical, evolutionary, and developmental) and offering different explanations for individual differences in the ability to register and process external environmental stimuli, all three theories which have been integrated into the over-arching meta framework of ES are united on one core theory. All contend that rather than a vulnerability, ES constitutes a heightened susceptibility to the environment which can be ‘for the worse’ in adverse environments such as maltreatment or lack of resources but also ‘for the better’ in advantaged, supportive environments. Three models, diathesis stress, differential susceptibility and vantage sensitivity, also predict variation in developmental outcomes as a result of both adverse and advantaged environments.

The following section will continue to examine what determines heightened sensitivity. The conditional adaptation model of BSC offers a set of developmental hypotheses concerning the distribution and prevalence of ES in the population. I will also lay out considerations that need addressing developmentally such as how developmental time periods relate to differential susceptibility, including whether susceptibility varies within and/or across individuals over time.

2.4 The distribution of ES in the population

This section will look first at a prediction based on evolutionary theory and evidence as to where ES is thought to emerge in the population. This will be followed by evidence for whether ES is best considered as a continuous or a categorical trait.

2.4.1 Where does heightened sensitivity emerge?

Adaptive calibration theory, like conditional adaptation, advances the notion that people who are more susceptible (responsive) to context are more likely to experience sustained developmental changes in reaction to contextual factors (del Giudice et al., 2011). Furthermore, the theory highlights the role of these contextual factors in shaping the mechanisms of sensitivity in individuals who are more susceptible to the effects of the environment. Conditional adaptations have been hypothesised to be the result of monitoring specific features of childhood environments as a basis for calibrating stress-response phenotypes to adaptively match those environments. Individual differences in physiological stress responses and neurobiological sensitivities to environmental circumstances emerge in early development (Ellis et al., 2011; Boyce, 2016). The development of these differences been described as triadic in that it is influenced by endophenotypic genetic proclivities (Boyce and Ellis, 2005) environmental attributes (Alexander et al., 2009) and the interaction between these (Boyce, 2016). The allostatic load model describes the relationship between increased exposure to stressors during development and hypersensitisation of the stress-response. In addition, evidence has been found for the variance in levels of ES being .47 heritable, which means that over half of the variance is influenced by unique environmental factors (Assary, 2021). In light of this, a substantial body of research has examined the links between exposure to different environmental conditions early in life, ranging from highly stressful to highly supportive, and the magnitude and patterns of physiological stress reactivity as an index of ES that have been associated with these. In the case of stress reactivity, conditional adaptation may bias early development in low- and high-stress contexts toward high sensitivity endophenotypes (Boyce et al., 2005; Ellis et al., 2005). A summary is now given of the empirical evidence for the extent to which markers associated with ES at the physiological level of analysis emerge in highly stressful, moderately stressful or highly nurturant conditions.

Exposure to highly stressful conditions, such as consistent experiences of early adversity, have been associated with upregulated stress reactivity (Conradt et al., 2014; Holochwost et al., 2017; del Giudice et al., 2011b). Associations have been found between greater reactivity in the adrenocortical and autonomic systems in children in adverse situations including socioeconomic factors: economic stress (Essex et al., 2002; Gump et al., 1999); socioeconomic adversity (Bush et al., 2011; Chen et al., 2004), as well as poor quality of parenting ranging from over controlling parenting (Taylor et al., 2013), to

insensitivity, maltreatment and neglect (Bugental et al., 2003; Enlow et al., 2014; Oosterman et al., 2010) and also exposure to maternal depression and psychological distress (Azar et al., 2007; M. J. Essex et al., 2002; Feldman et al., 2009) and parental conflict (Davies et al., 2008; El-Sheikh, 2005).

As opposed to consistently adverse conditions, intermittent exposure to moderately stressful conditions early in life has been found to associate with moderate physiological reactivity (B. Ellis et al., 2011; Levine et al., 2003; Macri et al., 2011; Parker & Maestripieri, 2011). As opposed to acute or chronic stressors, exposure to mild stressors is thought to enhance coping abilities in children and has been described as stress-inoculation (Eysenck & Cooper, 1983; Lyons & Parker, 2007; Rutter, 1987), thus promoting better psychological adjustment under conditions of mild adversity (Bush et al., 2011; Parker, et al., 2011; Seery et al., 2010).

More recently, evidence has been found to support the proposal of a curvilinear, U-shaped relation between early experiences and physiological response to challenge. As well as exposure to adverse environments, exposure to highly nurturant and supportive environments is associated with the functioning of stress response systems (Shirtcliff et al., 2017), BSC theory (Ellis, Essex, and Boyce, 2005). A common reactivity pattern among children in such supportive contexts is low basal/tonic levels of autonomic and adrenocortical system activity, but strong phasic responsivity to environmental challenges followed by fast recovery (Blair et al., 2008; Hackman et al., 2013).

Since then, the empirical literature suggesting that a subset of children growing up in stable, supportive contexts develop heightened physiological reactivity to challenging or novel conditions has increased (Alkon et al., 2014; Blair et al., 2008; DePasquale et al., 2018; B. Ellis et al., 2005, 2011b; Evans et al., 2013; Hackman et al., 2013; Luecken et al., 2009). A study looking at the effect of the developmental environment on physiological reactivity found participants from families with lower education exhibited greater reactivity to a simulation of a disadvantaged neighbourhood, while those from families with higher education exhibited greater reactivity to the simulated affluent neighbourhood (Hackman et al., 2019). Furthermore, while childhood adversity in terms of deprivation or neglect often results in a blunted HPA axis response (Reilly & Gunnar, 2019), there is evidence that the HPA axis can be recalibrated during adolescence if environmental conditions are benign (DePasquale et al., 2021). More studies are needed to ascertain whether the potential for such recalibration is greater in those with heightened ES.

In summary, based on conditional adaptation, BSC proposes that neurobiological susceptibility to the environment, both across and within populations, is non-randomly distributed. The U-shaped curve hypothesis predicts that highly susceptible phenotypes should disproportionately emerge, within populations, in both highly stressful and highly protected environments. In order to test this hypothesis, it would be necessary to measure the reactivity profile to ascertain whether it developed in the predicted direction (B. J. Ellis, Belsky, et al., 2011). The current study looked at the development of behavioural reactivity to positive and negative stimuli from 6-months to 12-months while examining the moderating effect of the environment (see Chapter six). The theory of BSC predicts that high ES should either develop or be maintained in both highly adverse and highly supportive settings. Furthermore, the prediction also applies between populations: a relatively high proportion of individuals with high ES should emerge both in populations that inhabit dangerous, unstable environments, and highly stable, well-resourced environments (Ellis et al., 2011).

2.4.2 Is ES continuously or categorically distributed?

Research into individual differences in ES has looked at whether it can be classed as a continuous or categorical trait. Initial research suggested that this heterogeneity of people's environmental sensitivity did not seem to be normally distributed. It was thought that in adults, individuals could be broadly categorised in terms of their stress response as an analogy to the work on infant reactivity (or behavioural inhibition), as defined by (Kagan, 1994). Early studies estimated that about 15–20% of the population could be considered high on the trait of Sensory Processing Sensitivity (SPS) (E. N. Aron et al., 2012; E. N. Aron & Aron, 1997). In this way, the population could be categorised into one of two groups. Those low in reactivity and less susceptible to environmental effects. In contrast those high in sensitivity are especially susceptible to both highly stressful and highly nurturing environments (Boyce & Ellis, 2005). However, two latent class analyses (a data-driven hypothesis-free method to test the structure of latent variables) carried out on over 900 (male) and 3581 (UK mixed ethnicity) undergraduate students revealed three groups which consisted of 30.5 percent falling in the low sensitive group, 29.2 percent falling in the highly sensitive group, and a third group with medium sensitivity making up the largest group in the samples at 40.3 percent (Lionetti et al., 2018; Pluess 2017). This third group became known as 'tulips'. This was also found to be

the case in children: besides being relatively independent from other common traits, the same latent class analysis suggests that there are three distinct groups with different levels of Environmental Sensitivity—low (approx. 25–35%), medium (approx. 41–47%), and high (20–35%) (Pluess et al., 2018)

Despite the usefulness of categories applied in research and by practitioners, the categorical approach has been criticised as most research has pointed to scores falling along a continuum. The issue is better conceptualised in terms of continuous variation in individual differences in neurobiological susceptibility. It is therefore more accurate to think of sensitivity as a normally distributed trait as even within the three groups there exists a continuum - a spectrum of sensitivity to the physical and social world (W. Boyce, 2019).

2.5 The development of ES

It is important to understand how ES develops within individuals including whether susceptibility varies within and/or across individuals over time. There is evidence for environmental effects influencing development even before birth - in utero (Gluckman et al., 2008; Peltola et al., 2017) and there is evidence that ES can be prenatally programmed (Hartman & Belsky, 2018b; Pluess & Belsky, 2011; Sharp et al., 2014). If, as BSC contends, ES is to some extent programmed by the developmental environment, then it is necessary to compare different markers of ES at different levels of analysis with respect to different domains of functioning across development in conjunction with the developmental environment to assess the extent to which sensitivity is moulded to enable individuals to fare as well as possible in their developmental niche.

Research also needs to address whether those who are most and least malleable in response to the environment (or features of the environment) early in life remain so later in life (Ellis, Belsky, et al., 2011). How do environmental exposures direct the development of ES? Can environmental exposures influence ES to exclusively negative effects (diathesis) or exclusively positive effects (vantage sensitivity). Does stability or change characterise ES and what determines this? Through what mechanisms and processes does stability or change in ES operate? Furthermore, does ES function differently in infants, children, and adults? It has been suggested that ES in children primarily moderates how sensitive developmental trajectories are to environmental conditions, whereas in adults, ES moderates the ability to adapt to new environments (Ellis, Belsky, et al., 2011).

Importantly, understanding differences in sensitivity to environmental effects during infancy is important because development is a process of hierarchical elaboration. The optimal development of higher-order functions is built on foundations that are laid down early on (Heckman, 2006; Karmiloff-Smith, 1998). These questions will be examined in greater depth in the next section when I shall turn to the second main question of this chapter which is how sensitivity is proposed to moderate the relationship between the environment and outcomes.

2.6 Is ES a unitary construct?

This section focuses on how sensitivity is proposed to moderate the relationship between the environment and outcomes. If sensitivity can have a bivalent effect on outcomes, it would seem necessary to hold that it is a unitary construct conferring equal sensitivity to positive and negative elements of the environment. The discovery that the same phenotypes are associated with disproportionate susceptibility to the effects of both adverse and supportive contexts on outcomes would suggest that it is. However, the following conceptual considerations are necessary. The first is the extent to which immediate reactivity constitutes developmental plasticity. The second therefore is whether heightened sensitivity constitutes greater reactivity to both positive and negative input/stimuli. The third is whether sensitivity is domain general or domain specific. In other words, are the same individuals sensitive to a variety of different environmental contexts (negative and positive) and with respect to a wide variety of developmental outcomes (domain general), or is ES domain-specific so that there are individual differences in sensitivity in different environmental contexts. Furthermore, do the mechanisms driving individual differences in sensitivity at different levels of analysis function independently or do they covary within individuals? Finally do different markers of sensitivity pre-dispose individuals to different developmental outcomes in response to the same environmental input, such as child maltreatment? The following section will address these issues.

2.6.1 Immediate reactivity and developmental plasticity

A differentiation needs to be made between immediate reactivity to environmental effects (i.e., response to current experience), and long-term developmental or phenotypic sensitivity to the effects of the environment (i.e., the ability of an organism to adapt its

phenotype over time to the conditions of the environment). The central construct in personality theories such as Strelau's (1983) theory of reactivity - in which temperament is a product of evolution and personality is a product of the social environment - or Stelmack and Geen's (1992) model of introversion is individual differences in the intensity of response to sensory stimulation in the moment. While both BSC and DST consider heightened immediate reactivity a necessary condition for differential susceptibility to the environment it is not sufficient. In addition to immediate reactivity, susceptible individuals are defined as experiencing sustained and enduring developmental change in response to environmental exposures. Therefore, the definition of environmental sensitivity includes moderating the effects of the developmental environment and exposures on developmental outcomes. Those with higher ES are more receptive to the environment and, as a result, experience more change over development in response to life experiences. This means that ES constitutes not only temporary fluctuations in functioning, but also sustained developmental change in response to environmental exposures. A link is thereby made between the concepts of "developmental plasticity" meaning any situation in which past experience (even recent) affects current behaviour, and "ontogenetic plasticity" which refers to situations in which experience at a given age or life stage (including the concept of sensitive periods (Knudsen, 2004)) affects the behaviour expressed at a later age or life stage as defined by Judy Stamps (Stamps, 2016). In elaborating a framework to try to explain why and how early adversity influences development, Ellis et al. (2022) delineate experience-expectant and experience-dependent mechanisms. Experience expectant mechanisms require typical developmental experiences that the brain 'expects' to encounter during specific sensitive or critical periods based on a species' evolutionary history (Werker & Hensch, 2015). The timing of these periods of heightened plasticity extends across both childhood and adolescence and differs across brain regions (Reh et al., 2020). Experience-dependent plasticity during development allows neural structure and function to be influenced more readily by lived experiences that occur during these early phases of life (Kolb & Gibb, 2014), potentially shifting longer-term developmental trajectories (Ellis et al., 2022).

However, consideration needs to be given to understanding the mechanisms by which increased reactivity to events over shorter time frames gives rise to outcomes over longer time frames. In addition, Wass (S. v. Wass, 2018a) has drawn attention to a seeming asymmetry in the model of short-term reactivity leading to greater long-term susceptibility to environmental effects. Greater short-term stress reactivity to adverse events leads to

hypersensitization of the stress response to negative events and increased allostatic load leading to worse developmental outcomes. However, this mechanism only explains how between-individual endophenotypic variability in short-term stress reactivity explains the relationship between total stress exposure and long-term stress reactivity. But, if ES is a one-dimensional construct, there is no theoretical reason why increased reactivity to positive stimuli should not lead to hypersensitization of ‘positive’ attention-related physiological changes through repeated exposure. Empirical evidence is lacking to link heightened reactivity to positive events to altered long-term outcomes in the same way that heightened reactivity to negative events is (S. v. Wass, 2018b).

2.6.1.i Is Environmental Sensitivity bivalent?

To countenance ES as having a bivalent long-term effect, it appears a pre-requisite to hold that it is a one-dimensional construct and thus individuals who experience a large reaction to a negative stimulus would also experience a large reaction to a positive stimulus. Temperament is thought to reflect an individual’s habitual behavioural tendencies to react to the environment. In a meta-analysis of SPS and temperament, Lionetti et al., (2018) found that SPS in adults only correlated with Negative Affect ($r = .34$). In addition, they found that SPS presented a consistent pattern of association with Neuroticism/Behavioural Inhibition, which is coherent with the notion that individuals that score high on SPS (i.e., those who are more sensitive to the environment) present a more inhibited approach in response to novel and unfamiliar situations (Aron & Aron, 1997). In contrast though, in children, SPS correlated with Negative ($r = .29$) and Positive Affect ($r = .21$) (Lionetti et al., 2019). Given that findings were stable across the child and adult samples, this result may have important implications for studies exploring reactivity to the environment from a developmental perspective (Lionetti et al., 2019). Therefore, as well as whether measures of ES at different levels of abstraction covary, it remains to be clarified whether high ES confers reactivity of equal intensity to positive and negative stimuli. It is worth noting that recent research on the genetic aetiology of ES found that it could be multi-dimensional in that some are more generally sensitive, whereas others have heightened sensitivity to either adversity or positive aspects of the environment (Assary et al., 2021). However, this research was conducted with adolescents and therefore epigenetics may have programmed phenotypes due to early environmental influences.

2.6.1.ii Is Environmental Sensitivity stable?

The extent to which ES is a stable characteristic within individuals still requires research. It is unknown whether some individuals may become more or less susceptible to environmental influences as they develop. Likewise, whether it is possible for individuals to be particularly susceptible at one point in time but not another. Furthermore, does ES evolve such that some individuals become more or less sensitive to either positive or negative elements of the environment? Developmental sensitivity in early childhood may also predict immediate reactivity or context sensitivity in early adulthood. In a study where young adults rated perceived stress during exam and non-exam days, those with a gene variant consistently associated with heightened developmental sensitivity - the short versions of the serotonin transporter gene (5-HTTLPR), (Verschoor et al., 2011) - reported both higher and lower stress, respectively, compared to those carrying other versions of the same gene (IJzendoorn et al., 2012).

Nevertheless, it is especially important to look at ES during infancy because at the level of populations, all infants and children are at heightened susceptibility to being affected long-term by their environment. But it is the children with the most sensitive phenotypes during this period of heightened general sensitivity who are the most susceptible to the quality of their developmental environment (Boyce, 2019). However, more research on the potential overlap between developmental sensitivity and immediate reactivity is required to clarify the relationship between these different aspects of environmental sensitivity (Stamps, 2016).

2.6.2 Is Environmental Sensitivity domain general?

Several predictors and markers of environmental sensitivity have been identified, from genetic factors to physiological and behavioural markers, capturing sensitivity at different levels of analysis (Belsky & Pluess, 2016). These same endophenotypic mechanisms, and behavioural phenotypes that operate as sensitivity factors, are thought to moderate the influence of environmental exposures on developmental and life outcomes. Most evidence for individual differences in Environmental Sensitivity is based on research reporting cross-over interactions where the effect of a contextual measure (e.g., parenting quality) on some behavioural outcome (e.g., social skills) is different depending on the value of just such individual traits that can be categorised into genetic (e.g., 5-HTTLPR;

(van IJzendoorn, Belsky, & Bakermans-Kranenburg, 2012), physiological (e.g., cortisol reactivity (Obradović et al., 2010a) and behavioural/psychological sensitivity factors (e.g., negative emotionality; (Kim & Kochanska, 2012).

Endophenotypes constitute a necessary link between genes and behaviour, whereby (single or multiple) genetic markers of differential susceptibility operate through neurobiological processes, and behavioural indicators of differential susceptibility are grounded in neurobiology (Ellis, Belsky, et al., 2011). Consequently, it is thought that whatever the level of analysis employed in each study, neurobiological susceptibility to the environment is the fundamental construct of interest. That ES has been found to be instantiated at multiple levels of analysis suggests that different phenotypes reflect an innate predisposition to general sensitivity (Ellis et al., 2007b; Obradović & Boyce, 2009).

Self or parent-report questionnaires have attempted to capture the hypothesised phenotypic trait of Environmental Sensitivity directly, nevertheless, uncertainty remains over whether an individual's environmental sensitivity varies across different domains of functioning (e.g., cognitive, emotional, social) or whether differences in sensitivity affect all domains equally (Pluess, 2015). For ES to be a unitary construct, the measures found to index ES at different levels of analysis would need to covary with the same individuals being sensitive to different environmental inputs.

2.6.2.i Sensitivity and responsivity

A consideration when studying ES is that whereas *sensitivity* refers to aspects of perception and internal processing of external influences (i.e., the input), *responsivity* refers to the resulting behavioural consequences (i.e., the output). Although differences in environmental sensitivity are largely responsible for the manifestation of differences in responsivity (Sih et al., 2008), sensitivity does not equate with responsivity (Pluess, 2015). Sensitivity can be conceived of as the bottom-up perception of stimuli in the environment. Without perception, there can be no processing of the information. The final stage is the output which can be measured at endophenotypic and phenotypic levels of analysis. The manifestation of the level sensitivity that can be easily observed i.e., behavioural reaction in the short term or temperament in the long term, will depend upon whether environmental conditions are sufficient to breach a threshold requiring such a reaction or whether they can be processed and regulated internally. This highlights the importance of multiple levels of analysis to understand the construct of ES more comprehensively.

2.6.2.ii Do emotions impose coherence over stress-response systems?

Theoretical assumptions have been made about coherence between the different stress response systems associated with ES, i.e., cognitive-emotional, physiological, and behavioural (Campbell et al., 2012). Emotion theories postulate that emotions impose coherence across experiential, behavioural, and physiological response systems (Ekman, 1992a; C. E. Izard, 1977a; Lang, 1988; R. S. Lazarus, 1991; Levenson, 1999; Panksepp et al., 1994). Most, but not all, of these theorists have taken a functional perspective, proposing that by imposing coherence across response systems, emotions facilitate the organism's response to environmental demands (Ekman, 1992b; R. S. Lazarus, 1991; Levenson, 1999; Plutchik, 1982; Witherington et al., 2001).

However, in contrast to the theoretically assumed coherence of response systems, empirical findings have been mixed. Psychophysicologists have found only weak correlations among experiential "subjective emotional stress experience" and physiological response systems in terms of arousal (Campbell & Ehler, 2012; Lupien et al., 2022). However, more recently, greater within-participant coherence between intensity of emotional experience and physiology was associated with greater well-being (Brown et al., 2020). Studies have also found only modest correlations among experiential, behavioural, and physiological measures in the context of specific emotional states such as fear (M. Bradley & Lang, 2000; Hubert et al., 1990; Rachman, 1978). Furthermore, even these weaker associations might occur only during intense prototypical emotional episodes (Russell, 2003; Scherer, 1982). It is thus possible that the construct of stress used by people to discuss their internal state of 'stress' is quite different from the construct of stress measured in animal and human laboratories using biomarkers of 'stress' (Lupien et al., 2022).

However, a distinction can be made between infants and adults. In infants, the construct of stress is unlikely to have acquired a subjective experience and can therefore be more reliably measured using biomarkers of 'stress'. Emotional episodes are an infant's primary means of communication. Infant emotions and emotional communications are far more organised than previously thought. The emotional expressions of the infant and the caretaker function to allow them to mutually regulate their interactions (Tronick, 2018). In addition, it is not necessary to be the primary caregiver of the infant to be able to reliably rate an infant's emotion intensity (Leger et al., 1996) suggesting that, in infants, emotions may impose more coherence on stress response systems than in adults, and therefore be a more reliable indicator of ES than in adults.

However, Dunn's four quadrant model of sensory processing (Dunn, 1997) explores the association between sensory processing and behaviour in a more nuanced way. The model proposes that the neurological threshold for response to a sensory stimulus is thought to range along a continuum from low to high depending on the amount of stimulation necessary for neural ensembles to discharge and depends on the balance between cortical excitation and inhibition. In this model, the threshold may differ for different sensory modalities (i.e., visual, auditory, tactile, and vestibular). Individuals with high thresholds may not be as responsive, so they may miss stimuli to which individuals with low thresholds respond. Behavioural responses also exist on a continuum based upon whether individuals have passive or active strategies in response to their environments. Though individuals with passive tendencies may internally respond to stimuli, they might not take action to change their environments, whereas at the active end of the continuum, individuals may tend to actively control the type and amount of sensory input in their environments (Dunn, 2007). The Infant-Toddler Sensory Profile (ITSP) (Dunn et al., 2002) is a 128/48-item questionnaire, which is the most common parent-reported measure of infants' sensory processing and is used to interpret a child's behaviour from a sensory perspective.

This suggests a more complex and sophisticated interaction between sensitivity and reactivity in infants that should be considered when assessing levels of sensitivity with infant behavioural strategies. That said, negative affect has been robustly found to moderate the relationship between developmental environment and developmental outcomes both for better and for worse. Less is known about whether increased expressions of positive affect are also indicative of ES. However, for the construct of ES to be bivalent, it would seem necessary to hold that the reaction norms of an individual to both positive and negative experience and exposures would covary. A more detailed analysis of the evidence for emotional reactivity as a marker of ES in infants will be presented in Chapter three.

2.6.3 Section summary

In summary, more research is needed to determine how environmental sensitivity moderates the relationship between developmental environment and developmental outcomes. Any such research needs to consider, the extent to which immediate reactivity constitutes developmental plasticity. If sensitivity can have a bivalent effect on outcomes, it would seem necessary to hold that it is a unitary construct conferring equal sensitivity to

positive and negative elements of the environment, but the extent to which immediate reactivity to positive and negative elements of the environment covary is under explored. Finally further research is needed to clarify the extent to which sensitivity is domain general. Developmental sensitivity to context may well be instantiated at all known levels of biological abstraction. Each level is hierarchically and mechanistically related to that just above and that just below on the scales of size and complexity. However, it may be easier to detect covariance between different markers of ES within infants. For the same reason, sensitivity and responsivity may be more closely related in infants than children and adults.

2.7 The developmental environment

No inquiry into the development of ES could be conceived without an examination of the environment in which an individual develops and functions. As has been repeatedly expressed throughout this chapter, evidence suggests that, highly sensitive children experience either the best or the worst of psychiatric and biomedical outcomes within the populations from which they are drawn depending on levels of nurturance and support versus harshness and unpredictability in their developmental environments (Bubier et al., 2009; Ellis et al., 2011; M. J. Essex et al., 2011; Obradović et al., 2010b, 2011). However, variation in environmental measures makes it difficult to ascertain precisely to which elements of the developmental environment infants are most susceptible.

There will follow a description of the conceptualisation of the early-life environment that is envisaged for this study. This will be followed by considering the importance of adequately measuring the developmental environment.

2.7.1 *Conceptualising the environment*

Evidence cited above (in section 2.4.1) supports the notion that sensitivity to the effects of the environment is heightened in more extreme environmental conditions be they harsh or nurturing. What role the environment plays in regulating the ES of individuals is still uncertain.

There are still many more studies looking at the effect of early adversity on long-term psycho-pathological and (mal)adaptive outcomes which focus on severe stressors such as institutional rearing or maltreatment (Hart & Rubia, 2012) as well as more moderate early adversity such as inter-parental conflict (Crockenberg & Leerkes, 2004; A. M.

Graham et al., 2013). Even the studies listed directly above (in the previous section) have tended to focus on the effects of adversity and a lack of adversity as opposed to the effects of advantage. However, despite a gradual increase (see section 2.4.1) there are still far fewer looking at the effects of nurturing environments on developmental outcomes. This is a result of the highly justified need to call attention to the risks of adversity for sub-optimal development. However, looking at the benefits of a nurturing environment provide a useful perspective. Socioeconomic status (SES) is one measure that has been used to assess the developmental environment. Despite the complex and imprecise nature of the concept of SES, it is predictive of a broad range of important life outcomes. Physical (Adler and Stewart, 2010) and mental health (McLaughlin et al., 2012), as well as intelligence and academic achievement (von Stumm and Plomin, 2015) all positively correlate with SES. Low SES also associates reliably with higher exposure to stressors in infants as indicated by stress responses, which can be measured using physiological markers such as heart rate variability and allostatic load (Lupien et al., 2009; Hackman et al., 2015). However, as SES is a complex construct it is difficult to know precisely which aspect of SES is particularly stressful for babies. It is conceivable that parents of lower SES would themselves be exposed to higher levels of stressors. Maternal depression and parental stress during infancy have been identified as potential risk factors for disruptions in parent-child relationships, cognitive development, and executive function (Beck, 2001; Grace, Evindar & Stewart, 2003; Hughes, Roman, Hart & Ensor, 2013; McLoyd, 1998).

As we are focusing on ES during the first year of life, when the infant is dependent on the parent or caregiver for its survival, the quality of the care an infant receives from their primary carer will have a significant impact on its stress response and other indicators of ES. Caregiving experienced early in life regulates the activity of critical stress-sensitive systems (Loman et al., 2010; Lunkenheimer et al., 2018). There is evidence for “stress contagion”, in terms of autonomic responses, between mothers and infants when mothers are exposed to stressors in a laboratory and then reunited with their infants (Waters et al., 2017).

In addition, evidence suggests that the expression of neural systems involved in stress reactivity in human infants may be influenced by even ordinary variations in maternal caregiving behaviour (MCB). Hane & Fox (2006) found that relative to infants who experienced high-quality MCB, infants who experienced low-quality MCB displayed significantly more fearfulness during the presentation of novel stimuli, less positive joint attention to a shared object, and more right-frontal asymmetry which has been associated

with negative emotion - especially feelings of fear (Diaz & Bell, 2012) and submission (Demaree et al., 2005). These findings suggest that variations in human maternal caregiving may influence the stress reactivity of offspring. The infants in the Hane and Fox sample represented a middle-class, low-risk demographic group, and the measure of MCB, which assessed degree of maternal sensitivity and intrusiveness, captured ordinary variations in MCB - not extreme instances of deprivation, abuse, or neglect. Thus, the findings indicate that normal fluctuations in the quality of early parental care are of substantial developmental relevance, even for low-risk populations.

Another potential mediator of the relationship between MCB and infant reactivity could be maternal anxiety. Evidence shows that maternal prenatal anxiety fosters negative emotionality in infancy and physiological reactivity and thus heightens susceptibility to postnatal environmental influences (Entringer et al., 2015). However, stresses encountered prenatally are likely to continue postnatally, thereby adversely affecting the development of children programmed (by prenatal stress) to be especially susceptible to environmental effects. Less investigated are the potential benefits prenatal stress may promote, due to increased plasticity, when the postnatal environment proves to be favourable. There are results that support the beneficial effects of prenatally up-regulated susceptibility. The infants of mothers with high prenatal anxiety, measured during late pregnancy, showed a larger decrease in anxious/depressive symptoms in response to postnatal maternal stroking during the first few weeks of life, than the infants of less anxious mothers (Sharp et al., 2014). This supports the hypothesis of Pluess and Belsky (2011) that there may be “prenatal programming of postnatal plasticity.” These findings are consistent with the conditional adaptation hypothesis from an evolutionary perspective even if postnatal plasticity would seem to be maladaptive from a developmental psychopathological perspective in adverse postnatal conditions.

An important methodological issue to consider in studies of ES is the importance of securing sufficient environmental variance. Exclusively targeting adverse environments will obscure any potential benefits of advantageous environments for those susceptible to such. For understandable reasons, studies of developmental psychopathology have almost exclusively targeted negative contexts. However, this has left a gap in the empirical literature for studies looking at the effects of positive environmental influences and even more specifically on the effects of those influences on highly susceptible individuals.

2.7.2 The importance of adequately measuring the environment

The importance of adequately measuring the environment has been demonstrated in reviews of studies into the interaction between genes and environment on developmental outcomes. The method of assessment of environmental adversity was an important determinant of the outcome of the study (Uher et al., 2010). Detailed interview-based approaches were associated with significant GxE findings, whereas non replications used self-report questionnaires. To reveal the interplay between genes and environment, therefore, one should assess the environment as precisely and validly as the genetic component. Therefore, in studies on infant ES and differential susceptibility, care should be taken to assess the environment (and behavioural outcome) as reliably and validly as possible by collection of a variety of measures, both self-report and observational in different settings as well as autonomic measures of both infant and parent so that aggregation of data across settings and measures can provide an accurate description of the context in which development takes place (Ellis, Boyce, et al., 2011).

2.8 Chapter summary

This Chapter has defined the concept of ES as the inter-individual variation in the threshold at which the complex and integrated system of responding to fluctuations in the environment is triggered. While the human ability to register and process external stimuli is universal, the neural networks, autonomic systems and behavioural responses are differently calibrated. Such individual differences have been found to moderate the effect of developmental environments on developmental outcomes both for better and for worse. Different models and theoretical explanations for the association between short-term reactivity and long-term outcomes have been offered. The theory of BSC highlights the differential susceptibility of different children to the same rearing environment as a result of physiological reactivity and distinguishes differential outcomes from the exclusively negative outcomes expected in prevailing diathesis-stress models of development which saw heightened sensitivity as a vulnerability only. In addition, BSC proposed the evolutionary notion of conditional adaptation to specific environments and the contribution this has made to understanding the curvilinear distribution of ES in the population. For DST differential susceptibility to the effects of the environment is framed as a form of evolutionary bet-hedging, which explains the necessity of different levels of ES in the

population to ensure dispersion of genes in unpredictable futures. To gain recognition for the trait of heightened ES, a psychometric tool was developed that captures sensitivity to environments directly as a phenotypic (temperament) trait known as SPS in adults and children. The model of vantage sensitivity captures sensitivity to exclusively positive aspects of the environment. Not only does it counter the vulnerability portrayal of ES, but it also extends the notion to reframing low ES not as resilience, but as ‘vantage resistance’. Despite the conceptual categorization of ‘high’ and ‘low’ ES, it is thought to be normally distributed in the population, although a higher incidence is predicted in highly adverse or highly advantageous environments.

Although both BSC and DST are evolutionary developmental theories, both focus on identifying the mechanisms indexing ES to better assess the effect of ES on developmental outcomes. Limited research has looked at the developmental trajectory of ES itself during the first year. To our knowledge no research has looked at the extent to which measures thought to reflect ES at different levels of analysis covary within individuals. Furthermore, when do any associations emerge and how do they develop in infancy? If bivalent developmental plasticity is conferred by heightened immediate reactivity, then is the latter also bivalent? Should individuals with heightened reactivity to negative stimuli show equal reactivity to positive stimuli? Finally, can ES be moulded by the developmental environment in the first year so that it becomes either a diathesis (hyper-vulnerable to adversity) or vantage sensitivity (disproportionately susceptible to support)? To address the imbalance of more evidence for ES constituting a vulnerability to adversity, there is a need to redress this by looking at the outcomes of individuals with high and low levels of ES in exclusively highly supportive settings.

The following chapter will provide evidence for the markers of ES reflecting neural and autonomic sensitivity as well as temperament and behavioural reactivity.

Chapter 3. Literature Review

3. Introduction

In this chapter I will present evidence from the literature for the measures of environmental sensitivity used in the studies in this thesis. Researchers working within the framework of ES have used different criteria to index ES including neural sensitivity, autonomic reactivity, and temperament, and behavioural reactivity. In this chapter I am going to be looking at neural, physiological, and both temperament and behavioural, markers of reactivity to environmental effects. Each of these putative indices of environmental sensitivity has been used to measure an individual's response to immediate environmental effects at different levels of analysis. Extant evidence that they also constitute a mechanism for differential susceptibility to the effects of the environment on developmental outcomes will be presented as a rationale for including them as markers of ES in the studies presented over the following chapters. Evidence will also be presented for the covariance of different markers of ES within individuals. However, to our knowledge, no research has been conducted into the extent to which all the measures presented here covary within an individual.

3.1 Measures of Environmental Sensitivity

For each of the hypothesised markers of ES (neural sensitivity, autonomic response, behavioural reactivity to both positive and negative stimuli, and temperament), I will present a description of the conceptualization used in this study, how it is measured and how it develops through infancy. This information was used to inform the methods used to operationalise each measure as a variable indexing ES in the studies which form this thesis. This will be followed by a review of the evidence for each as a measure of a different mechanism driving individual differences in ES. Evidence will be presented for each for the extent to which it reflects both immediate reactivity to environmental stimuli and susceptibility to the effect of exposures on long term outcomes. Where possible, evidence will be included of responses to both positive and negative stimuli and environments. Finally, I will review the existing evidence for associations between different indices of ES.

3.1.1 Measures of ES beyond the scope of this thesis

Two large bodies of research have been hugely influential in the field of ES and have made significant contributions to advancing knowledge about the mechanism of ES and what determines inter-individual variation in levels of susceptibility to environmental effects. One area of research is beyond the scope of this thesis and one area was regrettably impacted by technical difficulties which were compounded by the effects of the coronavirus pandemic. However, both are acknowledged. The first uses genetic criteria to assess an individual's level of ES.

At the genetic level of analysis, initially, candidate genes, such as a polymorphism (short alleles) of the serotonin transporter gene (5-HTTLPR) were studied extensively (Pluess et al., 2010; Verschoor et al., 2011). Carriers of the short allele were found to have a higher risk of developing depression after exposure to maltreatment in childhood (Caspi et al., 2003; Karg et al., 2011), and negative emotionality after prenatal stress exposure (Green et al., 2017). Dopamine-related genes (Bakermans-Kranenburg & van Ijzendoorn, 2011). The work on candidate genes has largely been discredited and instead the focus has turned to polygenic risk scores. Importantly, genetic evidence for increased susceptibility to the rearing environment for better and for worse has been observed in studies featuring genome-wide approaches such as polygenic scores based on thousands of genetic variants (Keers et al., 2016; Pluess et al., 2022; Nelemans et al., 2021, Assary et al., 2022).

Another index of ES that has received extensive attention is Hypothalamic Pituitary Adrenal (HPA) axis activity. In the previous Chapter the activity of the HPA axis in response to challenge was described. While the production of glucocorticoids promotes immediate survival by preparing the organism for a fight or flight response (Gunnar & Cheatham, 2003; Gunnar & Quevedo, 2007), there is distinct and stable inter-individual variability in the level of response (Kudielka et al., 2009; Zänkert et al., 2019). The trait of high HPA reactivity associates with worst and best functioning when the adversity of environments was respectively high and low (Saxbe et al., 2012; Laurent et al., 2013) providing evidence that it is a physiological marker of ES.

3.1.2 Neural measures of ES

To build on previous studies conducted by this author looking at the relationship between autonomic arousal and neural sensitivity (S. V. Wass et al., 2019) and unpublished work by this author looking at associations between neural sensitivity and behavioural response to stressors, this project focuses on event related potentials (ERPs) evoked in response to auditory and visual stimuli. Specifically, the bottom-up automatic perception of differences in stimuli. As one of the family of theoretical frameworks of ES, Sensory Processing Sensitivity (SPS) proposes an underlying phenotypic (temperament) trait characterised by, among other characteristics, greater awareness of environmental subtleties but also ease of overstimulation (Aron et al., 2012; Homberg et al., 2016). Further, research has revealed associations between SPS and cognitive, sensory, and emotional information processing in the brain (Acevedo et al., 2014, 2018; Jagiellowicz et al., 2016). This points towards a biological foundation for sensory processing sensitivity. For this reason, I included measurements of infants' automatic neural sensitivity to auditory and visual stimuli as a potential early marker of heightened ES.

3.1.2.i Describing ERPs

Sensory as well as cognitive and motor events result in the synchronous activation of thousands or millions of similarly oriented cortical pyramidal neurons firing in synchrony (Peterson et al., 1995). Event Related Potentials (ERPs) are the summed activation of excitatory postsynaptic potential and inhibitory postsynaptic potential (Luck, 2014). Ionic currents cause electrical changes that are detectable at the scalp. Electroencephalogram (EEG) records the electrical responses as they are elicited by a new stimulus or subject response. EEG has low spatial resolution. Therefore, beyond the major areas such as temporal and posterior or occipital, little inference can be made about the specific cortical generators of the signal. However, it is a very temporally specific electrophysiological technique with a temporal resolution in milliseconds. ERPs are time-locked to a specific stimulus and fluctuate between positive and negative voltage potentials over the cortical surface. Therefore, an ERP is a technique that can be used to assess how the brain is functioning in response to stimulation of the senses (e.g., sight, sound, touch, etc).

By presenting many instances of a particular stimuli such as a sound or visual object, the neural activity that is recorded at the scalp by electrodes can be time locked to the particular event of interest. Multiple segments in which the event occurred can then be

averaged. This procedure decreases the presence of noisy activity (i.e., background noise or EEG unrelated to experimental events) while maintaining event-related activity. After undergoing several signal processing steps (details of which are provided in chapters four and five) a waveform is produced. This will consist of positive and negative deflections or voltage changes (denoted by either a P or N) at specific latencies in milliseconds (Ibanez et al., 2012). Components of interest are usually named according to the direction of the deflection and the latency in milliseconds e.g., the positive deflection occurring 300ms after stimulus onset is referred to as the P3.

A distinction must be made between directed, ‘top-down’ attention, which increases neural responsiveness to sought-for stimuli (Summerfield & Egner, 2013). This ‘active’ attention - that is under voluntary control - is distinct from stimulus-driven, bottom-up, passive attention, (James, 1890; Kushnerenko et al., 2002). As infants have limited top-down processing (Kushnerenko et al., 2013), many studies have looked at the neural processes triggered by external stimuli, which constitute passive or automatic auditory attention, during the first year of life. The maturation of event-related potentials (ERPs) has been shown to parallel its development (Kushnerenko et al., 2013). The current study focused on pre-attentive change-detection as a measure of neural sensitivity.

3.1.2.ii Measuring difference waves

Difference waves are created by subtracting the amplitude of each sample (every 2ms at a sampling rate of 500Hz) in the averaged waveform in response to one condition from the other, leaving a waveform indicating the voltage changes and timing difference between the two conditions. Producing a difference waveform can highlight the difference between the waveforms of two conditions. From this difference waveform it is then possible to examine individual ERP components that differ between conditions.

3.1.2.iii The development of auditory components reflecting sensitivity

Auditory oddball paradigms, where frequently presented ‘standard’ tones are interspersed with less frequent ‘deviant’ tones and infrequent instances of white noise allow the investigation of auditory change-detection to both small and large spectral changes (Kushnerenko et al., 2013). Recording deviance-elicited brain responses using EEG is a feasible way to assess automatic auditory discrimination and regularity detection abilities in even very young infants (Kushnerenko et al., 2013).

During an auditory oddball paradigm, the brain's response to small acoustic changes is called the mismatch response (MMR). The MMR is a neurophysiological indicator of automatic, pre-cognitive change detection (Wetzel & Schröger, 2014) and demonstrates the brain's ability to perform complex comparisons between consecutive sounds automatically (Näätänen & Alho, 1995). It is thought to reflect heightened sensitivity to deviant stimulus within the auditory short-term memory provided that the trials are presented within a short enough timescale for the sensory memory not to have decayed (Bishop 2007; Winkler, 2007).

The MMR is often derived from the computation of a difference waveform whereby the ERPs to the standard stimulus are subtracted from the ERPs to the deviant stimulus allowing comparison of the ERPs to deviant and standard stimuli. The MMR is usually taken as the highest amplitude point within a given latency range (Marshall & Fox, 2007). Several theories explain this mechanism. However, in infants the relevant theories are founded in sensory processing. The MMR is theorised to be the result of change detection, whereby it represents sensory detection of acoustic deviance on one or more dimensions of the stimulus in comparison with the previous sequence (Schröger et al., 1995; Sorokin et al., 2010; Winkler et al., 1999) or it is the result of adaptation, when the MMR reflects the difference in stimulus-evoked action potentials between adapted and non-adapted sensory neurons (Dykstra & Gutschalk, 2015; May & Tiitinen, 2010).

Several features distinguish adult and infant MMRs. One major disparity is that the infant MMR has a positive rather than negative deflection with the onset around 150ms and reaching a peak after 200ms (Cantiani et al., 2016; Kushnerenko et al., 2002; 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 (a positive deflection around 300ms after stimulus onset) (Dehaene-Lambertz & Gliga, 2004; Gou et al., 2011; Halliday et al., 2014; Korpilahti & Lang, 1994; Mahajan & McArthur, 2012). In infants there can be a superposition of a negative component over a wider positive component in the same latency range, which divides the positive component into two subcomponents P150 and an early P3a. In the absence of this negative peak (presumably emerging N1) the response is often seen as one positive peak, meaning that the separation of this positive component into two might be artificial (Kushnerenko et al., 2002a, b; Kushnerenko, Tomalski, et al., 2013; Kushnerenko, Van den Bergh, et al., 2013; Morr et al., 2002). Finally, involuntary attention can be elicited by even small acoustic change in infants and children and therefore a mismatch positivity might be

elicited due to the recruiting of some involuntary attention mechanisms. However, in response to more salient acoustic contrasts, elicitation of the early P3a is observed much more consistently (Kushnerenko et al., 2002a, b; Kushnerenko, Tomalski, et al., 2013; Kushnerenko, Van den Bergh, et al., 2013).

In summary the MMR has been hypothesised to represent a neural “call to attention” to potentially important sensory stimuli presumably a precursor to an orienting response (Näätänen, 1992; Schroger, 1996).

3.1.2.iv The development of ERP differences in response to emotional faces

EEG can also be used to measure the neural responses involved in emotional face processing. Research investigating the expected development of emotional face processing in infants has shown that by the age of 5–7 months, the occipitotemporal N290 and P400 ERP components, which are associated with perceptual sensitivity to faces and the frontocentral Nc component associated with attentional engagement begin to reliably differ between fearful and non-fearful facial emotions (Hoehl & Striano, 2010; J. M. Leppänen et al., 2007; Nelson et al., 1996; Peltola et al., 2009; Yrttiaho et al., 2014). The N290 is observed as a negative waveform at around 250–350 ms on occipitotemporal electrodes and considered as an infant precursor of the adult face-sensitive N170 response (Haan et al., 2003) with its cortical generators likely located in the fusiform gyrus and the superior temporal sulcus (Guy et al., 2016; Sadeh et al., 2010). In 6-month-old infants, the P400 amplitude is greater for upright than for inverted human and monkey faces (Halit, De Haan, et al., 2003). The P400 may play a role in novelty detection; a greater amplitude response is sometimes seen to novel faces compared with familiar or standard faces (Key et al., 2009; Scott & Monesson, 2009). Leppänen et al. (J. M. Leppänen et al., 2007) also found a larger P400 in response to fearful as opposed to happy faces in 7-month-old infants.

3.1.2.vi The MMR as a measure of environmental sensitivity and susceptibility

The component known as the P3 is a fronto-parietal ERP component and is generally understood to be the central electrophysiological marker of involuntary attentional orienting to a prediction violating sound (Friedman et al., 2001; E. N. Sokolov et al., 2002; Squires et al., 1975) if the auditory change is large enough to trigger involuntary (bottom-up, saliency driven) attention mechanisms (Escera et al., 2000; Friedman et al., 2001). The P3 has also been described as a neural index of arousal (Sutton

et al., 1965). It has been linked to behavioural distraction from a task and impairment in performance (Wetzel & Schröger, 2014). The MMR as a positive discriminative response could arise from an obligatory response to a new stimulus, or possibly represent an infant mismatch response that is analogous to the P3 (Čeponien et al., 2002; Kushnerenko et al., 2002). More automatic orienting and attentional capture (represented by a large P3 component) could be interpreted as less inhibition of response (Kushnerenko et al., 2013) and therefore greater neural sensitivity (S. V. Wass et al., 2019). Other research has suggested that neural gain, the degree to which neural signals are amplified or suppressed contingent on relevance is reduced at times when pre-stimulus autonomic arousal is higher (Aston-Jones & Cohen, 2005; Hauser et al., 2016). In a previous study, 5–7-year-olds with high heart rate, indicating more activity in the “fight-or-flight” sympathetic nervous system, had a larger response to deviant tones, which was interpreted as reflecting higher attentional demands, as discussed in other studies (Garcia-Sierra et al., 2016; Rivera-Gaxiola et al., 2005), but less automatic auditory change detection (S. V. Wass et al., 2019). It is known that during hyper-arousal, neural systems involved in exogenous, salience-driven orienting become more active. This leads to a shift from ‘top-down’, more frontally mediated control at lower levels of physiological arousal to ‘bottom-up’ control by low-level aspects of the sensory stimulus at higher levels of arousal (Arnsten, 2009; Liston et al., 2009). However, in contrast to this, in infants at risk for autism, hyposensitivity to deviant compared to standard tones was indicated by a smaller mismatch response (Guiraud et al., 2011). This smaller MMR in the at-risk group also correlated with a lack of habituation to standard tones. According to the “over-arousal theory”, poor habituation to stimuli in the environment in children with autism contributes to general levels of over-arousal (as opposed to just autonomic arousal) (Rogers & Ozonoff, 2005). However, there is also accumulating evidence that supports the opposite hypothesis of under-arousal, which states that impairment of a child with autism’s ability to connect previous experiences with current ones prevents learning and generalisation and contributes to non-typical reactions and/or under-reactivity to stimuli (Rogers & Ozonoff, 2005). Guiraud and colleagues interpreted the smaller mismatch response in the at-risk group as showing how reduced habituation (little attenuation in the amplitude of responses to a repeated tone) leads to hyposensitivity to a stimulus change and at the same time an over-reactivity to repeated stimulation. Recently, greater change detection – inferred from a larger P3 in response to deviant tones was associated with better adaptation skills and cognitive development in infants (Lopez-Arango, 2021).

Sensory gating studies present repeated stimuli, such as auditory clicks in pairs to measure the inhibitory cerebral mechanisms which buffer higher cortical centres from being flooded with incoming irrelevant sensory stimuli (Boutros et al., 1995). A diminished response - measured as the amplitude of the P50 evoked potential in response to the second click compared to the first - is referred to as P50 sensory gating (Hunter et al., 2012). Attenuated sensory gating is associated with attentional deficits in childhood (Hutchison et al., 2017).

There is evidence supporting the view that the MMR to stimulus novelty and the P50 sensory gating due to stimulus redundancy are complementary neural functions, both of adaptive value in the allocation of attention: the filtering of background stimuli and the involuntary (i.e., passive, reflexive) switch of attention to significant stimuli, respectively. Individuals that exhibited less P50 suppression self-reported higher rates of filtering difficulties and individuals that exhibited stronger P50 suppression tended to show larger MMN waveforms. These findings suggest that the two components are possibly related but distinct pre-attentive processing systems (Kisley et al., 2004) and that that less efficient automatic processing of exogenous sensory stimuli results from decreased bottom-up neural sensitivity. Therefore, this study operationalised neural sensitivity as an increased ability to detect stimulus change resulting in a larger difference in the amplitude of response to standard and deviant tones. There is little evidence for whether immediate neural sensitivity to exogenous stimuli confers greater susceptibility to the effects of the environment on outcomes. However, sensitivity to small acoustic changes may confer advantages in certain learning situations – reduced sensitivity to change has been identified, for example, as a risk factor for conditions such as dyslexia (Baldeweg et al., 1999) and SLI (Rinker et al., 2007). However, greater neural responsiveness to small acoustic changes has been shown in adults with PTSD (Morgan and Grillon, 1999)

3.1.2.vii Emotional face processing as a measure of environmental sensitivity and susceptibility

Evidence does suggest that to the extent that children's experience with the world varies, so too does their interpretation and understanding of emotional signals (Pollak & Sinha, 2002). However, measures of emotional face processing have predominantly been operationalised as an outcome associated with the quality of the developmental environment rather than as a measure of ES and, as such, a predictor of outcomes. Some

facial expression-processing studies found greater wave amplitudes among maltreated children when processing angry faces (Cicchetti et al., 2005; S. Pollak et al., 1996, 2003). However, in an eye-tracking paradigm reduced attention to negative emotions at 7m was found to predict insecure/disorganised attachment at 14m suggesting reduced sensitivity to facial expressions of negative emotion is a testable trait that could link attachment disorganisation with later behavioural outcomes (Peltola et al., 2015). Furthermore, 9m infants were sensitive to differences in the eyes and mouths of female faces. Visual ERPs were most altered in response to changes in the eyes, whereas sensitivity to changes in the mouth were predictive of levels of language and communication (Key et al., 2009).

In adults, increased empathy has been associated with greater sensory processing sensitivity (Acevedo et al., 2014; Acevedo et al., 2017). In terms of ERPs, evidence suggests that N170 and late positive potential amplitudes are enhanced for those with higher empathy (Balconi & Canavesio, 2016; Choi et al., 2014). These findings have been interpreted as reflecting enhanced salience of or sensitivity to emotional stimuli for individuals with higher empathy. In addition, adults scoring highest on the trait of empathy had the largest N170 components in response to angry and disgusted faces (Clark et al., 2020).

3.1.3 RSA for autonomic nervous system sensitivity

In Chapter two, a brief description of one branch of the Autonomic Nervous System (ANS) was presented as an essential part of the Stress Response System (SRS) – the strength of activation of which moderates an individual's response to environmental challenge or threat. Here, a more comprehensive description of both branches of the ANS will motivate its inclusion in the current study as an index of ES. The ANS has two main components: the Sympathetic Nervous System (SNS), involved in quick response-mobilising ('fight or flight') reactions (Cacioppo, Berntson, et al., 2000) and the Parasympathetic Nervous System (PNS), involved in slow-acting, response-dampening ('rest or digest') responses (Ulrich-Lai et al., 2009).

The Neurovisceral Integration model (Thayer & Brosschot, 2005) implicates the brain's influence on the heart as affecting the extent to which individuals can successfully respond and adapt in the face of environmental challenges and self-regulate (Porges, 2007; Porges, 1995; Thayer & Lane, 2000). The central autonomic network (CAN) in the brain is proposed to regulate the ANS. The CAN comprises neuroanatomical structures such as the

medial prefrontal cortex, nucleus ambiguus, and amygdala. These structures receive input regarding the endogenous and exogenous environment and adjusts physiological arousal accordingly through efferent transmission to the sinoatrial node of the heart, which controls heart rate (Appelhans et al., 2008; Berntson et al., 1997). Polyvagal theory (Porges, 1995) highlights the brain's influence on the heart through the vagus nerve - the tenth cranial nerve (Porges, 1995, Porges, 2007). The vagus nerve serves organs in the thorax and abdomen (Câmara & Griessenauer, 2015). Vagal control of the heart decreases heart rate, thereby functioning as a vagal "brake" (Porges, 2007). Longer intervals between heart beats indicate PNS activity. When environmental challenge or threat necessitates, vagal withdrawal releases the brake, decreasing vagal control of the heart to facilitate the activation of the SNS. This mobilises physiological and cognitive resources to effectively cope and respond. Shorter intervals between heart beats indicates SNS activity indexed by an increase in beats per minute (BPM) (McCabe et al., 2000). Thus, greater vagal withdrawal reflects greater reactivity of the PNS and is generally considered to be an adaptive response to stress (Porges, 1995).

Changes in the SNS and PNS systems occur at different rates because they rely on different mechanisms to influence the heart. SNS activation is slower and causes changes in HR to occur over several seconds, whereas PNS regulation causes heart rate variation to occur much more quickly in milliseconds (Berntson et al., 1997). In this way the PNS is highly responsive to changes in the environment. However, the interplay of the two systems in regulating the variation in time intervals between heart beats is the basis of heart rate variability (HRV).

Most research on the ANS has studied ANS changes in response to unpredictable events – reflexive changes. These events could be unthreatening, of low intensity and surprising or novel or they could be potentially threatening, intense or particularly salient. The reflexive changes that occur in response to non-threatening, but surprising or incongruous contexts have been characterised as an orienting response (OR) (Sokolov, 1963). Stimuli that are unexpected and aversive however, elicit another type of reaction, which researchers characterised as the Defence Response (DR) (Pavlov, 1927). The OR is generally associated with changes in the parasympathetic branch of the ANS (E. Sokolov, 1963). The DR is predominantly associated with the sympathetic branch of the ANS (Cacioppo et al., 1994). The OR is characterised by a deceleration of HR following stimulus whereas the DR is characterised by an acceleration of HR (F. K. Graham & Clifton, 1966). The P3 component of the event related potential described above, and the

OR reflect complementary cognitive and physical contributions to the mobilization for action following salient, unexpected, novel, task-relevant, and other motivationally significant stimuli (Nieuwenhuis et al., 2011).

3.1.3.i Measurement of RSA

The two main methods used to quantify HRV levels and fluctuations are time-based and frequency-based approaches. Time-based methods for calculating HRV use the electrocardiogram (ECG) recording of “normal” beats or spikes in heartbeat (termed R-spikes) and calculate the distance between a sequence of intervals R-spikes. The QRS complex is the combination of three of the graphical deflections seen on a typical ECG with each letter corresponding to a different part of the heart’s action. The “R” of the complex is the area from which the values for analysis are taken. The distance (in milliseconds) between each “R” is defined as the “RR interval”. The extent to which the heart rate changes within a set amount of time will determine the amount of HRV. The Root Mean Square of Successive Differences (RMSSD) between each heartbeat is used to measure HRV and parasympathetic activity in the time-domain (Beauchaine, 2001, Xhyheri et al., 2012).

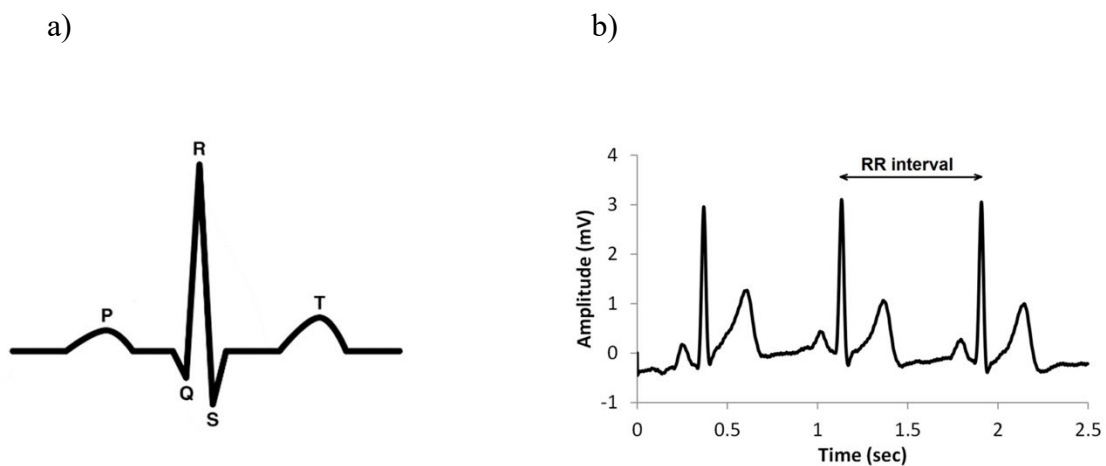


Figure 3. 1 a) The QRS complex is the combination of three of the graphical deflections seen on a typical ECG with each letter corresponding to a different part of the heart’s action; b) The distance (in milliseconds) between each “R” is defined as the “RR interval”

For frequency-based measures of HRV ‘high-frequency’ activity in the respiration range (e.g., 0.15-0.8Hz) is thought to index PNS activity (Bush et al., 2011). This component that can be extracted from the pattern of heart rate is known as respiratory sinus

arrhythmia (RSA). The frequency measure (RSA) and time-based measure (RMSSD) are highly related (Beauchaine, 2001; Xhyheri et al., 2012). Henceforth, PNS activity will be referred to as baseline RSA or RSA reactivity.

3.1.3. ia Baseline RSA activity and RSA reactivity

Although baseline and reactivity of RSA may be correlated with one another (S. Porges & Porges, 1996; Salomon, 2005), these indices reflect different regulatory processes. Baseline or resting levels of RSA reflect the capacity to respond and autonomic flexibility i.e., the extent to which the brain and its central autonomic network can flexibly respond and adapt or react to environmental challenges (J. F. Thayer & Lane, 2000). RSA reactivity (or differences in RSA from resting state to stress challenges) reflects acute changes in self-regulation and state mood in the physiological response compared to rest (Beauchaine, 2001, Porges, 1995). RSA reactivity serves as an important index of how much and how quickly the autonomic system reacts to environmental changes (S. W. Porges, 2007; J. Thayer et al., 2012).

3.1.3. ib Calculation of RSA reactivity

A systematic review identified variation in the calculation of RSA reactivity across studies (Hamilton & Alloy, 2016). The majority of studies (15) calculated reactivity by subtracting mean levels of RSA during the stressor task from the resting or baseline levels. Other methods used were the calculation of a residualized change score by regressing the average levels from the baseline period to the stressor task phase. Both methods consider the initial and task levels of fluctuations of RSA or reactivity (in various directions). Another method used ratio scores of RSA for the stressor versus rest, with greater scores indicating greater reactivity in response to the challenge (Shinba et al., 2013; Shinba et al., 2008).

3.1.3. ii Development of ANS reactivity

Research indicates that there are developmental changes in both resting ANS activity and ANS reactivity across the lifespan. The magnitude of stimuli-contingent responses increases over the first year of life (S. v. Wass, 2018b). Resting RSA increases over the course of the first year (Porges et al., 1973; Feldman, 2009; Doussard-Roosevelt et al., 1997) -so that by 12 months, all measures show arousal levels that are higher than

adults, and decline subsequently to adult levels (Wass, 2018). RSA reactivity to challenges increases during the early stages of life (Bar-Haim et al., 2000), stabilises during middle to later childhood and adolescence (El-Sheikh, 2005, Hinnant et al., 2011), and declines from adolescence to adulthood (Hollenstein, McNeely, Eastabrook, Mackey, & Flynn, 2012). More recently, data was integrated from five studies covering the 0.5- to 20-year age range from which heart rate (BPM), and PNS-parameters (eg, RSA) were collected. Cardiac PNS- and SNS-activity in childhood follows different maturational trajectories. Whereas PNS-activity shows a cubic trend with a plateau phase during middle childhood, SNS-activity shows a linear decrease from 0.5 to 20 years (Harteveld et al., 2021). Nevertheless, moderate stability of individual differences in vagal tone and baseline RSA has been found in infants from the age of 5 months (Stifter & Fox, 1998; Fox, 1989; Wagner et al., 2021; Dollar et al., 2020).

3.1.3.iii Bivalent effect of RSA activity in the short-term

There is empirical support for the view that high baseline RSA reflects greater physiological reactivity as well as flexibility in autonomic responding to the environment in infants. Porges and colleagues found that newborn infants with high RSA responded to the onset of a stimulus tone with greater heart rate acceleration, and to the offset of the tone with greater heart rate deceleration (S. W. Porges et al., 1973). A second study obtained similar findings when subjecting infants to changes in illumination. Other studies have also found that, in older infants, those with higher RSA showed larger heart rate decelerations during sustained attention (J. Richards et al., 1991; J. E. Richards, 1985, 1987).

High RSA has been associated with immediate reactivity to both positive and negative environmental effects (Beauchaine, 2001). The above evidence was interpreted as an improved ability to engage positively with engaging stimuli –with decreases in HR associated with better sustained attention (Richards & Casey, 1991). High RSA was also found to associate with increased likelihood of negative reactions to aversive stimuli (Gunnar et al., 1995; Porter et al., 1988). Higher resting RSA may be beneficial in allowing for more flexibility to respond, such that a greater degree of RSA withdrawal is available during challenge (Rigoni et al., 2017).

This can be seen as greater sensitivity in the short term to both positive and negative environmental stimuli, which supports the hypothesis that environmental sensitivity is a one-dimensional construct. However, it must be noted that these studies did not present the

same individuals with both positive and negative stimuli, which means it is difficult to ascertain whether the magnitude of reaction to positive and negative stimuli would positively correlate in the same person.

However, there is also evidence which is inconsistent with the idea that physiological reactivity is a one-dimensional construct, which is necessary for it to have a bivalent effect. In a cohort of 12-month-old, typically developing infants, the same infants who showed more reactivity (measured using a combination of movement, electro-dermal activity and HR) to positive, attention-eliciting stimuli, showed less reactivity to mildly aversive stimuli (Wass et al., 2018c; de Barbero et al., 2016). This showed that high RSA (thought to index PNS control - and greater HR reactivity) was correlated negatively with reactivity to negative stimuli but positively with reactivity to positive stimuli, suggesting that the ANS response of individuals differentiated between positive and negative stimuli, with some reacting more strongly to positive stimuli and some more strongly to negative stimuli. This evidence is inconsistent with the idea that physiological reactivity/sensitivity can have a bivalent effect because the same individuals did not have a reaction of equal magnitude to both positive and negative stimuli. However, this could be considered evidence for vantage sensitivity, which suggests that some individuals develop heightened sensitivity to exclusively positive environmental effects (Pluess & Belsky, 2013). As well as the notion of conditional adaptation suggesting that the environment can mould the sensitivity profile of individuals, it also posits that the quality of the developmental environment interacts with children's physiological reactivity in predicting children's socioemotional outcomes (Boyce & Ellis, 2005; El-Sheikh et al., 2001; Hastings, Sullivan, et al., 2008).

3.1.3.iv Bivalent effects of RSA activity in the long-term

There is a wealth of evidence in support of RSA indexing susceptibility to the effects of the developmental environment on developmental outcomes. This will be covered in detail in Chapter seven. Infants with high baseline RSA at 5-months exhibited the lowest levels of problem behaviour at 17-months if reared in an environment that fostered security, and they exhibited the highest levels of problem behaviour if reared in an environment that fostered disorganisation. However, in infants with low baseline RSA environment quality was unrelated to the amount of problem behaviours (Conradt et al., 2013). Evidence has also been found for RSA as a marker of differential susceptibility to the long-term effects of varying intrauterine conditions. Maternal prenatal anxiety and infant RSA interactively

predicted infant negative affect at 8–10 months. Among infants with high RSA, a significant positive association between prenatal anxiety and infant negative affect was observed, whereas prenatal anxiety did not predict infant negative affect among infants with low RSA (Peltola et al., 2017). Also, higher RSA in 9-13 yr olds meant supportive parenting was more protective (McQuade & Breaux, 2017). In general, significant negative relations between RSA and aggression were found primarily at high levels of environmental quality (Eisenberg et al., 2012).

There is some inconsistency in the literature as to whether low or high baseline RSA operates as a mechanism of increased susceptibility to environmental influences. Li et al. (2023) found that harsh parenting positively predicted negative affectivity among children with higher, but not lower, resting RSA, while Skibo et al. (2020) found low baseline RSA to be the differential susceptibility factor in a model testing associations between early caregiving environments and children's self-regulation. More research needs to be done on how the environment may affect the development of the ANS and levels of tonic and phasic RSA.

3.1.4 Temperament and behavioural reactivity

Temperament is constituted of individual differences in behavioural dimensions of emotional (affective) reactivity and regulation (H. Goldsmith, 1993; H. H. Goldsmith et al., 1987; Kagan, 1982). To elaborate, individual differences in emotional, motor, and attentional reactivity are measured by the latency, intensity, and recovery of response, and self-regulation processes such as effortful control that modulate reactivity (M. K. Rothbart & Derryberry, 1981). From early infancy, children show considerable variability in their habitual reactions to their immediate environment. One child may find moderately stimulating play overwhelming, can attend to one activity for long periods and demonstrate fearfulness whereas another child prefers vigorous play, has a short attention span, and seeks out exciting events. These reactions, together with the mechanisms that regulate them, constitute the child's temperament (M. K. Rothbart, 2007).

A distinction needs to be made between emotional reactions to immediate events (states) and the emotional traits which constitute temperament. Individual instances of emotional behaviours are never properly viewed as temperamental; patterns of consistent and stable individual differences in emotion manifestation are temperamental, or at least they are consistent with temperament theory (Planalp et al., 2017).

The important distinction between state and trait notwithstanding, the trait described herein as environmentally-sensitive suggests that some individuals appear more reactive to contextual factors than others. has variously been described as high and low reactive temperament and developmental plasticity in DST (Belsky, 1997), physiological stress reactivity in BSC theory (Boyce & Ellis, 2005; Ellis & Boyce, 2005) low sensory threshold and ease of excitation in SPS theory (Aron et al., 2012; Aron & Aron, 1997) and resilience and vulnerability in the diathesis stress model. Other psychological frameworks present behavioural differences in humans as inhibited/reactive (Kagan, 1989). extra- and introversion (Eysenck & Eysenck, 1968; Eysenck, 1981), behavioural inhibition system (BIS) and behavioural activation system (BAS) as described in motivational systems theory (Gray, 1981; 1982) and reaction norms (Manuck, 2009) to name the most relevant ones. While these established temperament theories differ significantly from each other, one thing they have in common is that they all describe—in one way or another—that variation in response to contextual factors between people - with some being more affected than others - is manifested in qualitatively different psychological and/or behavioural response patterns. It has been suggested that the underlying common denominator linking these diverse concepts is the notion that individuals differ in how they perceive and process environmental features, with some being generally more and some generally less sensitive (Aron et al., 2012). This interpretation suggests that ES is an important higher order personality dimension whose different aspects are reflected, captured, and described in many existing psychological concepts (Pluess, 2015).

3.1.4.i Development and stability of temperament

Manifestations of temperament develop rapidly during infancy (Rothbart, 1989). Temperament characteristics can be seen in the new-born and even measured in the foetus. Negative affect emerges first. The new-born shows distress and avoidant movements (M. K. Rothbart, 2007). Anger or frustration is seen at 2 to 3 months and researchers have reported a U-shaped developmental trajectory for anger reactions in infancy (Carranza et al., 2000, Rothbart, 1981). The decrease in anger responses occurring between 2 and 6 months of age has been linked to greater flexibility in attention shifting (Johnson, Posner, & Rothbart, 1991). In the second half of the first year, infants are likely to respond with anger when unable to grasp an attractive stimulus that has been placed out of reach, or when a caregiver has removed a forbidden object. Fear, in the form of behavioural

inhibition appears to be differentiated from general distress proneness by 7 to 10 months (Rothbart, 2007). Positive emotionality (e.g., smiling, etc.) is rarely expressed during the new-born period, but is observed more reliably between 2 and 3 months of age, increasing in expression throughout the first year of life (M. Rothbart, 2011). Physical approach is seen when developing motor systems permit, usually by 4 to 6 months (Carnicero et al., 2000.; Rothbart 1988.; Rothbart, 1986).

Early emerging differences in behavioural tendencies have been thought to be relatively stable through infancy and childhood, and to form the basis for later personality (Rothbart, M., & Bates, J. (1998). *Temperament* (Vol. III, pp. 105–176). This was because they were thought to be biologically based and linked to an individual's genetic endowment (Posner et al., 2007). However, more recent developmental and neuroscience research suggests that processes related to self-regulation and reactivity, individual differences in which constitute temperament, are sensitive to environmental influences (Diamond, 2013). Evidence for the plasticity of self-regulation indicates that its development, especially early in life - and therefore the development of temperament, is partly influenced by the context of the home and family environment and the quality of early parenting (Blair, 2010; Raver, 2004; Zeytinoglu et al., 2017).

3.1.4.ii Measuring temperament and behavioural affect

Individual differences in infant temperament are conveniently assessed by parent report but more convincingly assessed objectively via elicited behaviour in the laboratory or at home (Gagne et al., 2011). The laboratory temperament assessment battery (Lab-TAB) was designed to assess temperament dimensions through a series of episodes that mimic everyday situations. The Lab-TAB episodes and composites have been validated with parent reported Infant Behaviour Questionnaire (IBQ) (Rothbart, 1982) scales. In general, laboratory observed temperament was only modestly related to parent reported temperament. However, temperament measures were significantly stable across time. Relatively weak correlations between lab-based assessments of temperament and parent-reports of temperament may be reflective of the difference between state and trait. Even when responses across a sample from a lab-based assessment reflect individual differences, and these individual differences correlate with other responses from which a trait can be inferred, it is still possible that competing explanations for the correlated responses exist such as the state of tiredness or hunger at the time of testing (Planalp et al., 2017a). Only

measured emotional reactions to a variety of novel or threatening stimuli that converge across situation and extend over time (days, weeks, and longer) and demonstrate cross-situational consistency as well as longitudinal stability could be reliably considered the manifestation of a temperamental trait, using Allport's definition of the uniqueness of the individual supported by concepts such as the consistency of traits and the functional autonomy (contemporaneity) of motives (Allport, 1937).

3.1.4.iii Bivalent effect of negative temperament on long term outcomes

One reliable behavioural phenotypic marker of susceptibility to environmental effects in infancy and childhood is the psychological behavioural trait of negative temperament/emotionality (Kochanska et al., 2007; Pluess & Belsky, 2009; Zeijl et al., 2007) likely because of the predominance of vulnerability-oriented research based on a diathesis–stress model and thus focused on this putative “risk factor.” In terms of ES, negative affect has been framed as a diathesis if a poor environment saw the susceptibility marker go from latent to manifest. However, in support for the differential susceptibility model, more and less supportive parenting predicted, respectively, fewer and more behaviour problems at 8-11-years more strongly for children who had been rated as higher in negative temperament at 6-months (Zhang et al., 2022).

A large meta-analysis of temperament-parenting interactions did find negative emotionality, rather than surgency or effortful control to predict sensitivity to parenting (Slagt et al., 2016). Nevertheless, although negative temperament has been robustly associated with heightened sensitivity to the environment, these studies have measured ‘difficult temperament’ in different ways which makes comparison between studies challenging (Belsky & Pluess, 2009a). Furthermore, difficult temperament may be a multidimensional concept. Therefore, it remains to be determined which component reflects such sensitivity (Pluess et al., 2018b). In contrast Wittig et al., (2019) found that parent-reports of surgency, but not negative affect or duration of orienting in 6-month-olds moderated the relationship between parenting style and internalising and externalizing problems at 18-months.

Evidence supports the theory that high ES infants, as measured by individual differences in temperament, have a greater reaction range compared to those with lower ES: Marital conflict negatively affected children who were more temperamentally negative, but the same children had the lowest reports of problem behaviour in families with constructive approaches to dealing with disagreements (Hentges et al., 2015). Infants with more

negative temperaments saw a greater effect of maternal empathy on later externalising problems than infants with less negative temperaments for whom there was no effect of maternal empathy on externalising problems (Pitzer et al., 2011). At higher levels of environmental exposure to economic hardship, there was more effect on executive functioning for children with a negative temperament (Raver et al., 2013). Children with difficult temperaments were found to have fewer externalising problems when exposed to positive maternal discipline but more externalising problems when subjected to negative maternal discipline compared with children of relatively easy temperament (van Zeijl et al., 2007). In the same way, quality of childcare was found to have a greater effect on the level of behaviour problems for ‘difficult’ children compared to children with easy temperaments (Pluess & Belsky, 2009). Studies focusing on the effects of the environment on the developmental outcomes of older children also found negative temperament to be a moderating factor (Bradley & Corwyn, 2008; Pluess & Belsky, 2010; Stright et al., 2008). Negative emotion in the form of frustration moderated the relationship between mothers rejecting behaviour and increases in childhood externalising problems. No such parenting effects were evident for same-age peers scoring low on frustration (Lengua, 2008). Recently, negative emotionality was evaluated as a candidate mechanism linking prenatal maternal affective symptoms and offspring internalising problems during the preschool/early school age period (Green et al., 2022).

A relatively under-explored gap in the literature is whether infants who react with greater intensity of negative affect to negative stimuli also react with greater intensity of positive affect to positive stimuli. If, as evidence suggests, increased ES renders some individuals more susceptible to positive and negative environmental effects, surely infants who are rated as more negatively reactive, should also be more positively reactive. Longitudinal assessment of the Infant Behaviour Questionnaire/IBQ from age 3 to 12 months captured positive correlations between temperamental Positive Affectivity/Surgency and Negative Affectivity dimensions (Putnam & Stifter, 2005).

3.1.5 Evidence for correlations between indices of ES at different levels of analysis

The first aim of this study is to test whether measures of ES on different levels covary within individuals. Researchers working within the framework of ES have used different criteria to index ES. However, there is limited evidence for associations across multiple levels of analysis (Stamps, 2016; S. v. Wass, 2018b). Evidence for within-individual associations between measures that have been used to index ES is presented. There is agreement in the field that individual differences in ES originate from a more sensitive central nervous system (E. N. Aron et al., 2012a; Ellis, Belsky, et al., 2011; Pluess, 2015c). The neurosensitivity hypothesis (Pluess, 2015a, 2017a) claims that different sensitivity factors reflect different levels of analysis across various biological mechanisms that jointly reflect “neurobiological susceptibility” as the underlying central mechanism of environmental sensitivity (Belsky, 2005; Aron & Aron, 1997; Ellis et al., 2011; Pluess et al., 2012). The sensitivity of specific features of the central nervous system (e.g., amygdala and hippocampus structure and function) is determined by both direct and interactive effects of genetic and environmental factors (Pluess, 2017; Pluess et al., 2013).

Within the literature there is very limited evidence for associations between neural sensitivity to exogenous stimuli and other markers of ES. An association between ANS and neural markers of ES was found in research, to which the author contributed, which found in response to an auditory oddball paradigm, 5-7-year-old children with higher SNS activity showed larger positive amplitude responses 300ms after the onset of a sound in response to small acoustic contrasts (500Hz-750Hz) (S. V. Wass et al., 2019). This was consistent with findings which linked extreme emotional reactivity in 9m old infants with a larger positive response amplitude to deviant tones, which was interpreted as a more sensitive involuntary attention mechanism in the more emotionally reactive group (Marshall et al., 2009). To the author’s knowledge no other research has examined the relationship between arousal and variability in neural evoked responses, in human participants.

Other research looking at more than one acknowledged marker of ES, has found that they covary but that the direction of the association depends on the environment. RSA has been found to negatively associate with negative affect at high levels of environmental quality (Eisenberg et al., 2012b) and positively associate with negative affect at high levels of prenatal maternal anxiety (Peltola et al., 2017). Thus, negative affect was the outcome measure and not a measure of sensitivity to the environment or a predictor of outcomes. However, in another study, negative temperament was found to affect the likelihood that children would show increases in stress hormones as the quality of their care decreased (Gunnar & Cheatham, 2003).

In a similar finding to the above studies looking at autonomic activity and negative affect, while a significant gene (serotonin transporter polymorphism (5-HTTLPR)) -by-environment (history of stressful life events) interaction on endocrine stress reactivity was found, no main effect of either 5-HTTLPR or stressful life events on cortisol secretion patterns appeared (Alexander et al., 2009). This means the genetic and endocrine measures, which have both been used to index ES independently, did not associate in this study. Other research has looked at the association of two markers of ES with an outcome. Joint baseline activity among the PNS, SNS and HPA axis systems was related to temperamental differences in negative affect in 36-months old children (Kolacz et al., 2016). Finally, both physiological and behavioural reactivity moderated the association of both adverse and supportive aspects of the teacher–child relationship on symptom severity in grade 7 while controlling for grade 1 symptom severity (Essex et al., 2011).

3.1.6 Section summary

So far in this chapter, I have introduced the way an individual responds to external stimuli at the neural, autonomic, and behavioural level. I have considered the way reactivity develops and how it is measured in each of these proposed mechanisms driving individual differences in sensitivity. Finally, for each mechanism I have presented evidence for the extent to which it indexes immediate reactivity and susceptibility to long term outcomes and where possible whether these are bivalent both in the immediate and longer-term. Inconsistencies and gaps in the literature have been identified. For example, high RSA has been found to associate with increased physiological and behavioural reactivity to both positive and negative stimuli, suggesting bivalency of response, but in one study high RSA in 12-months-old infants was found to associate with more physiological reactivity to positive stimuli and less physiological reactivity to negative stimuli. However, the effect of the developmental environment was not considered in any of these studies. Based on the evidence and to address the identified gaps, the hypotheses that this thesis tested were formulated. These are presented in the next section.

3.1.7 Hypotheses

After reviewing the literature, we identified the following questions: The first is whether there is a single factor of environmental sensitivity which is instantiated at all

levels of analysis such that measures thought to index ES covary within individuals. I investigated whether those who show more ANS reactivity to environmental effects also show greater automatic, involuntary neural perception of differences in presented stimuli. Is there a parameter of individual differences such that some young infants show greater 'bottom-up' neural sensitivity, greater 'bottom-up' physiological stress reactivity independent of top-down control and does this correlate with measures of behavioural reactivity in the same infants. Do infants who react with high intensity to negative stimuli also react with equal intensity to positive stimuli? To countenance that ES may have a bivalent effect on outcomes it appears a prerequisite to hold that ES is a one dimensional such that those who are reactive to 'positive', attention-eliciting also react to 'negative', aversive stimuli. However, the responses to both positive and negative stimuli have not often been tested in the same babies. Therefore, the notion that heightened responsivity makes people more sensitive regardless of the nature of the stimuli, which makes them more susceptible not only to the negative effects of the environment but the positive ones too needs further investigation.

In addition, few studies have tested the same babies longitudinally to ascertain the extent to which their reactivity to both positive and negative environmental effects are reflective of a state at the time of testing or a trait, which would have more long-term consequences. However, during the first 12-months, a lack of association between measures at 6-months and 12 is likely to some extent to be reflective of differential development of the different mechanisms thought to index ES at different levels of analysis.

The second question is whether sensitivity to stimuli in the immediate term constitutes greater susceptibility to the effects of the environment on the developmental trajectory of ES itself. Is, as according to the theory of conditional adaptation, the ES of infants is calibrated to respond most to the elements of their environment which will enable them to survive or thrive within that environment?

The third related question is whether increased ES in the short term also constitutes greater susceptibility to the effect of the environment on long-term developmental outcomes either for better or for worse.

Informed by these questions, planned initial analyses were performed on data collected at 6-months and 12-months to test the following four hypotheses. Predictions were based on studies which have found the measures below to index ES in infants.

3.1.7.i Hypothesis 1

To test the notion that ES is a domain-general, unitary construct with bivalent effects, I predict that measures of infant reactivity to environmental stimuli indicated by higher baseline RSA during EEG and behavioural paradigms, and RSA reactivity during behavioural reactivity paradigms, the intensity of reactivity to lab-based positive *and* negative interactions, scores on IBQ scales of negative affect *and* surgency; and neural sensitivity to auditory oddball and emotional-face processing paradigms will correlate at 6-months.

3.1.7.ii Hypothesis 2

The second hypothesis is exploratory as I am agnostic as to the development of associations between the same measures at 6-months and 12-months of physiological and behavioural reactivity to both positive and negative environmental effects, positive and negative temperament, and neural sensitivity. Bivariate correlations between measures at 6-months and 12-months will be used to assess whether there is stability or change over time in associations between measures of sensitivity over the first year. We hope thereby to elucidate the developmental trajectory of ES.

3.1.7.iii Hypothesis 3

To explore associations between the developmental environment and the developmental trajectory of measures indexing ES at 6-months and 12-months, I will test a third hypothesis that predicts that environmental factors shape an individual's propensity for sensitivity into specific and distinct sensitivity types: general sensitivity; vulnerability; or vantage sensitivity (Pluess, 2015). The developmental environment will be measured using scores on GAD-7, ACE, and CHAOS questionnaires indexing parental exposure to stressors, as well as measures indexing the SES of the household including maternal education and household income. We predict that measures reflecting advantaged developmental environments will associate with: (a) greater infant reactivity at 12-months to positive stimuli when measures of 6-months ES were high; (b) relatively lower reactivity to positive stimuli at 12-months when 6-months ES was low; and (c) that the association between 6-months ES and 12-months reactivity to positive stimuli will be weaker or absent in infants at low levels of SES.

3.1.7.iv Hypothesis 4

As this is a longitudinal study, at the second visit, when the infants are 12-months, outcome variables were measured in the form of sustained attention, and scores on the IBQ scale of regulation and the subscale of duration of orienting. The fourth hypothesis will test the prediction that infants with high sensitivity to environmental effects, with advantaged developmental environments will have better self-regulation and sustained attention at 12 months

3.1.8 Chapter summary

This Chapter has set out the evidence used to justify the inclusion of the measures used in the following studies to reflect heightened sensitivity to stimuli and susceptibility to the effects of the developmental environment.

In the following section descriptive statistics and results of preliminary analyses will be presented. The results of these initial analyses informed further analyses which bridge the levels of analysis, noting associations between behavioural, physiological, and neural indices of sensitivity to context as well as the influence of the developmental environment on the development of ES as well as the interactive effect of the developmental environment and ES on the development of sustained attention and regulatory capacities at 12-months. Three empirical studies provided qualified support for the four initial hypotheses. These three studies are presented as Chapters five, six and seven.

Chapter 4. Early Life Sensitivity and Adaptation (ELSA) study

4. Introduction

The separate studies contained in this thesis in Chapters five, six and seven used data that was collected as part of an over-arching longitudinal study with the same participants. Two of the studies (in Chapters five and six) have been submitted to journals for publication and therefore there is some replication in the methods sections regarding participants albeit with variable N, which led to slight changes in the average ages and proportion of male and female infants. In the first section of this chapter, I will provide an overview of the whole study to provide context for the following chapters. In the second section I present the results of preliminary analyses to give descriptives of the data analysed in the studies which follow.

4.1 Study overview

This section will comprise ethics approval, recruitment - and the impact that the coronavirus pandemic had on the study design - and a description of the overall session procedure. The details of all measures are included in the respective studies and are therefore not included in this chapter to avoid replication.

4.1.1 Ethics

This project was accepted by the University of East London Research Committee (UREC). It was approved on 27th February 2019 (ETH1819- 0059), with approval of the amendment of the title on 10th January 2023 (ETH2223-0101). The author of the project passed the Research Integrity online exam on 11th September 2019 and received the enhanced clearance from the Disclosure and Barring Service (DBS) on 29th October 2015 (Certificate Number: 001507515425). The ethics applications and approvals are available in Appendix A. All parents signed informed written consent, which followed the University of East London Research Ethics Committee guidelines.

4.1.2 Participants

Due to anticipating relatively small effect sizes, which are not uncommon in the social sciences (Aguinis et al., 2005) the aim was to recruit 80 -100 typically developing infants with their primary carer. We approached local children's centres and baby groups and attended sessions to promote awareness of the UEL BabyDev lab, to explain our study,

answer questions and recruit essential new volunteers for the participant database. Families were informed of what participation would involve and that as this was a longitudinal study, we would need to see them three times over the course of a year when the infants were 6, 12 and 18m old. It must be noted that initial commitment to the research project was made before the Covid-19 pandemic. The third wave of testing, when the infants were 18m, had to be abandoned as the university campus was closed and the country entered lockdown. Families were asked if they would be willing to return from October 2020 when their infants were 24m. A sufficient number agreed to make attempting to collect data at 24m viable. However, in the event, restricted testing capacity due to strict limits to the number of participants allowed in the lab, health concerns, and repeated cancellations due to isolations meant that the attrition rate reduced the N to below 20. Amendments were made to accommodate testing the hypotheses with data collected at 6-months and 12-months. Data collection ran between February 2019 and December 2020 at the Baby Dev Lab, University of East London.

Parents were contacted via email a few weeks before their infant reached 6-months to invite them to the lab for the first visit as near to the infant reaching 6-months old as possible. Exclusion criteria were infants being premature, having a skin allergy, heart condition or any complex medical condition, parents being unable to speak English, and parents aged younger than 18.

Detailed information about the aims of the study and what each testing session would involve were sent to participants as well as a short summary in the body of the email. After explaining the study again at the beginning of each session, parents provided written consent for each element involved. At the end of the session participants were offered £20-worth of Love2Shop vouchers, a certificate, and a small gift for their baby per visit to thank them for their contribution. The same procedure was followed for the second visit when each infant was 12-months old.

At time point 1, 82 infants (52.4% males) and their primary caregivers (98% mothers) attended the lab (Infant *mean* age in weeks = 27.77, *SD*=0.59). As a part of the data collection, socio-demographic information was collected. The demographic characteristics of the sample at both data collection points (6-months and 12-months) are shown in Table 4.1. Half of the infants were White British and Other White (56.09%). The rest of the ethnicity distribution was mostly Mixed (23.17%), with Asian (9.76%), African (4.88%), Caribbean (3.66%), and others (2.44%). The maternal education of mothers participating in this study was notably high; 45.12% were educated to postgraduate level

and 39.02% were graduates. The income of families showed a more diverse picture with 10.8% having under £50,000, nearly 77% having between £50,000 and £150,000 and 12.3% having more than £150,000. 42.68% of households reported having more than one language spoken at home.

At time point 2, 68 infants (52.9% males) returned (Infant *mean* age in weeks = 54.45, *SD*=0.75), to the lab when they were 12-months old, making the attrition rate of the study 17.07%. Of those not returning, 9 mothers were too busy or declined to participate; 1 family moved to another country; 4 participants could not be invited due to the first breakout of the Covid-19 pandemic.

Of note, only one infant was brought to the lab by her father at both visits due to her mother being busy at the time of testing. We decided to include this family since the primary day care of the baby was shared by the father and mother.

Table 4. 1 Demographic details of participants at 6-months (*n* = 82) and 12-months (*n*=68)

Variable	6-months	12-months
Infant age in weeks- M(SD)		54.45 (0.75)
<i>Range</i>	27.77 (0.59) 20.9-32.7	48.8-60.5
Birth weight in kg - M(SD)		3.38 (0.53)
<i>Range</i>	3.35 (0.52) 2.21-4.90	2.21-4.91
Gender (%)		
female	47.56	47.06
male	52.44	52.94
Infant ethnicity (%)		
White British	40.24	36.76
Other White	15.85	16.18
African	4.88	5.88
Caribbean	3.66	4.41
Asian	9.76	10.29
Mixed	23.17	26.47
Other	2.44	-
Income (%)		
Under £50.000	10.8	9.3
£50.000-£100.000	43	42.6
£100.000-£150.000	33.9	33.3
£150.000-£200.000	6.1	7.4
>£200.000	6.2	7.4

Maternal education (%)		
Postgraduate	45.12	47.06
Undergraduate	39.02	44.12
A level	4.88	2.94
No formal qualifications	1.22	1.47
Number of languages spoken at home (%)		
One	57.32	60.29
Two	20.73	22.06
Three	9.76	11.76
Four	2.44	1.47

M=Mean, *SD*=Standard deviation

4.1.3 Measures

This study was a longitudinal design with an initial data-collection session when infants were 6-months old and follow-up assessments at age 12 months. No statistically significant correlations were found between age and gender of the infants with any measures of ES at either time point.

Data was collected on measures of sensitivity reflecting different levels of analysis. Information on obtaining these measures including equipment and procedures is included in the methods sections of the individual studies, so will not be detailed in any depth here. However which measures were used to index the sensitivity of infants, the developmental context and the developmental outcomes are given in subsections below.

Measures of stimulus-driven neural responsiveness and autonomic activity in the infants at 6 and 12-months are included in Chapter five. Measures of infant positive and negative behavioural reactivity to stimuli at 6 and 12-months as well as level of maternal education are included in Chapter six. In Chapter seven, details of 6-months infant RSA activity, measures indexing maternal SES and wellbeing and measures of infants' self-regulation and sustained attention at 12-months are included. Data was also collected on parent-reported temperament. Variables indexing negative affect and surgency were created using the scores on the IBQ scales of the same. This data was not used in the analyses presented in the following Chapters as preliminary analyses found no associations between parent-reported affect and other variables thought to index sensitivity. For qualitative details of the dimensions included in the two scales and the reported internal consistency of the scales see appendix B.

4.1.3.i Measures of infant sensitivity

Neural sensitivity: EEG data was collected while infants were presented with an auditory and a visual paradigm. An *auditory oddball paradigm* consisted of four blocks of 100 trials (400 trials in total). Each block of 100 trials consisted of 70 ‘standard’ 500 Hz tones; 15 ‘deviant’ 750 Hz tones; 15 ‘noise’ (broadband white-noise) segments. An *emotional face paradigm* consisted of four blocks of neutral and fearful expressions of 12 young (under 30-years) women’s faces taken from the NimStim faces database (Tottenham et al., 2009). Sensitivity was measured as the difference in the amplitudes of components evoked in response to the different conditions in both tasks.

Autonomic reactivity: ECG data was collected during presentation of the auditory and visual EEG paradigms. Baseline RSA was measured during five minutes immediately after the presentation of the excerpt from children’s television show ‘*Mr Tumble*’ when nearly all infants were calm and sitting quietly in their parent’s lap. RSA reactivity was calculated as average baseline RMSSD minus average trial RMSSD during the peekaboo and toy retraction tasks at 6-months and 12-months.

Behavioural negative reactivity: Procedures adapted from the Laboratory Temperament Assessment Battery (Lab-TAB; Goldsmith & Rothbart, 1999) were used to measure behavioural reactivity. The *toy retraction* task was designed to evoke mild and transient frustration and anger, in infants by preventing them from reaching an attractive toy with which they have been engaged in play, in a standardised setting.

Behavioural positive reactivity: The *peekaboo* task was designed to evoke joy and pleasure in infants. We used a modified version of the joy eliciting stimuli *peekaboo*. In our peekaboo task, an experimenter (instead of the infant’s mother) hides under the table and waits for 15 seconds before appearing suddenly and smiling and saying: “peek-a-boo!”. For both behavioural tasks, behaviour was video-recorded and coded for instances of pre-specified behaviour.

Temperament – negative: Infant temperament was measured at 6-months and 12-months using the Short Form of the Infant Behaviour Questionnaire-Revised (IBQ-R; Putnam, Helbig, Gartstein, Rothbart, & Leerkes, 2014). Negative temperament was measured using the IBQ-R scale of negative affect (comprised of the dimensions of sadness, distress to limitations, fear, and low falling-reactivity)

Temperament – positive: Positive temperament was measured using the IBQ-R scale of surgency (comprised of the dimensions of approach, smiling and laughter, high pleasure, activity level, perceptual sensitivity, and vocal reactivity)

4.1.3.ii Measures of the developmental context

Detailed demographic information including education, occupation, and annual income as well as information on the current home environment, the parent's childhood and their anxiety levels was collected by the administration of self-report questionnaires:

Adverse Childhood Experiences (ACE) Questionnaire (Felitti et al., 1998) – a standardised 10-item questionnaire to ascertain levels of abuse and household dysfunction to which the parent was exposed before the age of 18.

The Confusion, Hubbub and Order Scale (CHAOS) (Matheny, Wachs, Ludwig, & Philips, 1995) – a validated measure of confusion and disorganisation (high levels of noise, crowding, home traffic pattern) in the home environment of infants and toddlers. The scale comprises 15 items which respondents endorse as true or false. Seven items reflect routines and organisation (e.g., “First thing in the day, we have a regular routine at home”) and eight items reflect disorganisation, confusion, and noise (e.g., “It’s a real zoo in our home”). The routines and organisation items are reverse coded before adding the total number of items endorsed by the respondent. This total score reflects the extent of home chaos, with higher scores representing more disorganised, confused, and noisy home environments.

Generalised Anxiety Disorder scale (GAD-7) (Spitzer, Kroenke, Williams, and Lowe, 2006) a validated 7-item scale for screening for GAD and assessing its severity in clinical practice and research. It is designed to assess the respondent's health status during the previous 2 weeks. Scores of 0, 1, 2 or 3 are given for experiencing symptoms ‘not at all’, for ‘several days’, for ‘more than half the days’ and for ‘nearly every day’, respectively. The scores are then totalled and presented from 0 to 21. Scores of 5, 10 and 15 represent cut-off points for mild, moderate, and severe anxiety, respectively.

Demographic questionnaire - unstandardized questionnaire adapted from those used in ELAS, ELAS2 and TALBY studies at UEL BabyLab. It covers information about the birth, the infant, their parents, and their home environment that has been included in generating a Cumulative Risk Score for adverse outcomes for children reared in poverty (Conradt et al., 2013). For the purposes of the current study the variables indexing maternal and paternal education and household income were included in analyses. Education level was a continuous variable (7 – postgraduate, 6 – graduate, 5 – further education, 4 – A Levels, 3 – GCSEs, 2 – no formal, 1 – other) and gross annual income a continuous variable.

Coding of the standardised questionnaires was conducted following the standard published protocols.

4.1.3.iii Measures of developmental outcomes

IBQ Regulation 12-months - At 12 months of age regulation was assessed with the short form of the Infant Behaviour Questionnaire-Revised (IBQ-R; Gartstein Rothbart, 2003; Putnam, Helbig, Gartstein, Rothbart, & Leerkes, 2014), a widely used parent report measure of different facets of infant temperament.

Eye-tracking measure of sustained attention at 12 months - At 12-months infants took part in several eye-tracking tasks. We used a task to assess sustained attention at 12-months. A target (a subtending butterfly) was presented on the screen. When the infant fixated the target, the butterfly “flew” across the screen accompanied by music. When the infant looked away the target remained static on screen and the music stopped. On refixing the target, it recommenced moving until it reached the right side of the screen whereupon it grew, and congratulatory music and confetti appeared. The dependent variable was the infant’s ability to sustain their attention to the target, indexed by the proportion of the trial duration spent looking at the target so that it would continue moving across the screen.

IBQ duration of orienting subscale - The IBQ duration of orienting subscale includes the items pertaining to the infant’s attention to and/or interaction with a single object for extended periods during the preceding week. Items include: ‘How often during the last week did the baby look at pictures in books or magazines for 5 minutes or longer?’

4.1.4 Overall session procedure

Parents visited the Baby Lab at UEL with their infants at age 6-months and then at age 12-months. During each testing session, the same procedure was followed: Upon arrival, the infant was encouraged to play in the warm-up area of the lab while the experimenter informed the parent about the study and obtained consent. The infant’s head circumference was measured so that the appropriately sized EEG net could be selected and prepared. Then, the electrodes and wireless ECG monitors were placed both on the infant and mother. Mothers and the infants participated in three main experiments during their visits: a screen-based EEG experiment, a series of eye-tracking paradigms and six behavioural paradigms. Small breaks were taken in between these. The EEG paradigms are described in detail in chapter five. The behavioural experiments involved a set of six

behavioural tasks; a still-face paradigm, tasks designed to elicit joy (peek-a-boo, puppet show), frustration (toy retraction, arm restraint) and fear (masks). The order of behavioural tasks was counterbalanced as far as possible across the testing sessions to reduce carry-over effects. However, if the infant was visibly tired, upset or agitated, we would start with a joy-evoking task rather than a frustration eliciting task. EEG paradigms proceeded in the EEG lab at UEL, which is equipped with an EGI system. The behavioural paradigms proceeded in the observation unit of the lab where a table, a highchair for the infant, a chair for the mother and three cameras were placed in a divided room with computers. These paradigms were videotaped for later coding, and physiological data were collected concurrently. The eye-tracking data was collected in a dedicated eye-tracking lab. The current study focused on the toy retraction and peekaboo behavioural tasks. Any task was terminated if the infant was highly distressed or cried for more than 10 consecutive seconds or if the mother felt uncomfortable continuing the task for any reason. On occasion infants became too tired or distressed to participate in some tasks due to the prolonged and intensive data collection procedure. Since the infants were high-maintenance participants, parents were regularly asked if the infant needed feeding, changing or a nap during their visit to eliminate potential discomfort/distress. Parents remained with their infants during all tasks. Parents also completed all questionnaires in the lab to try to avoid any data loss which may have occurred if they took the questionnaires home. The entire session lasted between 3 to 5 hours depending on the infants' general mood.

Table 4. 2 All measures collected at each visit for both infant and parent

Measures	6-months visit infant	6-months visit parent	12-months visit infant	12-months visit parent
EEG auditory oddball	✓		✓	
EEG emotional faces	✓		✓	
Behavioural toy retraction	✓		✓	
Behavioural peekaboo	✓		✓	
IBQ		✓		✓
Questionnaire demographic		✓		✓
Questionnaire CHAOS		✓		✓
Questionnaire GAD-7		✓		✓
Questionnaire ACE		✓		
Eye tracking sustained attention			✓	

4.2 Results

In this section, first the results of preliminary analyses and descriptives will be presented for all measures indexing environmental sensitivity, the developmental context, and developmental outcomes. This will be followed by a factor analysis of the IBQ scales. The variables indexing surgency and negative affect were not included in any of the three studies which follow. Therefore, information pertaining to these measures is presented here for interest

4.2.1 Neural sensitivity – auditory task

Figure 4.1. shows the distribution of the P3 component in response to standard, deviant and noise tones at 6-months and 12-months. The grand average waveform at 6 months in response to standard and deviant tones and white noise show that in response to the frequently presented standard tones (70 trials per block) the P150 component is followed by a small negative deflection (N250), and then a small positive peak (P300). ERPs to deviant tones and white noise represent a typical waveform consisting of a large and prolonged positive peak (merged P150 and early phase of P3a) (Kushnerenko et al., 2002). This resulted in the largest difference in amplitude of response to the frequently presented standard tones and the less-frequent deviant tones occurring at around 300 ms post stimulus onset. The grand average waveform at 12 months in response to the same stimuli show that while there is still a large and prolonged positive peak (merged P150 and early phase of P3a) to the white noise condition, the waveform to deviant tones at 12-months resembles that to standard tones at 6-months. This resulted in the largest difference between standard and deviant tones remaining at the latency of the P3 component. Inspection of individual waveforms confirmed that despite considerable inter-individual variation, the highest point in the difference wave was most consistently at this latency. In line with theoretical considerations – the infant MMR is thought to occur at this latency and the P3 indicates automatic orienting – and previous research with infants and children, we decided to retain the same time-window (200-400 ms post stimulus onset) to extract the average amplitude response.

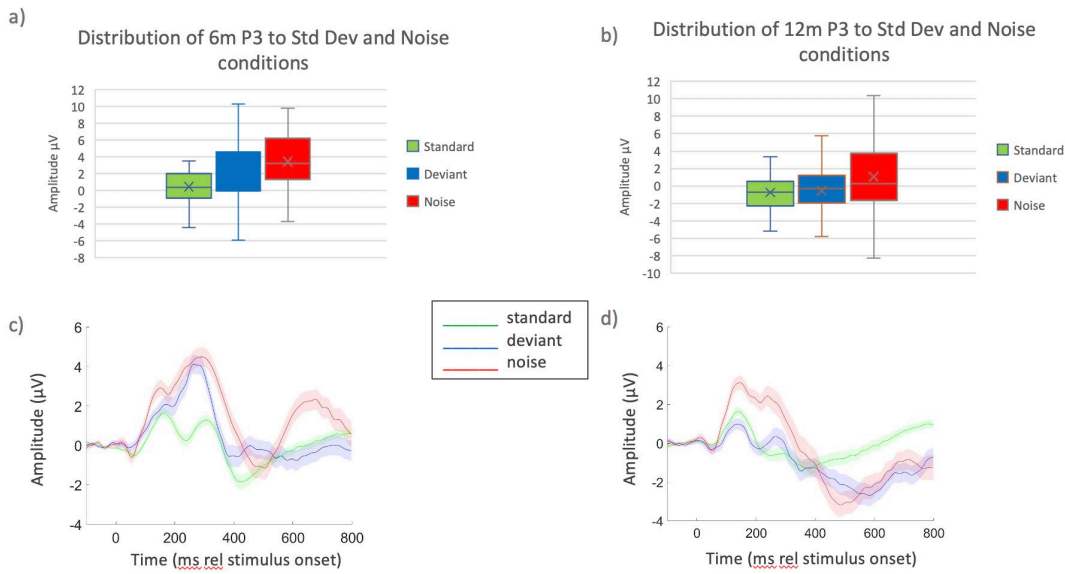


Figure 4. 1 Distribution of the P3 component to standard, deviant and noise tones at 6-months (a) and 12-months (b); Grand Average waveforms to standard, deviant and noise tones at 6-months (c) and 12-months (d).

4.2.2 Neural sensitivity - visual task

Figure 4.2. Shows the distribution of the P1, N290 and P4 component in response to neutral and fearful at 6-months and 12-months grand average ERPs in response to fearful faces and neutral faces at 6-months and 12-months. The grand average waveforms clearly show P1, N290 and P4 components in response to faces at both ages. We did not find a difference between conditions at a group level at either 6-months or 12-months.

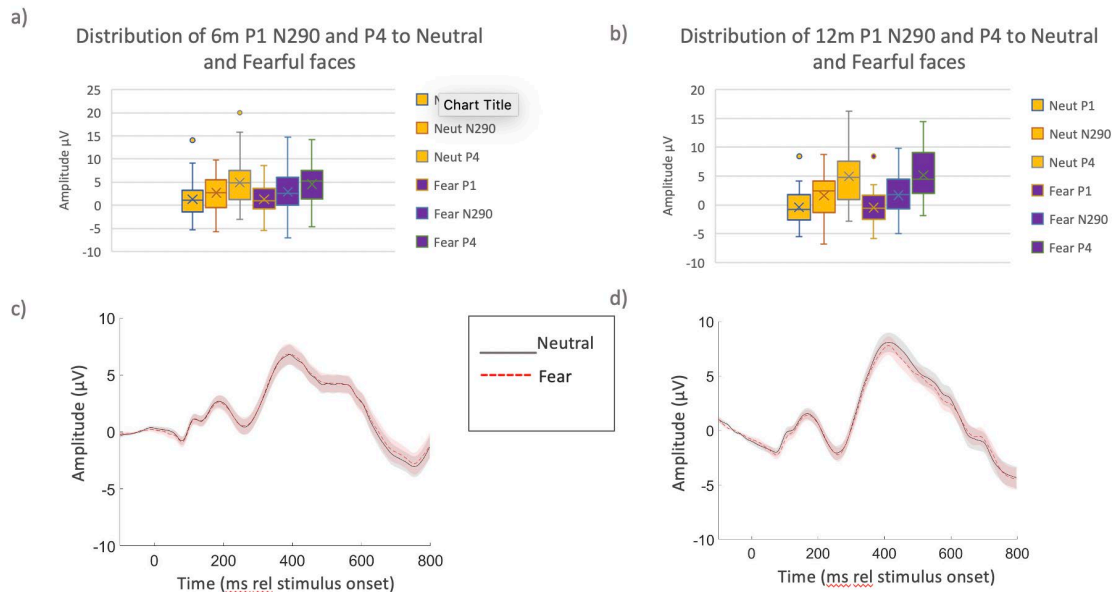


Figure 4. 2 Distribution of P1, N290 and P4 component neutral and fearful faces at 6-months (a) and 12-months (b); Grand Average waveforms to neutral and fearful faces at 6-months (c) and 12-months (d).

4.2.3 Negative behavioural reactivity – toy retraction

Figure 4.3. shows that at both 6-months and 12-months there was a significant difference between measured negative affect during free play and negative affect during toy retraction trials. The difference was greater at 12-months (c) than 6-months (d). This can be seen in the time series data showing average levels of negative reactivity at each second of the 90s task with elevated behavioural reactivity during the three 15s trials highlighted in green boxes (e). Average RSA was higher during toy retraction trials than the free play session in between at 6-months suggesting vagal withdrawal during free play. At 12-months, average RSA levels were higher during free play sessions than toy retraction trials suggesting vagal withdrawal and autonomic arousal in response to toy retraction trials at 12-months.

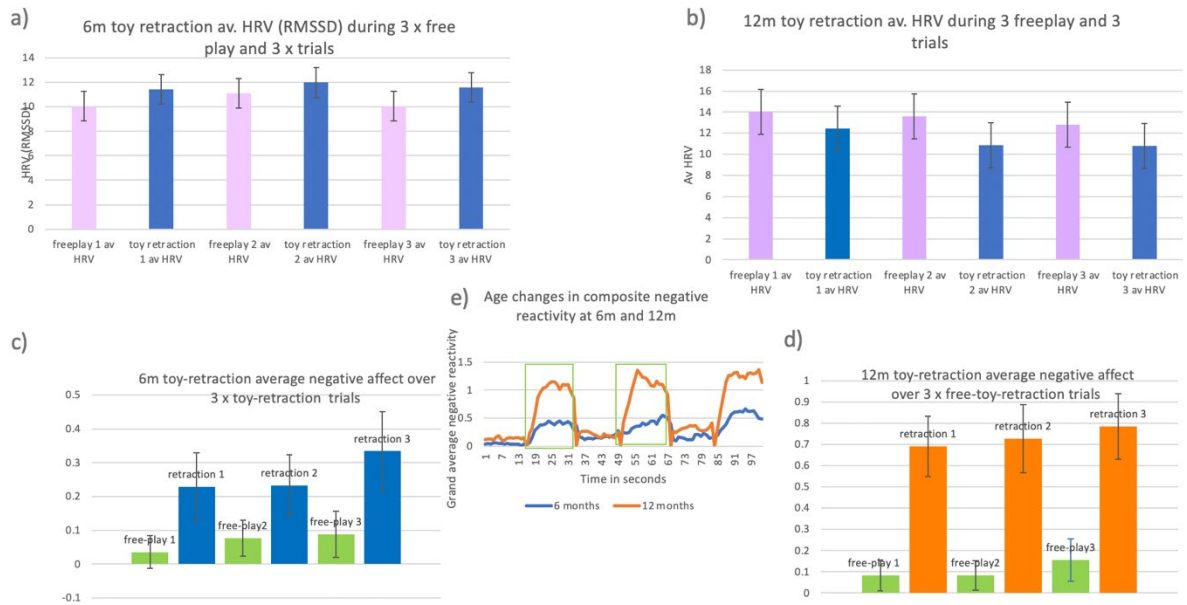


Figure 4. 3 Average RSA levels during three free play and three toy retraction trials at 6-months (a) and 12-months (b); Average negative reactivity in response to free play and toy retraction trials at 6-months (c) and 12-months (d). Time series indicates age-changes in negative reactivity at 6-months and 12-months (e).

4.2.4 Positive behavioural reactivity – peekaboo

Figure 4.4. shows that at both 6-months and 12-months there was no significant difference between measured positive affect during 15s preparation and positive affect during 15s peekaboo trials. Time series data showing average levels of positive reactivity at each second of the 90s task shows more positive reactivity at 12-months than 6-months. At 12-months elevated behavioural reactivity is evident during the three 15s trials highlighted in green boxes, but also during the preparation episodes when the experimenter is under the table (e). Average RSA was slightly higher during preparations than the peekaboo trials at 6-months suggesting vagal withdrawal and autonomic arousal during the peekaboo sessions. At 12-months, there is no difference in average levels of RSA during preparation and peekaboo trials.

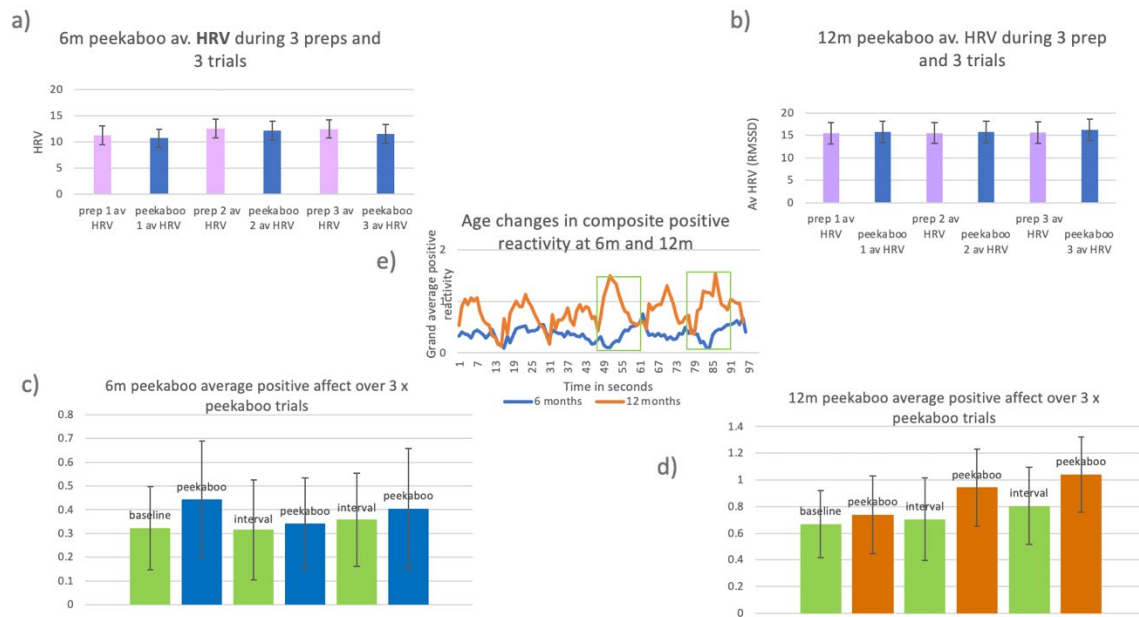


Figure 4. 4 Average RSA levels during three preparation and three peekaboo trials at 6-months (a) and 12-months (b); Average positive reactivity in response to preparation and peekaboo trials at 6-months (c) and 12-months (d). Time series indicates age-changes in positive reactivity at 6-months and 12-months (e).

4.2.5 Baseline RSA and RSA reactivity

Baseline RSA was measured as the average RMSSD during the 15s preceding the first trial in both peekaboo (when the experimenter was under the table) and toy retraction (when the infant was playing with the toy). Reactivity was measured as baseline minus the average RSA during the three 15s trials when the toy was withdrawn (toy retraction) and the experimenter appeared from under the table saying “peekaboo!” (peekaboo). At 6-months there was a positive correlation between baseline RSA and RSA reactivity for peekaboo (N55 $r = .498$ $p < .001$) and toy retraction (N55 $r = .378$ $p = .004$) (Fig. 4.5 a and b). As baseline RSA increased, the difference between baseline and trial is positive meaning RSA decreased from baseline to trial indicating vagal withdrawal and increased autonomic arousal in response to behavioural toy retraction and peekaboo interaction trials. At 12-months, there is a negative correlation between baseline RSA and RSA reactivity for the peekaboo task (N48 $r = -.445$ $p = .002$) and a positive correlation between baseline RSA and RSA reactivity for the toy retraction task (N56 $r = .62$ $p < .001$) (Fig 4.5 c and d). For the peekaboo task, at higher baseline RSA, the difference between baseline and trial is negative meaning RSA increased from baseline to trial indicating vagal control and decreased autonomic arousal in response to behavioural peekaboo interaction trials. For toy retraction at 12-months, at higher baseline RSA, the difference between baseline and trials is positive

meaning RSA *decreased* from baseline to trial indicating vagal withdrawal and increased autonomic arousal in response to the toy retraction. Studies have linked decreases in heart rate to increased attention to a non-threatening situation (peekaboo) – orienting response, whereas increases in HR have been linked to a defence response to aversive (toy retraction) stimuli. We noted a change in the reactivity profile of the current sample from 6-months to 12-months. At 6-months both behavioural tasks elicit a putative defence response. At 12-months the autonomic reaction differentiates between the two tasks with a decrease in arousal in response to the attractive task and an increase in arousal to the task designed to be aversive.

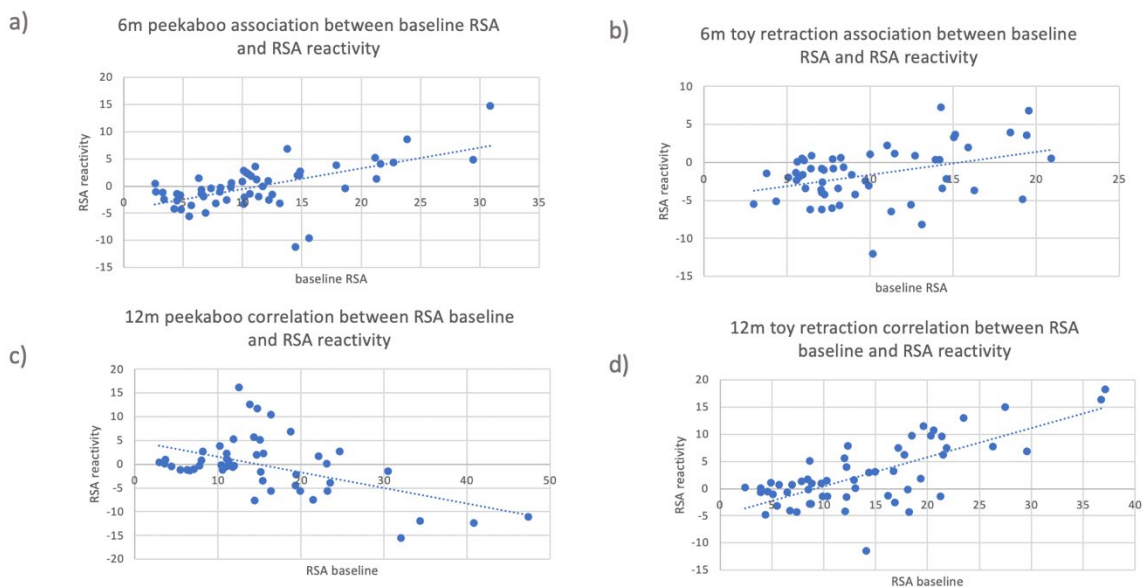


Figure 4. 5 plots of correlations between baseline RSA and RSA reactivity to peekaboo (a) and toy retraction (b) at 6-months; and peekaboo (c) and toy retraction (d) at 12-months.

We also collected ECG data from infants during presentation of the auditory and visual EEG paradigms. We sampled the 5 minutes immediately after the presentation of the except from children’s television show ‘*Mr Tumble*’ when nearly all infants were calm and sitting quietly in their parent’s lap. Table 4.3 shows unadjusted bivariate correlations between RSA baseline and RSA reactivity (baseline minus trial) during the peekaboo and toy retraction tasks at 6-months and 12-months and RSA baseline during a 5-minute sample during the EEG paradigm.

Table 4. 3 Unadjusted bivariate Pearson's correlations between ECG variables denoting RSA baseline and RSA reactivity at 6-months and 12-months (6-months N=56, 12-months N=48)

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. 6-months PB baseline	-								
2. 6-months PB react	.54**	-							
3. 6-months TR baseline	.57**	.23	-						
4. 6-months TR react	-.02	.05	.38**	-					
5. 12-months PB baseline	.35*	-.01	.53**	-	-				
6. 12-months PB react	.34*	.15	-.21	-	-	-			
7. 12-months TR baseline	-.01	.25	.36*	.01	.64**	-.24	-		
8. 12-months TR react	.39*	.43**	.06	-	.24	-.15	.62**	-	
9. 6-months EEG RSA baseline	.46**	.12	.54**	.18	.43**	-	.38**	.48	-
10. 12-months EEG RSA baseline	.50**	.15	.46**	.03	.69**	-.07	.60**	.16	.47**

** = $p < .001$ * = $p .05$

4.2.6 Temperament – IBQ scales

Table 4.4 shows the mean (SD) scores on each of the 14 subscales at 6-months and 12-months. Significant positive correlations were found for nine of the fourteen subscales from 6-months to 12-months. Soothability, distress recovery, cuddliness, perceptual sensitivity and sadness did not correlate from 6-months to 12-months.

Table 4. 4 Mean (SD) scores on IBQ subscales at 6-months and 12-months. Pearson's correlations between the 6-months and 12-months measures.

<i>IBQ subscale</i>	<i>6-months (N = 76)</i>	<i>12-months (N = 64)</i>	<i>Pearson's R</i>
<i>(av. increase ↑ or decrease ↓ 6-months-12-months)</i>	<i>Mean (SD)</i>	<i>Mean (SD)</i>	<i>6-months – 12-months</i>
Activity level ↑	4.04 (.92)	4.28 (.98)	.36**
Distress to limitations ↑	4.05 (.86)	4.32 (.96)	.27**
Fear ↓	3.80 (.72)	3.40 (1.3)	.29*
Duration of Orienting ↑	3.90 (.84)	4.17 (1.1)	.41**
Smiling and laughter ↑	3.96 (1.0)	4.71 (.89)	.40**
High pleasure ↑	4.03 (1.1)	6.02 (.67)	.38**
Low pleasure ↓	4.70 (.88)	4.40 (1.1)	.35**
Soothability ↑	4.68 (.86)	5.40 (.76)	-.04
Rate of Recovery from distress (R) ↑	4.32 (.78)	5.10 (.97)	.17
Cuddliness ↑	3.70 (.90)	4.80 (.84)	-.09
Perceptual sensitivity ↓	4.15 (.79)	3.83 (1.6)	.16
Sadness ↓	4.70 (.88)	4.00 (.95)	-.19
Approach ↑	4.61 (.73)	5.80 (.60)	.26*
Vocal reactivity ↓	4.75 (.93)	4.70 (.99)	.46**

*Pearson's correlations ** p<.001 * p<.05*

Table 4.5 shows the correlation between the three main IBQ scales of surgency, negative affect and regulation at 6-months and 12-months. Scores on all three scales correlate between 6-months and 12-months. Surgency and regulation correlate at 6-months and 12-months. Regulation and negative affect correlate negatively at 6-months

Table 4. 5 Unadjusted bivariate Pearson's correlations between IBQ scales at 6-months and 12-months (6-months N=80, 12-months N=48)

	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>
<i>1.Surgency 6-months</i>	-				
<i>2.Negative affect 6-months</i>	.15	-			
<i>3.Regulation 6-months</i>	.30**	-.36**	-		
<i>4.Surgency 12-months</i>	.50**	.07	.05	-	
<i>5.Negative affect 12-months</i>	-.08	.43**	-.24	.25*	-
<i>6.Regulation 12-months</i>	.34**	-.14	.40**	.31*	.01

*Pearson's correlations ** p<.001 * p<.05*

4.2.7 Preliminary analysis

To test our first hypothesis, that measures indexing ES would correlate at 6m, we first looked at unadjusted bivariate correlations between the different sensitivity markers considered in the dissertation at neural (auditory and visual sensitivity), autonomic (heart rate, RSA), temperament and behavioural levels. Table 4.6 shows correlations within but not between levels of analysis. Measures indexing neural sensitivity to auditory and visual stimuli correlated as did measures indexing positive and negative reactivity. Further analyses exploring these correlations and how they develop from 6m to 12m are explained in chapters five (neural sensitivity) and six (behavioural reactivity). The results of this preliminary analysis are discussed at greater depth in Chapter eight.

Table 4.6. *Bivariate correlations between variables indexing 6m Environmental Sensitivity*

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. <i>P3 diff</i>	-								
2. <i>P1 diff</i>	.36**	-							
3. <i>N290 diff</i>	-.37**	-.86**	-						
4. <i>P400 diff</i>	.34**	.61**	-.83**	-					
5. <i>6m neg react</i>	-.05	-.18	.13	.00	-				
6. <i>6m pos react</i>	.16	-.05	-.06	.08	.27*	-			
7. <i>Baseline RSA</i>	.14	.10	-.30*	.25	.20	.10	-		
8. <i>Baseline BPM</i>	-.29*	-.15	.39*	-.34*	-.04	-.06	-.64**	-	
9. <i>Negative temp</i>	-.07	-.11	.18	-.05	.00	-.27	-.17	-.04	-
10. <i>Positive temp</i>	-.01	.13	-.10	.17	.16	-.02	-.19	-.07	.12

** = $p < .001$ * = $p .05$

4.2.8 Developmental Environment – demographic variables

Figure 4.6 shows frequency histograms of the raw variables indexing the developmental environment of the infants in the study. These plots reveal that scores on the measures indexing maternal wellbeing (ACE and GAD-7) are positively skewed and maternal education is negatively skewed with higher scores representing higher levels of education.

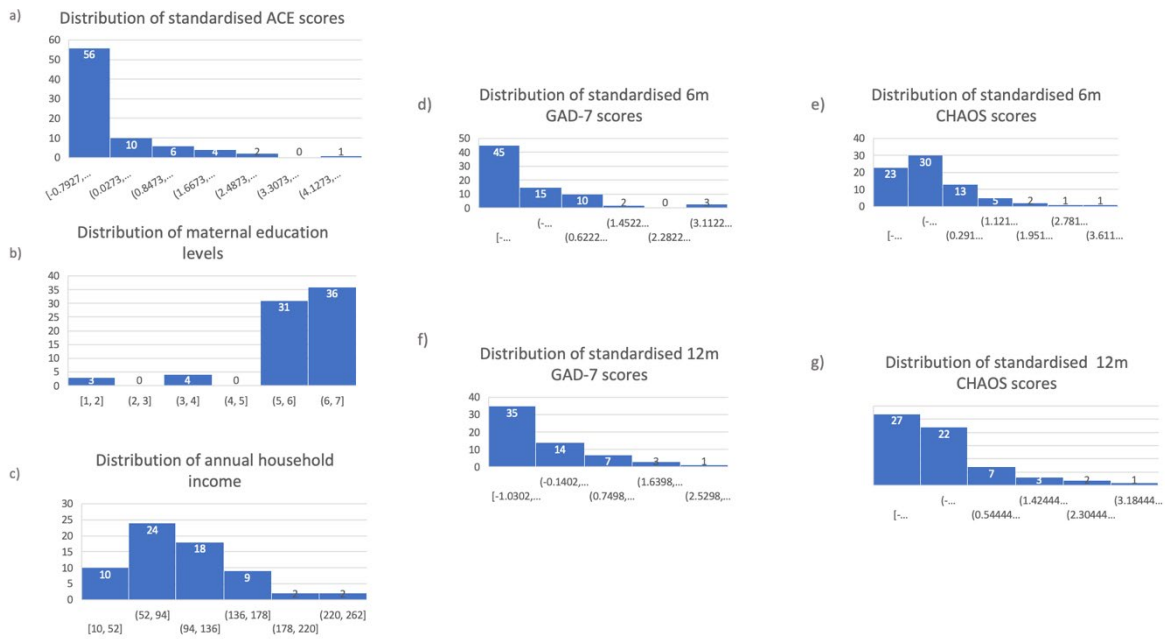


Figure 4. 6. Distribution of demographic variables: ACE scores (a); maternal education (b); household income (c); 6-months GAD-7 scores (d); 6-months CHAOS scores (e); 12-months GAD-7 scores (f); 12-months CHAOS scores (g.)

The scores on the standardised questionnaires (GAD-7, CHAOS and ACE) were all positively skewed so were log transformed adding a constant to account for zeros in the data. For the ACE questionnaire, Cronbach’s α was .65. For CHAOS and GAD-7 at the 6-month and 12-month visits Cronbach’s α ranged from 8.2 to 8.7

Table 4.7 shows Spearman’s bivariate correlations between variables indexing socioeconomic status (maternal education and household income), home environment (CHAOS) and maternal wellbeing (ACE and GAD-7 scores). These variables were chosen to measure the quality of the developmental environment of the infants in the study. Levels of maternal and paternal education correlated positively. Level of ACE to which the mother was exposed before the age of 18 correlated negatively with paternal education and

household income. Scores on GAD-7 and CHAOS were strongly positively correlated from 6-months to 12-months.

Table 4. 7 Descriptive statistics and bivariate correlations between raw scores for demographic variables at 6-months (N =79) and 12-months (N =62)

	M (SD)	1	2	3	4	5	6	7
1. Mat education	6.2 (1.2)	-						
2. Pat education	5.9 (1.3)	.29*	-					
3. Income	96.1 (48.7)	.02	.02	-				
4. ACE	1.3 (1.6)	-.12	-.27*	-.28*	-			
5. 6-months GAD-7	4.0 (3.9)	-.12	-.13	-.05	.15	-		
6. 12-months GAD-7	3.5 (3.4)	-.10	-.18	-.05	.20	.62**	-	
7. 6-months CHAOS	25.4 (7.6)	.11	-.21	-.09	.18	.15	.42**	-
8. 12-months CHAOS	25.2 (8.4)	-.12	-.11	-.13	.16	.22	.41**	.66**

** = $p < .001$ * = $p .05$

Further analyses looking at how the developmental environment moderates the relationship between behavioural reactivity at 6-months and 12 will be explored in Chapter six. Further analyses looking at the moderating effect of the autonomic measure of ES (RSA) of the relationship between the development environment and developmental outcomes will be explored in Chapter seven.

4.2.9 Developmental outcomes

Due to problems related to data collection during the second and third periods of lockdown, necessitated by the coronavirus pandemic, insufficient data was collected at 24m to reliably assess developmental outcomes for the whole sample. Therefore, the decision was made to use data collected at 12-months to assess developmental outcomes.

4.2.9.i Regulation at 12-months IBQ scale: The internal consistency of items included in the Regulation scale was $\alpha = .698$. To explore the slightly low alpha for regulation, we examined ‘scale if item deleted’ and found that removing one item ‘how often during the last week did the baby enjoy listening to a toy in a crib?’ would raise the alpha to .719. The average Regulation for the infants included in the analyses was 4.70 (SD = 0.577; range = 3.60-6.17).

4.2.9.ii Sustained attention at 12-months eye tracking: The dependent variable was the infant’s ability to sustain their attention to the target. The proportion of the trial duration spent looking at the target so that it would continue moving across the screen mean (SD)

[range] was 57.63 (16.09) [18.59 92.25] and was normally distributed: skewness -.123 kurtosis-.554.

4.2.9.iii Duration of orienting at 12-months IBQ subscale: The internal consistency of the subscale - duration of orienting – of the factor of Regulation was sufficient ($\alpha = .72$) if one of the items was removed. The removed item was as follows: ‘how often during the last week did the baby play with one toy or object for 10 minutes or longer?’ All other items relating to this subscale asked for duration of orienting of between 2 to 10 minutes. The average score for duration of orienting was 4.60 (SD = 1.11; range = 1.50-6.17).

4.2.10 IBQ factor analyses

To assess the factor structure of the 6-months IBQ scales of Negative Affect, Surgency and Regulation, a KMO test of sampling adequacy and a Bartlett’s test of sphericity were conducted. The KMO test revealed a score of .71, which is above the recommended value of .6 for sample adequacy (Kaiser, 1974). Bartlett's test showed significant findings $X^2(91) 753.76 p<.001$ indicating that the variables were correlated enough to conduct factor analysis. All items showed mid to high communality. Table 4.8 shows the results of principal component analyses with a direct oblimin rotation which revealed that the IBQ temperament questionnaire at 6-months displayed four factors. The first factor explained 41.7% of the variance and consisted of the items ‘high pleasure’, ‘smiling and laughter’, ‘low pleasure’, ‘soothability’, ‘duration of orienting’, ‘vocal reactivity’ and ‘rate of recovery from distress’. The second factor explained 13.3% of the variance and consisted of the items, ‘fear’ and ‘distress to limitations’. The third factor explained 13.0% of the variance and consisted of the items, ‘sadness’ ‘approach’ and ‘perceptual sensitivity’. The fourth item explained 8.7% of the variance and consisted of the items ‘cuddliness’ and ‘activity level’.

Table 4. 8 Factor loadings based on Principal Components Analysis (PCA) with Direct Oblimin rotation for 14 subscales from the 6-months IBQ (N = 79)

Item	Factor 1	Factor 2	Factor 3	Factor 4	Comm
6 High Pleasure	.93				.84
5 Smiling and Laughter	.90				.79
7 Low Pleasure	.88				.79
8 Soothability	.82				.80

4	Duration of Orienting	.67		.65
14	Vocal Reactivity	.63		.52
9	Distress Recovery Rate	.53		.70
3	Fear		.80	.78
2	Distress to Limitations		.80	.70
12	Sadness		-.94	.88
13	Approach		-.89	.86
11	Perceptual Sensitivity		-.69	.80
10	Cuddliness			.76
1	Activity Level			-.71
				.79

Note: Comm. = Community; Factor loadings < .50 were suppressed

To assess the factor structure of the 12-months IBQ scales of Negative affect, Surgency and Regulation, a KMO test of sampling adequacy and a Bartlett's test of sphericity were conducted. The KMO test revealed a score of .70, which is above the recommended value of .6 for sample adequacy (Kaiser, 1974). Bartlett's test showed significant findings $\chi^2(91) = 283.61, p < .001$ indicating that the variables were correlated enough to conduct factor analysis. Furthermore, all items displayed mid to high communality.

Table 4.9 shows the results of a principal component analysis with a direct oblimin rotation which revealed that the IBQ temperament questionnaire at 12-months displayed three factors. The first factor explained 28.1% of the variance and consisted of the items 'smiling and laughter', 'low pleasure', 'vocal reactivity', 'high pleasure', 'duration of orienting', 'perceptual sensitivity' and 'approach'. The second factor explained 16.4% of the variance and consisted of the items, 'distress to limitations', 'rate of recovery from distress', 'soothability', 'fear' and 'sadness'. The third factor explained 11.2% of the variance and consisted of the items, 'cuddliness' and 'activity level'.

Table 4.9 Factor loadings based on Principal Components Analysis (PCA) with Direct Oblimin rotation for 14 subscales from the 12-months IBQ (N = 64)

<i>Item</i>		<i>Factor 1</i>	<i>Factor 2</i>	<i>Factor 3</i>	<i>Comm</i>
5	Smiling and Laughter	.86			.71
7	Low Pleasure	.75			.60
14	Vocal Reactivity	.74			.57
6	High Pleasure	.66			.44
4	Duration of Orienting	.61			.59
11	Perceptual Sensitivity	.57			.57
13	Approach	.51			.62
2	Distress to Limitations		-.69		.51

9	Distress Recovery Rate	.66	.44
8	Soothability	.65	.52
3	Fear	-.55	.42
12	Sadness	-.54	.46
10	Cuddliness	.87	.81
1	Activity Level	-.60	.56

Note: Comm. = Communality; Factor loadings < .50 were suppressed

In the current study, we did not replicate the three-factor structure of the IBQ found in previous studies (Sanson et al., 1987). We found a four-factor structure at 6-months and although we did find a three-factor structure at 12-months, the factors did not include the same subscales that have been found to form the composite scales of negative affect, positive affect/surgency and regulation. At 6-months, the first two factors, which together accounted for 55% of the variance did reflect a dissociation between subscales which form the composites for positive affect and regulation as factor 1 and the subscales which form the composite for negativity as factor 2. Factor 3, which accounted for 13% of the variance did not represent any meaningful dissociation as items pertaining to positive, negative and regulation scales were all included in the factor at negative values. Factor 4 which accounted for 8.7% of the variance included items relating to activity levels. At 12-months, three factors accounted for 55.7% of the variance. The first factor, which accounted for 28.1%, contained items reflecting sensitivity to the environment (low pleasure and perceptual sensitivity) and surgency (high pleasure, approach, vocal reactivity). The second factor contained items reflecting self-regulation and low negative affect. The third factor contained items reflecting activity levels.

4.3 Chapter summary

This Chapter has provided an overview of the study as a whole including ethical approval, recruitment, participants, a brief overview of all measures indexing i) infant sensitivity, ii) the developmental environment and iii) developmental outcomes and finally details of the overall procedure at data collection sessions. In the second section, results of preliminary analyses of the data and descriptive statistics of the variables are presented. One measure of infant sensitivity – parent-reported temperament, was not included in any of the proceeding studies. Therefore, the results of exploratory factor analyses are presented on the 6-months and 12-months data.

The following chapters comprise separate studies testing the four hypotheses of this thesis. Chapter five looks at the association of visual and auditory sensitivity at the endophenotypic neural level and the association of neural sensitivity with autonomic activity. Chapter six looks at the association between behavioural reactivity to positive and negative stimuli. Together they provide qualified support for hypothesis one that predicted measures of sensitivity at the neural and autonomic level would associate to some extent as well as providing evidence that early in development reactive infants are so to both negative and positive stimuli. Associations between mechanisms and to both positive and negative stimuli did not persist from 6 to 12-months suggesting that for this sample, the reactivity profiles had developed and changed from 6-months to 12-months.

Chapter six also looks at the effect of the developmental environment on the extent to which infants displayed more positive behavioural reactivity or more negative behavioural reactivity. Evidence was found in support of the third hypothesis that the developmental environment would moderate the relationship between sensitivity at 6-months and 12-months. Chapter seven looks at whether environmental sensitivity moderates the effect of a supportive environment on developmental outcomes.

CHAPTER 5. The development of the relationship between auditory and visual neural sensitivity and autonomic arousal from 6-months to 12-months

Abstract

The differential sensitivity hypothesis argues that environmental sensitivity has the bivalent effect of predisposing individuals to both the risk-inducing and development-enhancing influences of early social environments. However, the hypothesis requires that this variation in environmental sensitivity be general across domains. In this study, we focused on neural sensitivity and autonomic arousal to test domain generality. Neural sensitivity can be assessed by correlating measures of perceptual sensitivity, as indexed by event-related potentials (ERP) in electrophysiology. The sensitivity of autonomic arousal can be tested via heart rate changes. Domain generality was tested by comparing associations in perceptual sensitivity across auditory and visual domains, and associations between sensitivity in sensory domains and heart rate. We contrasted ERP components in auditory (P3) and visual (P1, N290 and P4) detection-of-difference tasks for N=68 infants longitudinally at 6 and 12 months of age. Domain generality should produce correlated individual differences in sensitivity across the two modalities, with higher levels of autonomic arousal associating with increased perceptual sensitivity. Having controlled for multiple comparisons, at 6 months of age, the difference in amplitude of the P3 component evoked in response to standard and deviant tones correlated with the difference in amplitude of the P1 N290 and P4 face-sensitive components evoked in response to fearful and neutral faces. However, this correlation was not found at 12 months of age. Similarly, autonomic arousal correlated with neural sensitivity at 6 months but not at 12 months. The results suggest bottom-up neural perceptual sensitivity is domain-general across auditory and visual domains and is related to autonomic arousal at 6 months but not at 12 months of age. We interpret the development of the association of these markers of ES within a neuroconstructivist framework and with respect to the concept of interactive specialisation. By 12 months of age, more experience of visual processing may have led to top-down endogenous attention mechanisms that process visual information in a way that no longer associates with automatic auditory perceptual sensitivity.

Keywords: Environmental Sensitivity; infant neural sensitivity; infant EEG; auditory oddball; emotional faces; infant autonomic arousal,

5.1 Introduction

Individuals vary systematically in their sensitivity or “permeability” to experiential and contextual influences on development and health (Boyce, 2015). Environmental Sensitivity (ES) theorists posit that there is a common factor of sensitivity along which individuals differ in their ability to register and process environmental stimuli (Pluess, 2015). Those who are especially sensitive to environmental effects in the immediate term are unusually susceptible not only to the risk-inducing but also to the development-enhancing influences of early social environments (Belsky et al., 2007; Boyce & Ellis, 2005; Ellis et al., 2011).

But what exactly does it mean, mechanistically, for one individual to be more sensitive than another to both risk-inducing and development-enhancing influences? Within the field of ES, a wide range of traits have been used to index sensitivity that can be categorised into genetic (polygenic risk scores (Nelemans et al., 2021)), physiological (e.g., cortisol reactivity (Obradović et al., 2010), autonomic nervous system activity (Weyn et al., 2022) and behavioural/psychological sensitivity factors (e.g., negative emotionality (Kim & Kochanska, 2012) (For a review see Belsky & Pluess, 2013). Much research is based on reporting cross-over interactions where the effect of a positive (maternal empathy (Pitzer et al., 2011)) or negative (maternal depression (Netsi et al., 2015; Sacchi et al., 2018)) contextual measure on some behavioural outcome (infant sleep (Netsi et al., 2015), infant motor activity (Sacchi et al., 2018), later externalising problems (Pitzer et al., 2011) is moderated by the value of a sensitivity measure. This provides support for the bivalency of sensitivity propounded by ES theorists. However, studies that look specifically at only one index of sensitivity are not able to address whether an individual’s environmental sensitivity varies across different levels of measurement or whether differences in sensitivity in all domains covary (Pluess, 2015; Stamps, 2016). Theoretically all measures of immediate environmental sensitivity should correlate for it to be a domain-general trait. In addition, to our knowledge, no previous research has looked at whether the elements of the environment to which infants are most sensitive changes across brain and perceptual development with the aim of understanding whether the responses which index ES change across development. This study considers two branches, one considering correlations between the sensitivity of different perceptual modalities within the neural domain, the other from perceptual modalities to autonomic arousal and thus between the neural and autonomic domains, all being possible proximal measures of environmental sensitivity.

The hypothesis that environmental sensitivity (ES) has the bivalent effect proposed by differential susceptibility theory requires that sensitivity be general across domains. This paper set out to examine whether individual differences in ES to immediate environmental effects, as previously operationalized in separate studies looking at neural responses to visual and auditory perception, associated within individuals. Furthermore, whether the environmental effects to which infants are most sensitive change over development in terms of how any association between the measures of sensitivity in the different domains developed from 6-months to 12-months.

Theories of brain and perceptual development are relevant to understanding how any associations between the sensitivity of visual and auditory neural domains develop. Interactive Specialization is situated within a broader context of work on “neuroconstructivism” (Elman et al., 1996; Mareschal et al., 2007; Karmiloff-Smith, 2009). It posits that the way environmental stimuli are processed changes repeatedly as a function of development as the infant progressively selects and processes different kinds of input. Furthermore, in early postnatal development, perception of stimuli is thought to be driven exogenously by features of the stimuli, but through development, endogenous top-down processes are thought to increasingly affect which features are perceived (Colombo 2001; Haith 1980; Johnson et al. 1991; Ruff and Rothbart 2001). It has also been suggested that increased expertise in processing input specific to one’s own environment is gained at the expense of a heightened ability to perceive all exogenous input. This occurs through processes such as synaptic pruning (Kerszberg et al., 1992), leading to “perceptual narrowing” (Scott et al., 2007) and the increasing specialisation of functional cortical areas with development (Neville et al., 1992; Durston et al., 2006). Theories on the development of face processing in particular have looked at whether the degree of domain specificity in the cortical face-processing system changes with development. One account argues that the cortical tissue activated by faces is initially activated by a broad range of visual stimuli, but over time it develops from a broadly tuned, non-specific, complex figure recognition system into one tuned to upright human faces of the type most encountered in their environment (Nelson 1993, 2001), which decreases the ability to discriminate complex figures with which there is less experience. Thus, early in development, an initial broad multisensory perceptual tuning is thought to be the result of a relative lack of cross-modal interactions, meaning that young infants do not integrate even co-occurring, low-level features of sensory information into a single percept, as they do later in development (Boothe, 2010), and instead process input from auditory and visual modalities separately

and in parallel (Lewkowicz & Ghazanfar, 2009). A domain-general level of sensitivity would suggest that individual differences in sensitivity in the visual domain will associate with individual differences in sensitivity in the auditory domain.

Event-related potentials (ERPs) evoked in response to external stimuli have been used to chart the development of pre-attentive processes of perception (Kushnerenko et al., 2002). In the auditory domain, neural markers of automatic auditory perception can be induced using oddball paradigms where frequently presented ‘standard’ tones are interspersed with less frequent ‘deviant’ tones. Recording deviance-elicited brain responses using EEG is a feasible way to assess automatic auditory discrimination and regularity detection abilities in even very young infants (Kushnerenko et al., 2013). The mismatch response (MMR) is a neurophysiological indicator of automatic, pre-attentive change detection between consecutive sounds and heightened sensitivity to deviant stimulus (Näätänen & Alho, 1995; Wetzels & Schröger, 2014). In infants younger than 12 months of age the MMR is often found as a positive deflection between 150 and 300ms post change onset (Morr et al., 2002; Garcia-Sierra et al., 2011; Kushnerenko et al., 2013). One way to interpret individual differences in ERP amplitude is in terms of differences in involuntary attentional orienting. This is because a (positive) deflection at this latency means the MMR can merge/overlap with the P3a, which is generally understood to be the central electrophysiological marker of involuntary attentional orienting to a novel or unexpected sound (Friedman et al., 2001; Squires et al., 1975). It indexes involuntary (bottom-up, saliency driven) attention mechanisms (Escera et al., 2000; Friedman et al., 2001). This automatic orienting and attentional capture could be interpreted as less automatic inhibition of response (Kushnerenko, 2002) and therefore greater automatic neural sensitivity to environmental effects (Wass et al., 2018). Furthermore, a larger positive component to the deviant stimulus has been found to associate with markers of ES in infants such as negative reactivity to sensory stimuli (Marshall & Fox 2009)

In the visual domain, the sensitivity of the sensory system is linked to the processing of emotional information (Grossmann, 2010). A common indicator of involuntary neural sensitivity in infants is increased neural responsiveness to emotional over neutral faces (James et al., 2018). From 6-months, ERP components associated with infant perceptual sensitivity to faces (occipitotemporal P1, N290 and P4 components) are reliably larger for fearful facial expressions than neutral faces as well as other negative or positive facial expressions. In 7-month-old infants the P4 was larger in response to fearful than neutral or happy faces (Leppänen et al., 2007). 7-month-old infants had a larger P4 for

fearful than angry faces (Kobiella et al., 2007). 7-month-old infants rated higher in perceptual sensitivity had larger N290 responses to fearful than to happy faces (Jessen & Grossmann, 2015). The largest differences have been found over occipitotemporal regions implicated in face perception but not frontocentral regions implicated in attention (Safar & Moulson, 2020). This has been interpreted as increased early perceptual sensitivity in detecting low-level facial signs of threat such as wide-open eyes and increased size of the white sclera around the dark pupil in fearful faces (Johnson, 2005; Whalen et al., 2004) presaging the attentional bias for fearful faces (James et al., 2018).

In the autonomic domain, one autonomic correlate of sensitivity in infants, is higher heart rate (HR), which has been found to associate with hypervigilance (Mammen et al., 2017). Associations between autonomic activity and sensory perception are largely limited to behavioural markers such that increased autonomic arousal associates with decreased voluntary attention control and increased responsivity to salient targets (Alexander et al., 2007; Arnsten, 2009; Liston et al., 2009). Only recently have researchers looked at how neural sensitivity, measured in terms of involuntary auditory attention using an auditory oddball task, varies with levels of autonomic arousal (Wass et al., 2019). They found that 5-7-year-old children with higher autonomic arousal showed larger P150/P3a amplitudes in response to small acoustic contrasts (500Hz-750Hz). This supported the notion that higher autonomic arousal associated with less inhibition of response to exogenous stimuli, which meant that even small acoustic contrasts could potentially elicit a P3a-like automatic orienting response.

The current study collected ERP data from infants presented with an auditory-oddball paradigm and a visual emotional faces paradigm. We examined whether individual differences in bottom-up, neural sensitivity, indexed by the difference in the amplitude of components evoked in response to auditory and visual stimuli were correlated over temporal and occipital regions respectively implying domain general sensitivity, or uncorrelated, implying that neural sensitivity is domain specific. We also examined how this domain specificity or generality changed between 6m and 12m. In addition, we examined the relationship between neural sensitivity and autonomic arousal. Based on previous findings, we predicted that to support the theory that ES is domain general, increased autonomic arousal should associate with heightened neural sensitivity to differences in auditory stimuli as well as differences in visual stimuli.

5.2 Method

5.2.1 Participants:

Infant-parent dyads attended the BabyLab at the University of East London on two occasions – first when the infants were 6m old and a second visit when the infant was 12m old. The participating parent-infant dyads were recruited from local children’s centres, baby sensory classes and new-parent support groups. Parents gave informed consent prior to the commencement of data collection.

A priori power analyses (conducted using G*Power 3.1) (Faul et al., 2007) revealed that to achieve power of .80 (80 percent chance of correctly rejecting the null hypothesis) at the $p < .05$ level, to detect bivariate correlations with an effect size of around .3, we would need a minimum sample size of $N=84$. To allow for adjusted p values (at the $p < .01$ level), due to multiple comparisons, we would need a sample size of 127. We initially aimed for a sample of at least $N=100$ infants to provide enough statistical power to detect significant results.

5.2.1.i Participant exclusions

At phase-one, 82 typically developing infants, (male 42 female 40), with a mean (*SD*) age of 27.5 (2.4) weeks on the day of testing, attended.

EEG – 6m: Data from a number of participants at phase one were unavailable due either to insufficiently good quality recording from one of the measures (designated so after visual inspection of the raw data and referral to video and session notes on the affective state of the infant during the recording) and were dropped before being processed ($N=6$), or fewer than 70 percent of the maximum number of auditory oddball trials in each condition trials on which to base the analysis (Monroy et al., 2021) ($N=8$) or fewer than 50 percent of the maximum number of emotional faces trials ($N=16$) (Leppänen et al., 2007). In total EEG data were available for $N=68$ and $N=60$ participants for the auditory oddball and emotional faces paradigms, respectively.

ECG – 6m: Insufficiently good ECG data (designated so after visual inspection of the raw data when the analysis software had identified almost the entire recording as noisy based on the default noise detection level of medium) led to a loss of data from $N=8$ participants.

ECG data were available for N=74 participants; both ECG and EEG data were available from N = 60 and N=55 for the auditory oddball/emotional faces tasks respectively. The average age (*SD*) of participants who contributed both usable ECG and EEG faces data was 27.08 (2.23) weeks on the day of testing.

At phase-two, 68 of the initial cohort of 82 babies returned (male 36 female 32) with a mean (*SD*) age of 53.03 (3.04) weeks on the day of testing. Insufficiently good quality EEG data led to the loss of data from N=12 participants (see above). Insufficiently good ECG data (see above) led to a loss of data from N=5 participants. After pre-processing, participants were excluded due to not reaching the inclusion threshold for minimum numbers of trials (fewer than 70 percent of the maximum number of trials in each condition for auditory oddball and fewer than 50 percent of the maximum number of trials in each condition for emotional faces) for the EEG auditory oddball data N=5 and for the faces data: N = 9. In total, EEG auditory-oddball data were available for N=51 participants and EEG faces data were available for N=47 participants; ECG data were available for N = 63 participants; both ECG and EEG data were available from N = 46 for the emotional faces data and N = 49 for the auditory oddball data. The average (*SD*) of participants who contributed both usable ECG and EEG data on the second visit was 53.8 (2.99) weeks on the day of testing.

5.2.2 Equipment

EEG was recorded using a high-density 128-channel HydroCel Geodesic Sensor Net (HGSN) produced by EGI (EGI, Eugene, OR). The EEG signal was referenced to the vertex, recorded at a 500 Hz sampling rate with band-pass filters set from 0.1–100 Hz using an Infinite Impulse Response filter. Prior to recording, the impedance of each electrode was manually checked to ensure that they were below 100 k Ω . ECG was recorded using a BioPac (Santa Barbara, CA) system recording at 1000Hz. ECG was recorded using three disposable Ag–Cl electrodes, placed in a modified lead II position. Stimuli were presented using Matlab. A camera placed just above the stimuli-presentation screen video-recorded the behaviour of the infants for coding of looking behaviour during the visual paradigm.

5.2.3 Procedure

Infants were seated on parents' laps and presented with four, approx. 60-second blocks each of a visual and an auditory paradigm presented in an interspersed manner. In

addition, to attract attention and calm infants, and thereafter to maintain attention, a 60-second excerpt showing nursery rhymes sung by the children's TV entertainer Mr Tumble was shown prior to each block of auditory stimuli - making 12 blocks in total. If participants were engaged with stimuli and calm, testers would proceed straight to the next block without pausing. In total, data-collection, including preparation, recording, breaks and EEG cap removal, lasted approximately 40 minutes per participant.

Auditory oddball paradigm. This consisted of four blocks of 100 trials (400 trials in total). Each block consisted of: 70 'standard' 500Hz tones; 15 'deviant' 750Hz tones; 15 'noise' (broadband white-noise) segments. The intensity of the tone and white-noise sounds was 70 dB sound-pressure level (SPL). The harmonic tones of 500 and 750 Hz fundamental frequency were constructed from the three lowest partials, with the second and third partials having a lower intensity than the first one by 3 and 6 dB, respectively. The harmonic tones were used instead of sinusoids for two reasons. Firstly, because it has been shown previously that complex tones result in larger N250 amplitudes in children than sinusoids (Čeponienė et al., 2001). Secondly, because we aimed to use the same paradigm that was used in a number of longitudinal and cross-sectional studies in infants and children in order to increase our understanding of the previously observed effects (Kushnerenko et al., 2007).

The duration of all sounds was 100 ms, including 5-ms rise and 5-ms fall times. The interstimulus (offset-to-onset) interval was 700 ms. The order in which the trials were presented was pseudo-randomised in order to ensure that two deviant and noise trials were always separated by at least two standard trials.

Emotional face paradigm. This paradigm consisted of the neutral and fearful expressions of 12 young (under 30-years) women's faces taken from the Nim Stim faces database (Tottenham et al., 2009). The faces were pseudo-randomised so that the same face did not appear more than twice consecutively. Both facial expressions –neutral and fearful - appeared 23 times (+/- 2) each per block. There were four blocks, making 92 trials of each facial expression in total. The reason that 12 different faces were chosen for this study was to provide a variety of ethnicities that would reflect the demographic spread of participating families. A fixation appeared on the screen for 1000ms followed by a face for 500ms (see Fig.1. for example fixations and faces). This meant that the ISI between faces was 1000ms. Evidence suggests that the optimal ISI for infant engagement and sustained attention during stimulus presentation is 600– 1,000 ms, which increases the presentation complexity and provides sufficient time for information processing (Xie & Richards, 2016).

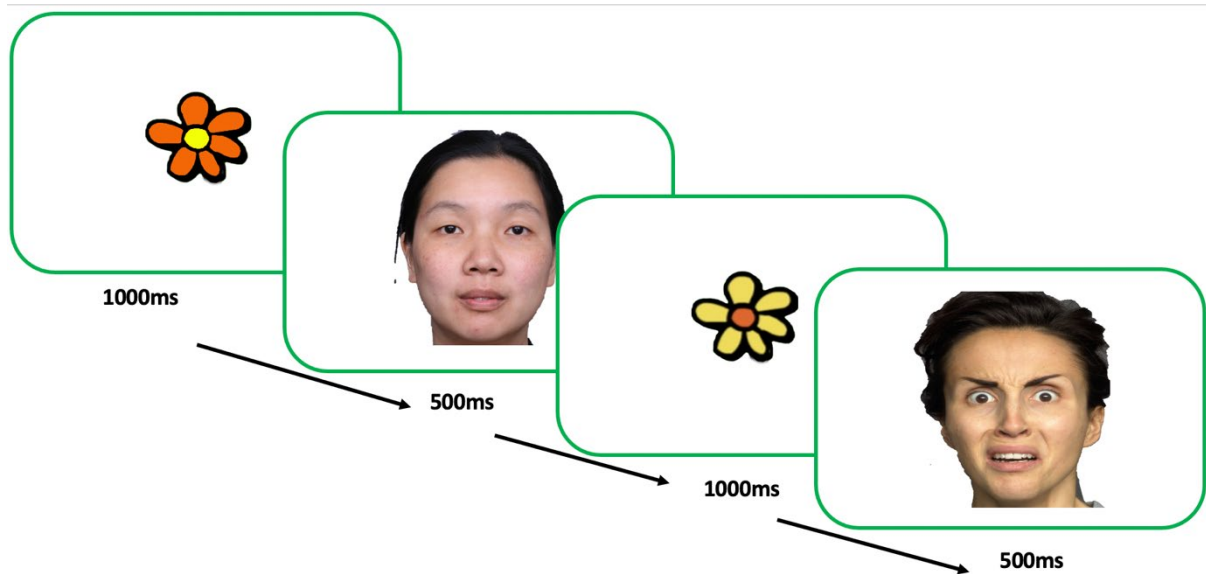


Figure 5. 1presentation sequence of stimuli for emotional face processing paradigm

5.2.4 Data analysis

EEG data was processed using NetStation software (version 5.4.2). The vertex-referenced EEG was algebraically recomputed to an average reference. The signal was low-pass filtered off-line at 30 Hz using a Finite Impulse Response filter and segmented into epochs starting 100 ms before and ending 800 ms after the stimulus onset. Artifact detection settings identified bad channels as those in which the amplitude exceeded $200\mu\text{V}$ using a moving average of 80ms. With infant nets there are no horizontal or lower eye channels. Blink detection is performed on a moving average of 80ms from the upper eye-channel minus its inverse. The threshold for exclusion was $140\mu\text{V}$. Channels were marked bad for the entire recording if bad for greater than 30 percent of segments. Trials were marked bad if they contained more than 30 bad channels (see supplementary materials 2. for additional artifact detection specifications). Activity in bad channels was replaced with the average activity of surrounding good channels using spherical spline interpolation; For higher channel counts such as 128 used here, this approximation increases in validity compared to systems using fewer channels. The average number of channels interpolated was 18.97 (15.2%) at 6m and 11.78 (9.5%) at 12m.

EEG - Auditory oddball task

Exclusions. At 6m, the mean (range) [SD] number of trials included was 224 (210–270) [19] for standard; 47 (42–60) [4] for deviant; 48 (42–60) [4] for noise¹; At 12m the mean (range) (SD) number of trials included was 254 (196–280) [19] for standard; 55 (42–60) [4] for deviant; 55 (41–60) [4] for noise. This number of accepted trials has proven to be sufficient for this type of paradigm (Kushnerenko et al., 2013a; Guiraud et al., 2011; DehaeneLambertz and Dehaene, 1994; Friederici et al., 2007; Kushnerenko et al., 2013b, 2008).

Extracting average amplitude and latency. The valid ERPs obtained for each stimulus type were first averaged to create a per-participant mean waveform. The average of fronto-central channels was used (24, 20, 13, 19, 12, 11, 6, 5, 4, 124, 118, 112 (see fig. 2. c)) as the largest MMR/P3 was expected to occur over this area (Gumenyuk et al., 2005, 2004) and because it corresponded to those used to analyse data collected using the same paradigm previously (Kushnerenko et al., 2007, 2002b; Wass et al., 2019). Epochs were baseline-corrected to the average amplitude in the 100ms pre-stimulus period. The grand average (GA) waveform showed a clear difference between the amplitude of the P3 component in response to standard and deviant tones (see fig. 2. a and b). Therefore, the mean amplitude of the ERP to standard tones between 200 and 400 ms post stimulus onset was subtracted from the mean amplitude of the ERP to deviant tones in the same window to create a difference score between standard and deviant tones. Analysing the difference wave within this time-window was also in line with longitudinal and cross-sectional research using the same paradigm (Kushnerenko et al., 2007, 2002; Wass et al., 2019). As the ERPs represent the overlapping activity of several components which can commence at the same time or follow each other very quickly in infants both 'positive mismatch' and 'negative mismatch' components can be observed at about the same latencies. Therefore, the positive or negative orientation of the difference wave can reflect different processes in individual infants. Average amplitude was chosen as the most objective way to compare values between the standard and deviant conditions (Luck, 2014). This is because the latency of the peak is variable and sometimes it is not possible to identify the peak at all in young infants.

¹Running the analysis using an equal number of pseudo-randomly selected standard to deviant trials produced a waveform which did not differ from that in which all standard trials were used. All standard trials were used in the analyses here in order to minimise any decrease in the signal-to-noise ratio (SNR) of the difference wave as a result of fewer trials in the standard condition.

EEG – Emotional faces task

Exclusions. The video-recording of the infant during the emotional faces blocks was coded in one-second bins whether they were looking (1) or not (0). Using a Matlab script, trials were excluded in which the infant was not looking at the screen. At 6m, the mean (range) [SD] number of trials included was 67 (46–91) [10] for neutral faces; 68 (48–91) [9] for fearful faces. For the 12m data, Matlab events recorded when the infant was attending to the screen during the emotional faces paradigm. Trials were excluded in which the infant was not attending to the screen. At 12m the mean (range) [SD] number of trials included was 47 (39–59) [5] for neutral faces; 46 (40–58) [5] for fearful faces.

Extracting average amplitude and latency. The Grand Average (GA) waveform showed clear P1, N290 and P4 components in response to both face conditions (see Fig. 3. a and b). Therefore, the mean amplitude of the response to neutral faces in windows corresponding to the components P1 and P4 (between 50 and 150 ms and 350 and 450ms post stimulus onset) was subtracted from the mean amplitude of the response to fearful faces in the same windows. As the N290 is a negative-going component the mean amplitude of the response to fearful faces was subtracted from the mean amplitude response to neutral faces in the window 250-350ms post stimulus onset to create a difference score reflecting the absolute size of the difference in amplitude response evoked by the two conditions for this negative component. The average of occipital channels was used (64, 58, 51, 52, 59, 65, 69, 53, 60, 66, 70, 61, 67, 71, 62, 72, 75, 76, 77, 78, 83, 84, 85, 86, 89, 90, 91, 92, 95, 96, 97, 98 (see Fig. 4. c)) as the largest infant facial perception components (P1, N290 and P4) were expected to occur over this area for a 128- electrode EEG cap (Haan et al., 2002; Halit et al., 2003; Vogel et al., 2012; Leppanen et al., 2007)

ECG

Raw ECG data were analysed using Kubios software (Tarvainen et al., 2014). The R-wave time instants are automatically detected by applying the built-in QRS detection algorithm based on the Pan–Tompkins algorithm (Pan and Tompkins, 1985). The software automatically identified noise segments (using default setting of medium) based on the raw ECG data and from the interbeat interval data (RR or pulse-to-pulse intervals). Automatic artifact detection and rejection criteria were used to identify artifactual beats from the time series data consisting of differences between successive RR intervals and corrected in

Kubios. The method has been validated (Lipponen & Tarvainen, 2019). Information on the algorithms used to process the raw ECG data in Kubios is included in Appendix C. Heart rate was averaged across the duration of the recording while infants were presented with stimuli in order to replicate analyses using the same paradigm with 5-7-yr-old children (Wass et al., 2019).

5.2.5 Statistical Analysis

After correcting for multiple comparisons using the Benjamini-Hochberg correction to control the false discovery rate, Bayesian statistics were used throughout. Bayesian statistics allow accepting and rejecting the null hypothesis to be put on an equal footing by providing a direct measure of the strength of evidence not only for but also against the study hypothesis, unlike frequentist statistical approaches, which do not determine whether non-significant results support a null hypothesis over a theory, or whether the data are just insensitive (Andraszewicz et al., 2015). Analyses were carried out using JASP software (Love et al., 2019). Bayesian Factor (BF) 10 gives the likelihood of the data under the alternative hypothesis divided by the likelihood of the data under the null so that BF10 values greater than 1 signal more confidence in rejecting the null hypothesis and values less than 1 signal more evidence in favour of the null. The BF01 is simply $1/\text{BF10}$, that is, the likelihood of the data under the null compared to the alternative. The BFs above 1 indicate correlations for which the evidence from the current study is more likely under the hypothesis that there is a relationship between those variables in the population than not. A BF greater than 3 indicates “moderate” evidence for the study hypothesis that the two variables are correlated in the population. A BF greater than 10 indicates “strong” evidence for the study hypothesis that the two variables are correlated in the population. Prior and posterior information about the correlation summarizes how our knowledge about the unknown population correlation, in which all possible values from -1 to 1 were considered equally likely (prior), has changed as a result of information gathered in our study to put more weight on positive or negative values (posterior) (Nuzzo, 2017).

5.3 Results

In Analysis 1 we examine the relationship between auditory and visual neural sensitivity at 6m and 12m. In Analysis 2 we examine the relationship between autonomic states and neural sensitivity at 6m and 12m.

5.3.1 Preliminary analyses – descriptive Auditory task

Fig. 5.2. shows the grand average ERPs at 6 months in response to standard and deviant tones and white noise (Fig. 2a); the deviant-standard difference waveform (Fig. 2b); and the electrode locations used to calculate all auditory ERPs (Fig. 2c). ERPs to standard tones consist of the P150 followed by N250, and then the P300. ERPs to deviant tones and white noise represent a typical waveform consisting of a large and prolonged positive peak (merged P150 and early phase of P3a) (Kushnerenko et al., 2002). This resulted in the largest difference in amplitude of response to the frequently-presented standard tones and the less-frequent deviant tones occurring at around 300ms post stimulus onset. Topoplots show the development of the voltage distribution in seven 100ms bins from 100ms before stimulus onset to 500ms after stimulus onset showing an average of activity 50 ms around the peak (Fig 2d and 2e)

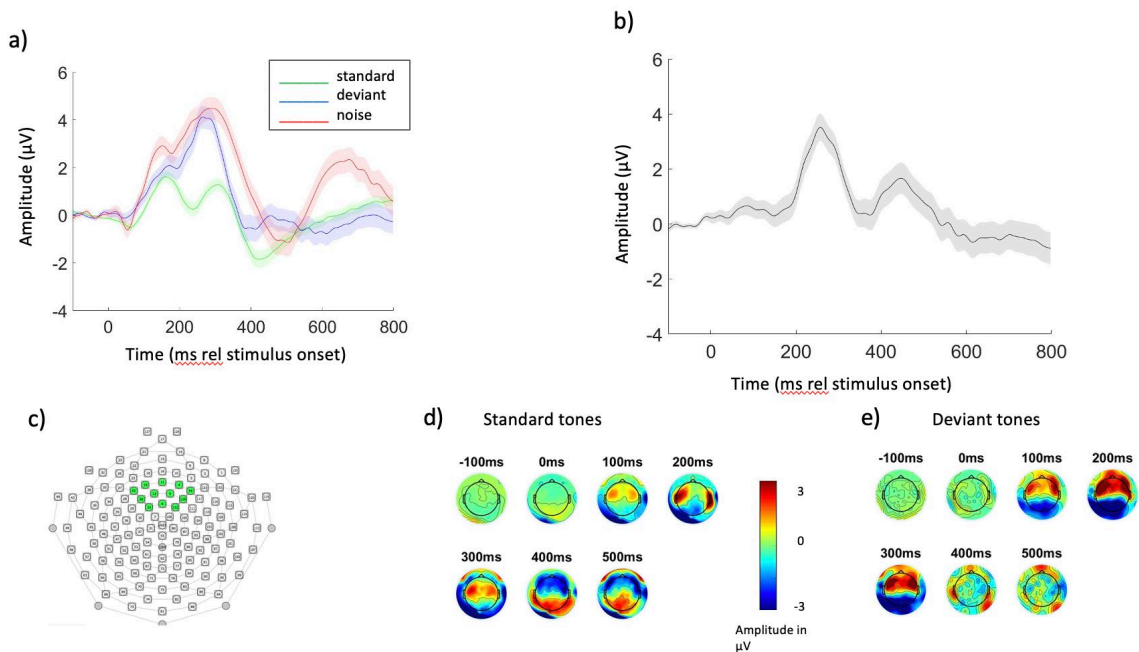


Figure 5. 2 a) Grand average ERPs at 6-months to auditory oddball task. Shaded areas represent the error bars, calculated as the Standard Error of the Mean b) Deviant-Standard difference wave (grand average). Shaded areas represent the error bars, calculated as the Standard Error of the Mean. c) Electrode locations used to calculate all ERPs. The locations used are marked in green. d) and e) Topoplots showing response to standard d) and deviant e) tones at 100ms intervals starting at 100ms pre-stimulus onset and ending 500ms post stimulus onset. Each topoplot shows an average of activity 50 ms around the given value (i.e. -100ms shows the average from -150ms to -50ms).

Fig. 5.3. shows the same information from the 12-months visit: grand average ERPs following the standard, deviant and noise tones at 12-months (Fig. 3a)); and the deviant-standard difference waveform (Fig. 3b)). ERPs to standard tones consist of the merged P150 and early phase of the P3 (or a P3 with a shorter latency), whereas ERPs to deviant tones represent a less merged double peak for the P150 and P3 in the same time window. This resulted in a deviant – standard difference wave peaking at a lower amplitude than at 6-months at around 300ms post stimulus onset.

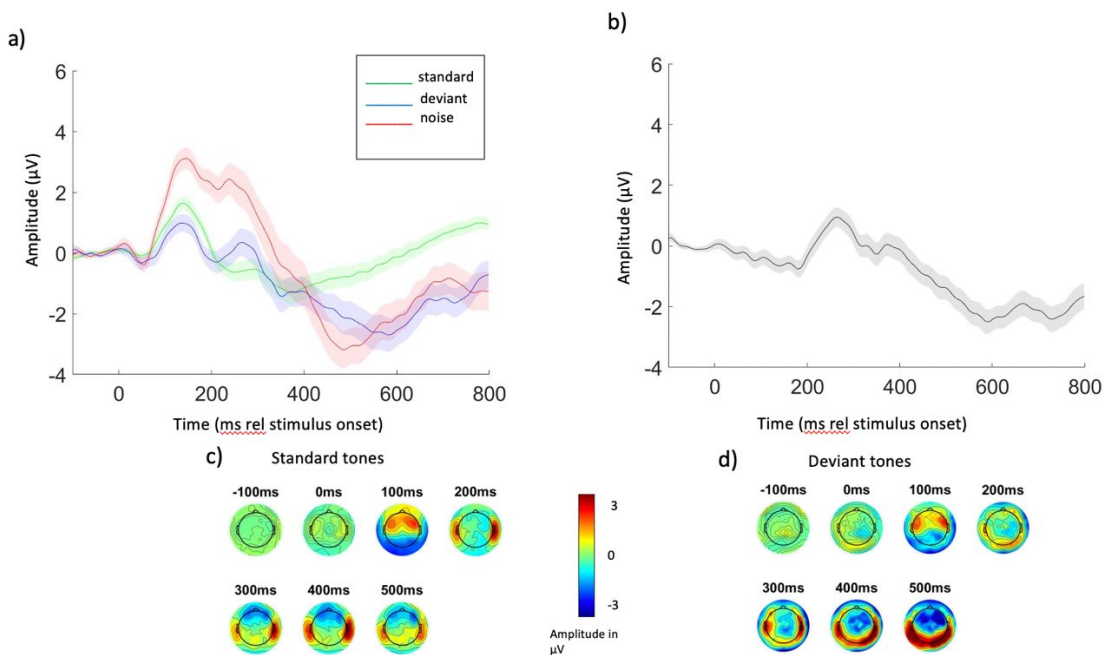


Figure 5. 3 a) Grand average ERPs at 12-months to auditory oddball task b) Deviant - Standard difference wave (grand average). Shaded areas represent the error bars, calculated as the Standard Error of the Mean c) and d) Topomaps showing response to standard c) and deviant d) tones at 100ms intervals starting at 100ms pre-stimulus onset and ending 500ms post stimulus onset. Each topoplot shows an average of activity 50 ms around the given value (i.e. -100ms shows the average from -150ms to -50ms).

Visual task

Figure 5.4. Shows the grand average ERPs in response to fearful faces and neutral faces at 6-months and 12-months. The grand average waveforms clearly show P1, N290 and P4 components in response to faces at both ages. Topomaps show the development of the voltage distribution in seven 100ms bins from 100ms before stimulus onset to 500ms after stimulus onset showing an average of activity 50 ms +/- around the given value at both 6-months and 12-months.

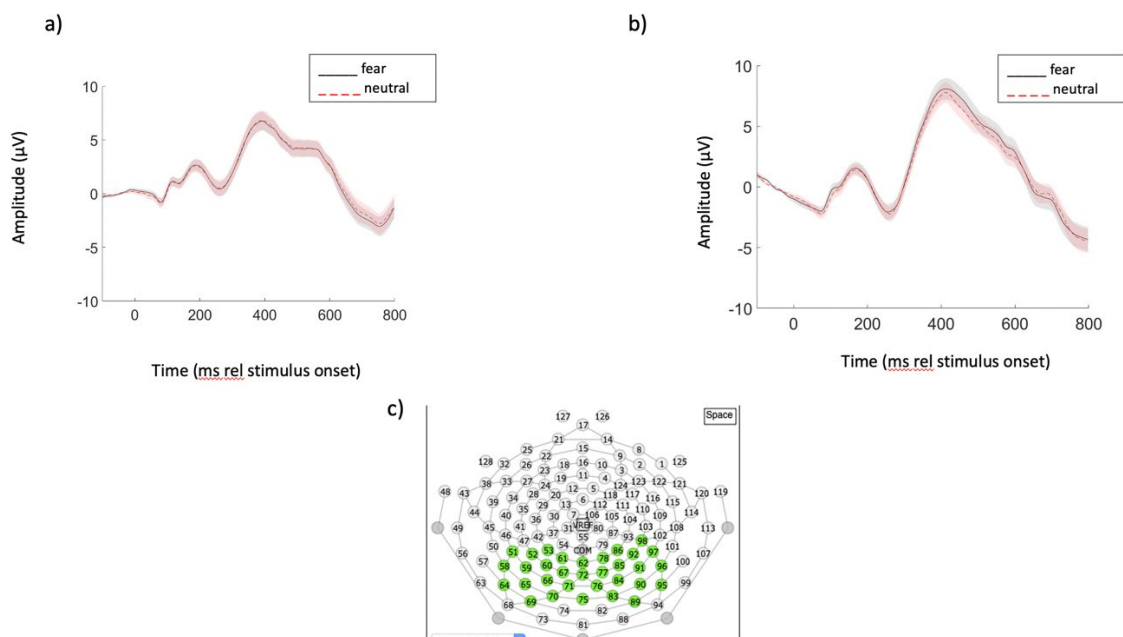


Figure 5. 4 a) grand average ERPS to emotional faces at 6-months. and b) 12-months. Shaded areas represent the error bars, calculated as the Standard Error of the Mean c) Electrode locations used to calculate all ERPs. The locations used are marked in green.

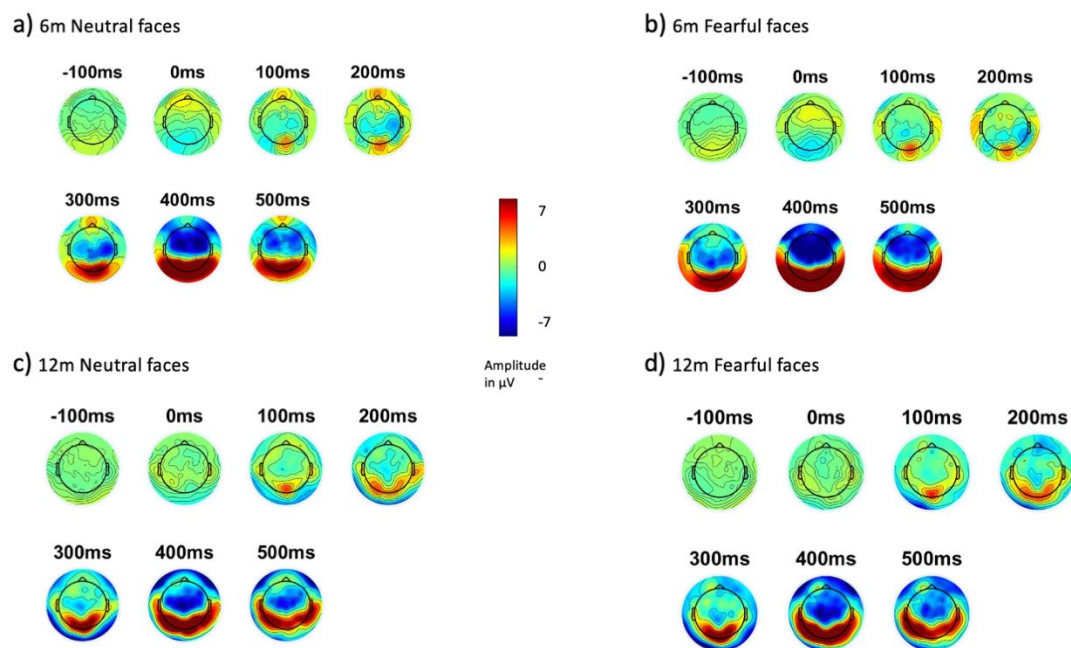


Figure 5. 5 a) and b) topomaps showing 6-months response to neutral a) and fearful b) faces at 100ms intervals starting at 100ms before stimulus onset and ending 500ms post stimulus onset. c and d) topomaps showing 12-months response to neutral c) and fearful d) faces at 100ms intervals starting at 100ms before stimulus onset and ending 500ms post stimulus onset. Each topoplots shows an average of activity 50 ms around the given value (i.e. -100ms shows the average from -150ms to -50ms). Topomaps were produced on data that was subject to channel interpolation outside of the main preprocessing

5.3.2 Analysis 1 – the development of associations between automatic neural sensitivity to auditory and visual stimuli

In Analysis 1 we examine how the relationship between neural sensitivity to auditory and visual stimuli develops between 6-months and 12-months of age.

6-month data

First, we examined the associations between our auditory (the difference in amplitude of the P3 to standard and deviant tones) and visual (the difference in amplitude of the P1, N290 and P4 to neutral and fearful faces) neural sensitivity measures at 6-months. Scatterplots illustrate the strength and direction of the correlation between each set of two variables (Fig. 5.6. a, c, f); The BFs above 1 indicate correlations for which the evidence from the current study is more likely under the hypothesis that there is a relationship between those variables in the population than not. That there is a positive relationship between the

P3 auditory difference component and the P1 visual difference component in the population is nine times more likely from our evidence than not. That there is a negative relationship between the P3 auditory difference and the N290 visual difference component is 12 times more likely than not. That there is a positive relationship between the P3 auditory difference and the P4 visual difference component is five times more likely than not. Plots showing the prior and posterior distributions of the true population correlation show how evidence from the current study has updated the prior distribution (Fig. 5.6. b, d, f).

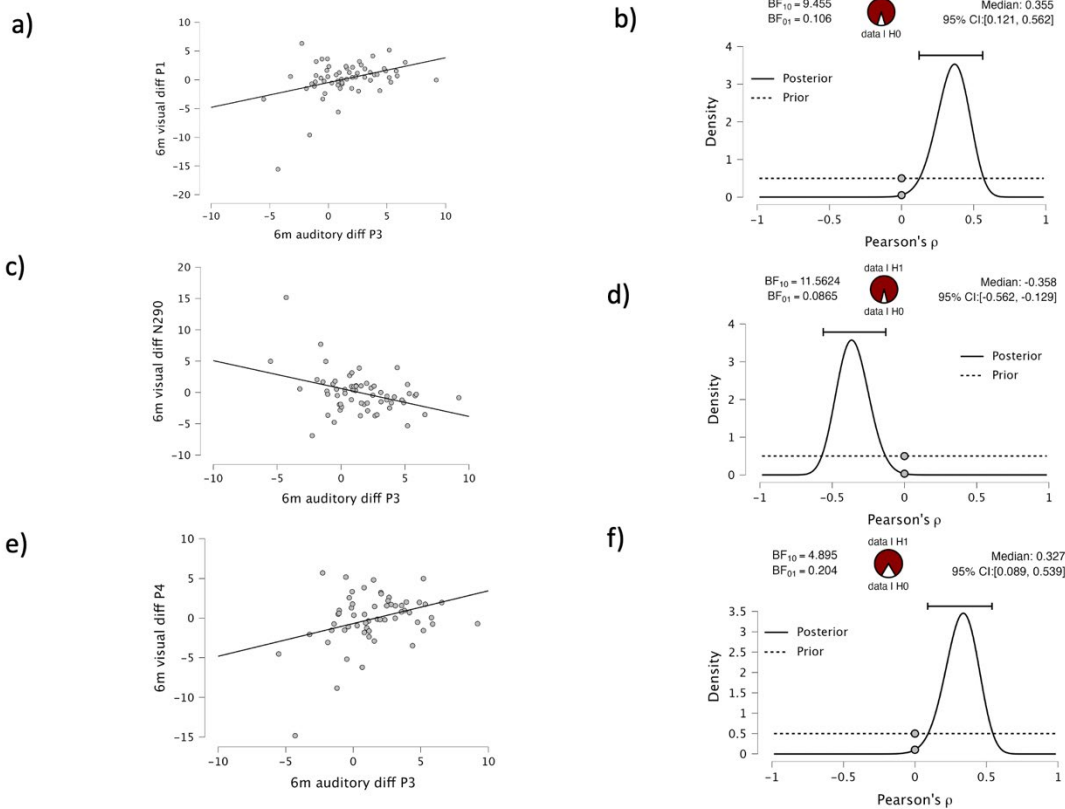


Figure 5. 6 Correlations between measures of visual and auditory sensitivity at 6-months: Scatterplots showing strength and direction of the Bayesian Pearson correlation between the two variables analysed (Fig. 6.a, c, e); Plots showing the prior and posterior distributions of the true population correlation (Fig. 6. b, d, f). The BF is also presented graphically with the unit circle in the output. The shaded area corresponds to the evidence in favour of the alternative hypothesis (indicated in the graphic in Fig. 6 b) by “Data | H1”, and the unshaded area corresponds to evidence in favour of the null “Data \ H0”). The ratio of the shaded area to the unshaded area can be seen to be about 9:1 (6b), 12:1 (6d) 5:1 (6f), which is the value of BF10).

Table 5.1. shows the results of Bayesian Pearson correlations and Bayes Factor (BF) analyses. The Bayes Factor (BF10) for the relationship between the difference in the auditory P3 between standard and deviant tones and the visual P1 between neutral and fearful faces at 6-months is 9. The BF for the negative relationship between the difference in the auditory P3

between standard and deviant tones and the visual N290 between neutral and fearful faces at 6-months is 12. The BF for the relationship between the difference in the auditory P3 between standard and deviant tones and the visual P4 between neutral and fearful faces at 6-months is 5. All results indicate there is moderate-strong evidence for rejecting the null hypothesis at 6-months.

*Table 5. 1 Bayesian Pearson Correlations for neural auditory and visual sensitivity measures at 6-months. Some of the Bayes Factors are exceptionally high: the BF for the association between visual diff P1 and visual diff P4 is 6.036 *106. This example shows how a Bayesian analysis allows researchers to report a useful estimate of the exceptionally high strength of evidence (6 million to 1 in favour of the alternative hypothesis) that would not be possible with a p value*

Bayesian Pearson Correlations				
Variable	1. 6-months auditory diff_P3	2. 6-months visual diff P1	3. 6-months visual diff N290	4. 6-months visual diff P4
1. 6-months auditory diff P3	n	—		
	Pearson's r	—		
	BF ₁₀	—		
2.6-months visual diff P1	n	59	—	
	Pearson's r	0.363	—	
	BF ₁₀	9.455	—	
3. 6-months visual diff N290	n	61	60	—
	Pearson's r	-0.373 *	-0.917 ***	—
	BF ₁₀	11.562	4.017e+21	—
4. 6-months visual diff P4	n	59	60	60
	Pearson's r	0.341	0.680 ***	-0.869 ***
	BF ₁₀	4.895	6.036e+6	2.254e+16

* BF₁₀ > 10, ** BF₁₀ > 30, *** BF₁₀ > 100

12-month data

Next, we conducted identical analyses on the 12-month data. Scatterplots illustrate the lack of a correlation between the two variables (Fig. 5.7. a, c, e); The BF01 above 1 indicates correlations for which the evidence from the current study is more likely under the null hypothesis that there is no relationship between those variables in the population. Plots showing the prior and posterior distributions of the true population correlation show how evidence from the current study has updated the prior distribution (Fig. 5.7. b, d, f).

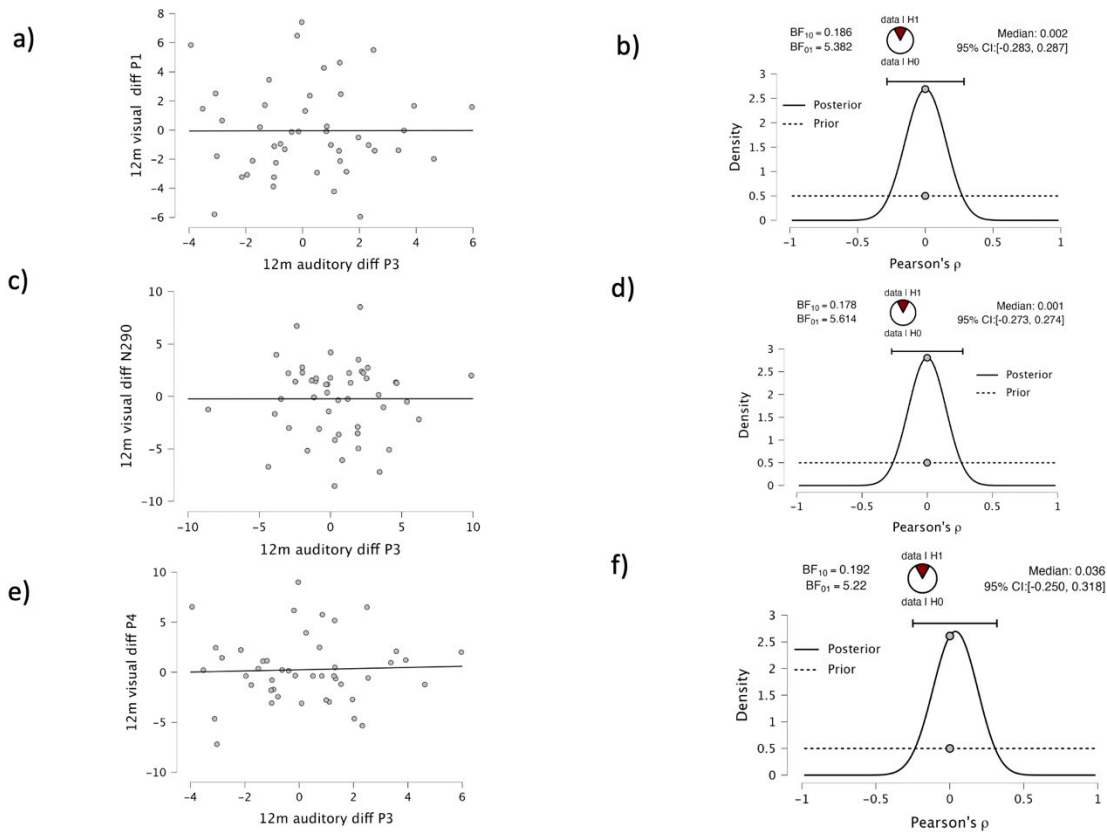


Figure 5. 7 Correlations between measures of visual and auditory sensitivity at 12-months: Bayesian correlation pairwise plots showing strength and direction of the Bayesian Pearson correlation between the two variables analysed (Figs. 7.a, c, e); Plots showing the prior and posterior distributions of the true population correlation (Figs. 7. b, d, f).

Table 5.2. shows the results of the Bayesian Pearson correlations and Bayes Factor (BF) analyses for the 12-month data. The BF10 (the likelihood of the data under the alternative compared to the null) for the relationship between the difference in the P3 component for standard and deviant tones and the difference in the P1 component for neutral and fearful faces at 12-months is 0.2. The BF10 for the relationship between the difference in the P3 component for standard and deviant tones and the difference in the N290 component for neutral and fearful faces is 0.2. The BF10 for the relationship between the difference in

the P3 component for standard and deviant tones and the difference in the P4 component for neutral and fearful faces is 0.2. This can be interpreted as our evidence being “moderately” more likely under the null hypothesis that these measures of neural sensitivity are not correlated in the population at 12-months.

Table 5. 2 Bayesian Pearson Correlations for neural auditory and visual sensitivity measures at 12-months

Bayesian Pearson Correlations					
Variable	1. 12- months auditory diff P3	2. 12- months visual diff P1	3. 12- months visual diff N290	4. 12- months visual diff P4	
1. 12- months auditory diff P3					
n	—				
Pearson's r	—				
BF ₁₀	—				
2. 12- months visual diff P1					
n	46	—			
Pearson's r	-0.021	—			
BF ₁₀	0.186	—			
3. 12- months visual diff N290					
n	47	47	—		
Pearson's r	0.001	-0.943 ***	—		
BF ₁₀	0.178	6.738e+19	—		
4. 12- months visual diff P4					
n	46	47	47	—	
Pearson's r	0.035	0.766 ***	-0.865 ***	—	
BF ₁₀	0.189	3.431e+7	1.498e+12	—	

* BF₁₀ > 10, ** BF₁₀ > 30, *** BF₁₀ > 100

Overall, the results from Analysis 1 indicate that at 6-months of age, indices of neural sensitivity to auditory information (P3) and visual information (P1 and P4) are correlated

positively, whereas the auditory difference P3 is negatively correlated with the visual difference N290. However, by 12-months of age any association between these measures has disappeared.

5.3.3 Analysis 2 – the association between autonomic arousal and visual and auditory neural sensitivity

For the second analysis, we examine how autonomic arousal related to neural sensitivity at 6-months and 12-months. We operationalised autonomic arousal as heart rate (HR) in beats per minute (BPM) averaged across the recording. Neural sensitivity on the auditory task was operationalised as the amplitude difference in the P3 components in response to standard and deviant tones. Neural sensitivity on the visual task was operationalised as the amplitude difference in the P1, N290 and P4 components in response to fearful and neutral faces. At 6-months, HR correlated negatively with the auditory P3 difference and the visual P4 difference. However, HR correlated positively with the visual N290 difference. No correlation at a statistically significant level was found between HR and the difference between facial expressions in the P1 component. Follow-up analyses showed that autonomic arousal associated with a larger negative-going N290 in response to fearful but not neutral faces.

Scatterplots illustrate the strength and direction of the correlation between each set of two variables (Fig. 5.8. a, c, e). Our evidence shows that a negative relationship between average HR in BPM over the entire recording and the difference in the P3 component for standard and deviant tones and the P4 component for neutral and fearful faces is twice and four times respectively as likely as no relationship in the population. The BF10 for the positive relationship between average HR in BPM over the entire recording and the difference in the N290 component to neutral and fearful faces shows that a positive correlation is 12 times more likely in the population than not.

Plots showing the prior and posterior distributions of the true population correlation show how evidence from the current study has updated the prior distribution (fig. 5.8. b, d, f)

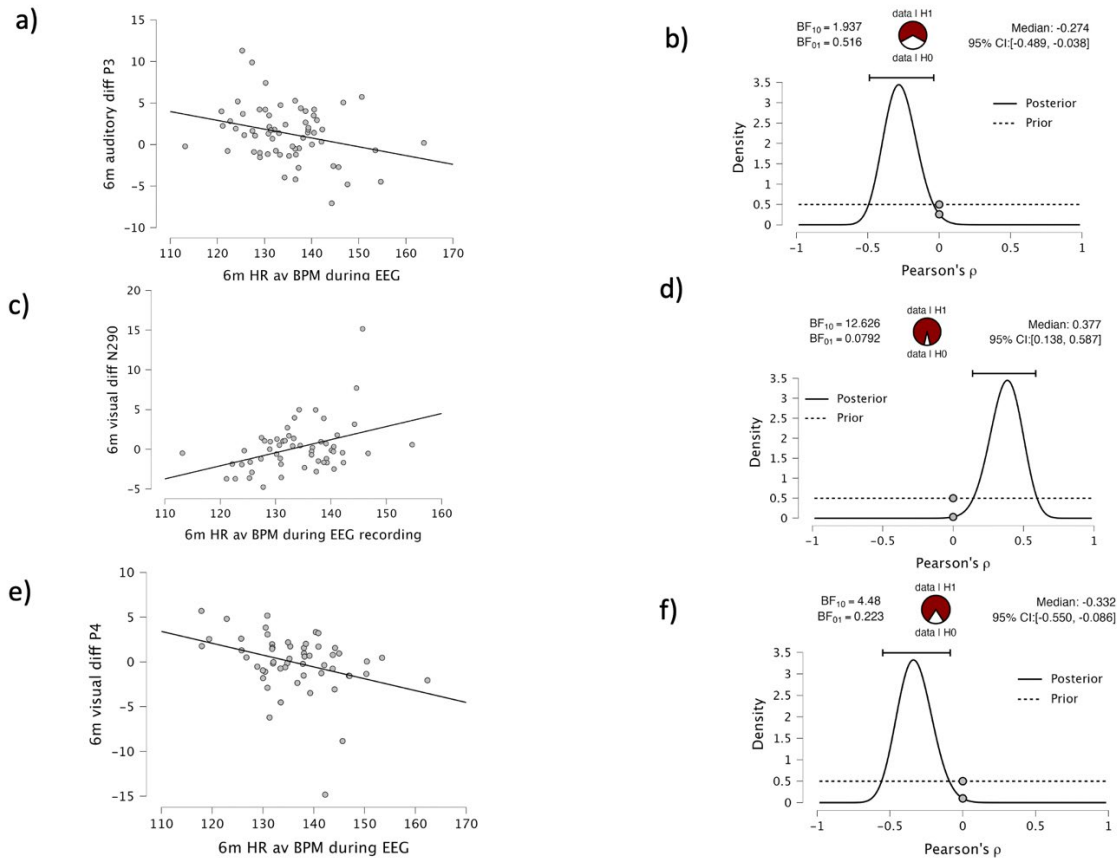


Figure 5. 8 Correlations between measures of HR and visual and auditory sensitivity at 6-months: Bayesian correlation pairwise plots showing strength and direction of the Bayesian Pearson correlation between the two variables analysed (Figs. 8. a, c, e); Plots showing the prior and posterior distributions of the true population correlation (Figs. 8. b, d, f).

Table 5.3 shows the Bayesian Pearson Correlations for the autonomic and neural measures.

Table 5. 3 Bayesian Pearson Correlations for autonomic and neural measures at 6-months
Bayesian Pearson Correlations

Variable	1. BPM 6-months	2. 6-months auditory diff P3	3. 6-months visual diff N290	4. 6-months visual diff P4
1. BPM 6-months				
n	—			
Pearson's r	—			
BF ₁₀	—			
2. 6-months auditory diff P3				
n	62	—		

Bayesian Pearson Correlations

Variable	1. BPM 6-months	2. 6-months auditory diff P3	3. 6-months visual diff N290	4. 6-months visual diff P4
Pearson's r	-0.287	—		
BF ₁₀	1.933	—		
3. 6-months visual diff N290 n	55	61	—	
Pearson's r	0.394 *	-0.371 *	—	
BF ₁₀	12.626	10.900	—	
4. 6-months visual diff P4 n	53	59	60	—
Pearson's r	-0.341	0.254	-0.869 ***	—
BF ₁₀	3.564	1.025	2.254e+16	—

* BF₁₀ > 10, ** BF₁₀ > 30, *** BF₁₀ > 100

Scatterplots in Figure 5.9. show the strength and direction of the correlation between autonomic arousal and the N290 to fearful faces at 6-months (Fig. 5.9 a) and 12-months (Fig. 5.9 b). Plots showing how the evidence has updated the prior distributions for the relationship at 6-months to be 3 times more likely than not (Fig. 5.9. C) and at 12 months, that there is no relationship between the variables being three times more likely than that there is.

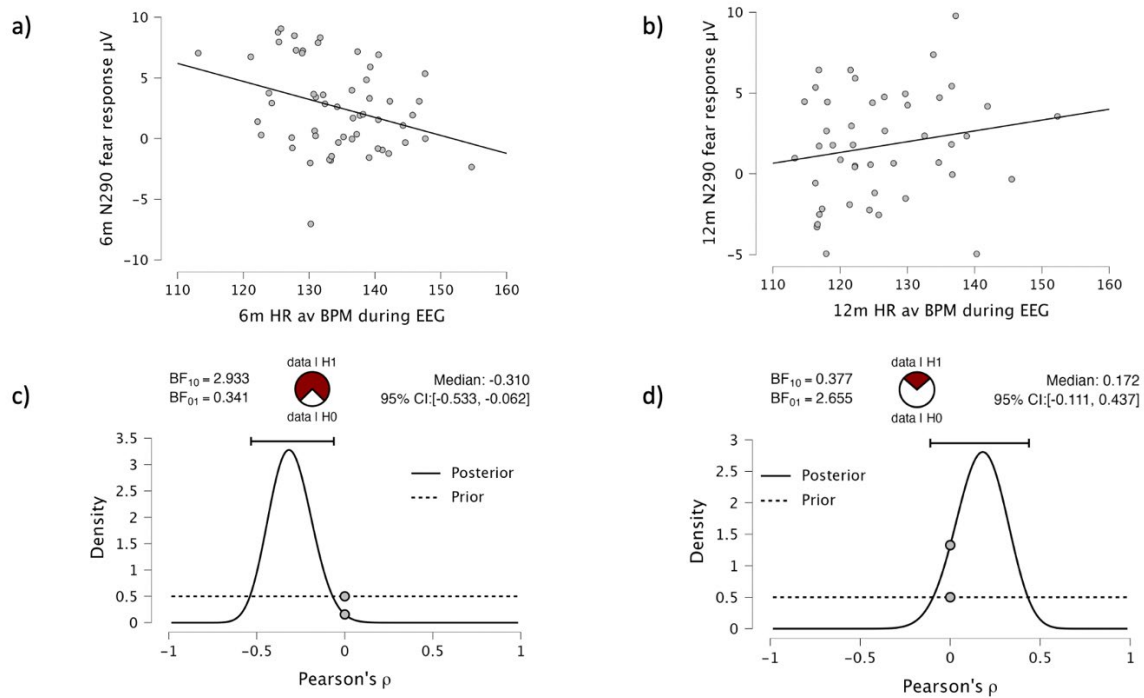


Figure 5. 9. Correlations between measures of HR and visual N290 response to fearful faces at 6-months and 12-months: Bayesian correlation pairwise plots showing strength and direction of the Bayesian Pearson correlation between the amplitude of the 6-months N290 to fear and HR at 6-months (Fig. 5.9. a) and the amplitude of the 12-months N290 to fear and HR at 12-months (Fig. 5.9. b); Plots of prior and posterior distributions of the true population correlation (Figs.5.9. c, d).

Table 5.4. shows the Bayesian Pearson Correlations for autonomic arousal and N290 in response to fear at 6-months and 12-months.

Table 5. 4 Bayesian Pearson Correlations for measures of autonomic arousal and N290 response to fearful faces at 6-months and 12-months

Bayesian Pearson Correlations

Variable	1. BPM 6-months	2. BPM 12-months	3. 6-months fear N290	4. 12-months fear N290
1. BPM 6-months				
n	—			
Pearson's r	—			
BF ₁₀	—			
2. BPM 12-months				
n	59	—		
Pearson's r	0.446**	—		
BF ₁₀	72.957	—		
3. 6-months fear N290				
n	55	52	—	

Bayesian Pearson Correlations

Variable		1. BPM 6- months	2. BPM 12- months	3. 6- months fear N290	4. 12- months fear N290
4. 12- months fear N290	Pearson's r	-0.325	-0.023	—	—
	BF ₁₀	2.933	0.175	—	—
	n	43	46	41	—
	Pearson's r	-0.049	0.183	0.085	—
	BF ₁₀	0.199	0.377	0.223	—

* BF₁₀ > 10, ** BF₁₀ > 30, *** BF₁₀ > 100

These results indicate that at 6-months there is a negative relationship between physiological arousal and neural sensitivity as operationalised in this study at the auditory P3 component and visual P4 component. However, individuals with higher autonomic arousal during the EEG recording session, responded with a larger difference in amplitude between fearful and neutral faces at the N290 component.

Next, we repeated an identical analysis based on the 12-months data. Scatterplots illustrate the strength and direction of the correlation between each of the sets of two variables (Fig. 5.10. a, c, e); Our evidence shows that no relationship between average HR in BPM over the entire recording and the difference in the P3 component for standard and deviant tones and the, N290 and P4 components for neutral and fearful faces is five, six and four times more likely, respectively, than there being a relationship in the population. Plots showing the prior and posterior distributions of the true population correlation show how evidence from the current study has updated the prior distribution (fig. 5.10. b, d, f).

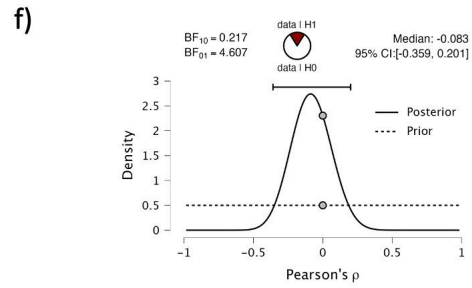
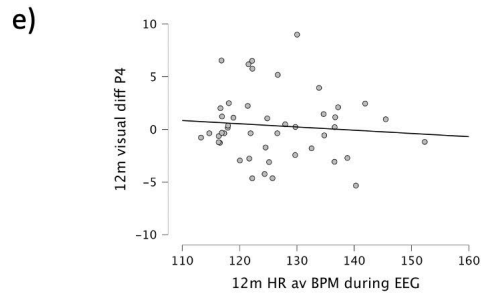
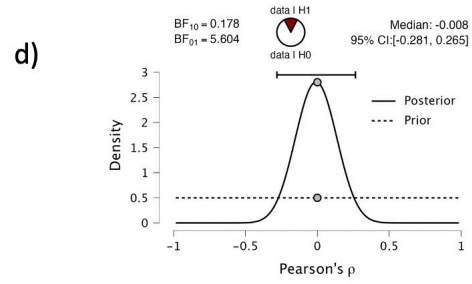
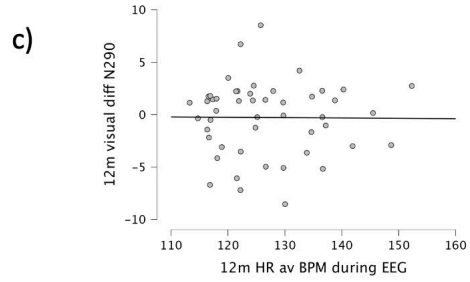
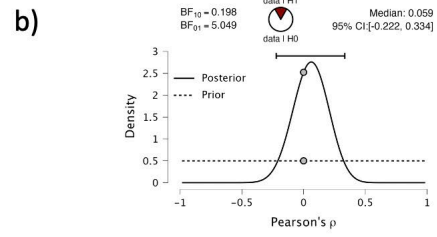
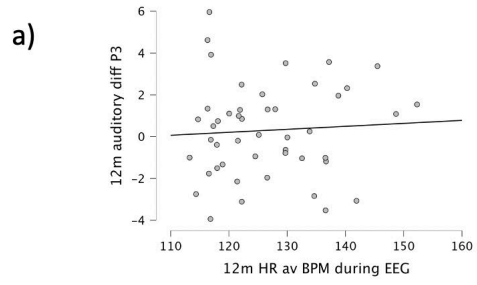


Figure 5.10. Correlations between measures of HR and visual and auditory sensitivity at 12-months: Bayesian correlation pairwise plots showing strength and direction of the Bayesian Pearson correlation between the two variables analysed (Figs. 5.10.a, c, e); Plots showing the prior and posterior distributions of the true population correlation (Figs. 5.10. b, d, f)

Table 5.5. Bayesian Pearson Correlations for autonomic and neural measures at 12-months

Bayesian Pearson Correlations

Variable	1. BPM 12-months	2. 12-months auditory diff P3	3. 12-months visual diff P1	4. 12-months visual diff N290	5. 12-months visual diff P4
1. BPM 12-months					
n	—				
Pearson's r	—				
BF ₁₀	—				
2. 12-months auditory diff P3					
n	50	—			
Pearson's r	0.045	—			
BF ₁₀	0.178	—			
3. 12-months visual diff P1					
n	46	46	—		
Pearson's r	-0.086	-0.021	—		
BF ₁₀	0.215	0.186	—		
4. 12-months visual diff N290					
n	49	49	47	—	
Pearson's r	-0.009	0.001	-0.943 ***	—	
BF ₁₀	0.178	0.178	6.738e+19	—	
5. 12-months visual diff P4					
n	46	46	47	47	—

Pearson's r	-0.089	0.035	0.766 ***	-0.865 ***	—
BF ₁₀	0.217	0.189	3.431e+7	1.498e+12	—

* BF₁₀ > 10, ** BF₁₀ > 30, *** BF₁₀ > 100

Overall, the results from Analysis 2 indicate that at 6-months, higher physiological arousal associated with decreased neural sensitivity in the auditory domain (specifically, a larger difference between the amplitude of responses to standard of deviant tones at the P3 component) and the visual domain (a larger difference between the amplitude of responses to fearful and neutral faces at the P4 component). However, higher physiological arousal also associated with increased neural sensitivity as measured by the difference between the amplitude of responses to fearful and neutral faces at the N290 component. Autonomic arousal did not correlate with any measures of neural sensitivity at 12-months.

5.4 Discussion

We used ERP paradigms to measure auditory and visual neural sensitivity in infants at 6 and 12-months while concurrently measuring inter-individual differences in autonomic arousal. Our results had two main features of interest. The first was that at 6 months, neural sensitivity (indexed as difference-detection between conditions) correlated across auditory and visual modalities. Specifically, while there were no differences between responses to fearful and neutral faces at a group level, for those infants with a larger difference in response amplitudes of the P3 component between the standard and deviant conditions in the auditory paradigm, there was also a larger difference in response amplitudes of the P1 and P4 between the neutral and fearful conditions in the visual paradigm. We also found a negative association between the difference in response amplitude of the N290 to neutral and fearful conditions and the difference in response amplitudes of the P3 to the standard and deviant conditions in the auditory paradigm. The same associations were not present at 12-months. Second, at 6m, infants' autonomic arousal negatively correlated with the auditory difference P3 and the visual difference P4 but positively correlated with the visual difference N290. Any association between autonomic arousal and neural sensitivity

disappeared at 12 months despite the 6m and 12m EEG measures having comparable levels of noise and variability. We shall discuss these two main findings in turn.

Topoplots of our results show that different cortical regions are being activated in response to the visual and auditory stimuli. While this implies specialisation of cortical areas for visual (occipital) and auditory (temporal) perception, our measures of neural sensitivity nevertheless correlate at 6m. This correlation of sensitivity measures between neural domains supports the hypothesis that ES is domain general, which is a pre-requisite for differential susceptibility to *both* positive *and* negative environmental effects. A domain-general level of sensitivity, in terms of the early stages of visual and auditory processing has been considered evolutionarily adaptive – to facilitate making novel and serendipitous associations with environmental cues in an uncertain environment (Chiappe & MacDonald, 2005) and as such an index of heightened susceptibility to the effects of the developmental environment for better or for worse.

It is important to note that the auditory and visual stimuli used in this study were not presented concurrently and would not ordinarily co-occur. However, neural responses to both have been used previously to index sensitivity of response in the visual and auditory neural domains. The results of this study suggest this sensitivity was general across neural domains at 6m but not 12m. Different accounts of neural and perceptual development will be explored for their contributions to understanding the development of the mechanisms of differential susceptibility and to highlight relationships between theories that are not often linked.

The development of sensitivity, from being domain-general to domain specific, that we found, is in line with accounts that hold that initially separate sensory systems become integrated through repeated experience of concurrent information provided by the different sensory modalities (Birch & Lefford, 1963, 1967). While this may seem counterintuitive, evidence for this account comes from studies of the development of audiovisual speech integration. Prior to 4.5-months, infants perceive even concurrently presented auditory and visual information via separate sensory systems (Bristow et al., 2009; Desjardins & Werker, 2004; Nardini et al., 2010). This early parity of sensitivity to both modalities (even when presented concurrently) is indicated by an absence of the McGurk/fusion effect, which sees perception in one modality (auditory) attenuated by perception in another

(visual) (McGurk & MacDonald, 1976). Intersensory integration of different modalities comes at the expense of a level of sensitivity that is domain general. Our findings corroborate accounts of a level of sensitivity that is initially domain general at 6m -whether perceiving multi-modal or unimodal stimuli - and thereafter develops differentially in the different domains at 12m.

The fact that sensitivity measures correlated between domains in this study at 6-months but not 12-months, may be due to a shift away from predominantly stimulus-driven, bottom-up perception. Some accounts of the ontogeny of face-processing argue that postnatally, sub-cortical orienting involving the amygdala modulates activity in face-sensitive cortical regions before the arrival of visual information through the cortical route (Johnson, 2005). This pathway is thought to be maximally sensitive to low-spatial-frequency (LSF) aspects of faces, which selectively differentiates expressions such as fear with wider eyes and open mouths. This early sensitivity to LSF aspects of faces may also be reflected in the functional specificity of components and the direction in which they correlated in this study.

We found a positive association between the P3 auditory component, reflecting pre-attentive, bottom-up difference-detection mechanisms and the P1 and P4 visual components. In adults, the longer-latency visual ERP components, greater than 400ms after stimulus onset, are thought to reflect top-down mechanisms such as recognition of facial identity (Barrett et al., 1988; Barrett & Rugg, 1989; Eimer, 2000; Itier & Taylor, 2004) and/or retrieval of semantic information related to faces (Paller et al., 2000). However, the earlier adult N170 component is thought to be related to stages of structural encoding of the physical information in faces, with some studies suggesting that it may only reflect eye detection (Bentin et al., 1996) as opposed to encoding of the entire configuration of facial features (Eimer, 2000). In addition, the adult N170 component can be unaffected by any emotional expression, supporting the hypothesis that structural encoding and expression analysis are independent processes (Eimer et al., 2002). In infants, there is evidence that the adult N170 is preceded by the N290 and P4 components. However, before 12 months of age, the P4 (unlike the N290) component does not seem to be face-specific (Halit et al., 2003). Furthermore, Halit et al. (2004) found the amplitude of the P4 was not sensitive to the difference between face and visual-noise stimuli in 3-month-olds, while the amplitude of the N290 displayed a huge difference (Halit et al., 2004). Research has also shown that the P1 is an obligatory visual component indexing low-level sensory processing and is not face-specific but associated with differences in low-level visual features that exist between

face and non-face stimuli (Conte et al., 2020). However, after 7-months, a developmental shift is thought to occur from featural to configural processing of faces. Cohen and Cashon (2001) report that before the age of 7 months, infants process specific features of complex objects but after the age of 7 months they are able to integrate those features into a whole object (Cohen & Cashon, 2001; Conte et al., 2020).

In line with the above evidence from the literature, it is proposed that the difference between the amplitude of the early P1 and P4 components to the fearful and neutral faces at 6m in this study may be explained by the encoding of the lower-level, perceptual information in the isolated features of the faces such as larger eyes and open or down-turned mouths in the fearful category (Halit et al., 2003). Adult studies have seen larger amplitude N170 components evoked to open as opposed to closed mouths (Puce et al., 2007; Wheaton et al., 2001). Therefore, the components which precede the N170 in infants -the P1 and P4 - are more likely to be affected by the spatial differences of fearful as opposed to neutral faces detected by exogenous attention. The difference in amplitude of the N290 evoked by the two visual conditions may be partially explained by the recruitment of greater top-down, pre-frontally mediated processing, which would not associate positively with indexes of exogenous perception – the auditory P3 and the visual P1 and P4.

In terms of auditory perception, this differentiation between exogenous perception of low-level sensory features and the more experience-mediated endogenous processing of stimuli corresponds with the proposition that two different mechanisms underlie the auditory tracking of the speech envelope: one derived from the intrinsic oscillatory properties of auditory regions; the other induced by top-down signals coming from other non-auditory regions of the brain (Rimmele et al., 2018). Under non-speech listening conditions, the intrinsic auditory mechanism dominates (Assaneo et al., 2019), which corresponds with the automatic change detection in the processing of non-semantic, lower-level features of non-speech sounds in this study. The disappearance of the association between the amplitude of visual and auditory components by 12m in this study may capture a transition from bottom-up, stimulus-driven processing of faces to more top-down processing - based on experience - which no longer correlates with the auditory mismatch response which is thought to be automatic and independent of voluntary attention (Cheour et al., 2010; Háden et al., 2016; Wanrooij et al., 2014).

The dissociation of visual and auditory sensitivity by 12m could also be due to the differential development in the two modalities. There is ample evidence that, very early in

development, audio and visual development rates differ. Differential onset of the functioning of sensory systems results in relative independence among emerging systems, thereby reducing competition which helps regulate subsequent neurogenesis and functioning (Turkewitz & Kenny, 1982). Synaptogenesis and synapse elimination occurs at different rates in different cortical regions in humans. Synaptic density in the auditory cortex is maximal at 3-months of age and synaptic elimination ends at around 12-years, whereas synaptic density in the visual cortex is maximal between 9 and 15-months and synaptic elimination ends at around late adolescence (Huttenlocher and Dabholkar, 1997). Myelination begins earlier in the occipital lobe than in the temporal lobe after birth (Yakolev and Lecours, 1967). Complexity measures, such as multiscale entropy (MSE) (Costa et al., 2002) can index maturational changes in brain function. Lippe et al. (2009) found that, while EEG signal complexity increased from one month to 5 years of age in response to auditory and visual stimulation, infants' signal complexity for the visual condition was greater than auditory signal complexity, whereas adults showed the same level of complexity to both types of stimuli. The differential rates of complexity change may reflect a combination of innate and experiential factors on the structure and function of the two separate sensory systems.

The second branch of our findings on the domain generality of ES was that higher heart rate (HR) (measured in BPM averaged across the entire EEG recording) was associated with a larger difference in response amplitude of the visual N290 component to fearful and neutral faces and a smaller difference in the response amplitudes of the visual P4 component and the auditory P3 component in the 6-month-old infants. While HR correlated between 6m and 12m, any associations between autonomic arousal and automatic neural sensitivity had disappeared by 12-months despite equal amounts of noise and variability at the two time-points (see error bars in Figures 2. 3. and 4.) In the same auditory change-detection paradigm as used in this study, while responses to large acoustic contrasts (bursts of white noise) evoked large P3 responses (indexing exogenous, stimulus-driven orienting or distractibility) in all 5-7 year-old children regardless of HR, children with high autonomic arousal also showed a larger P3 component in response to small acoustic contrasts (500Hz-750Hz) (Wass et al., 2019). It was proposed that in trials with high HR, the overall brain excitability was higher and therefore more prone to involuntary attention. Thus, even small acoustic contrasts (frequency deviant) could potentially elicit a P3-like response. Therefore, for this study we hypothesized that higher HR would associate with greater neural sensitivity indexed by a larger difference in the amplitude of response to

the two conditions in the visual and auditory paradigms. However, we only found a larger difference in the amplitude of response to fearful and neutral faces at one component – the N290. This finding may be explained by the follow-up analyses, which showed that high HR correlated with larger N290 (but not P1 or P4) responses to fearful faces. The differential response at the different components will be addressed below.

Heightened autonomic arousal is an index of sympathetic nervous system (SNS) activity which is involved in quick response mobilising ('fight or flight') (Cacioppo et al., 2000) and as such is considered a defence response (Pavlov, 1927) associated with hypervigilance and sensory reactivity to environmental stimuli (Cheung & Porges, 2013). Relatedly, prior research has found associations between sensory-reativity and emotional-face processing in children. Projections from the amygdala (part of the neural system responsive to threat (Tovote et al., 2015)) to the occipital cortex may serve to enhance the processing of visually salient stimuli, including facial expressions of emotion (Eimer et al., 2003) and especially fearful expressions (Morris et al., 2002).

The difference in the direction of the correlations between components indexing neural sensitivity and measures of physiological arousal may again be explained by the functional specificity of the components. As mentioned above, previous studies have found evidence of a difference in response amplitude of the N290 between face and non-face visual stimuli suggesting the N290 is face-specific (Halit et al., 2003). However, the P1 is thought to be an obligatory visual component indexing low-level sensory processing and is not face-specific (Conte et al., 2020) and the P4 is thought to reflect structural processing of faces in infants, (Porter et al., 2021) but also does not seem to be face-specific (Halit et al., 2003). The fact that detection of difference at these visual components correlates positively with detection of difference in the P3 auditory component may be because all three index stimulus-driven low-level perception of the sensory properties of the stimuli in the two modalities. For the same reason, the direction of the correlation between HR and the amplitude of the difference between these components is the same - slower heart rate, which is thought to reflect an orienting response (Sokolov, 1963) was associated with greater neural sensitivity in terms of perception of difference between conditions in stimuli for the auditory P3 and the visual P4 component.

This study set out to test the hypothesis that measures of ES would correlate, supporting the notion that sensitivity should be domain general in order to confer susceptibility to all elements of the developmental environment. Evidence presented here suggests that neural sensitivity, in terms of automatic exogenous perception of salient

stimuli, covaries in different modalities at 6m and that autonomic arousal associates with neural sensitivity in both the visual and auditory neural domains; but thereafter, sensitivity in the different domains follows different developmental trajectories. An initial, domain general level of neural sensitivity in different sensory modalities is the result of an early heightened sensitivity of stimulus-driven perception. Relevant to the differential susceptibility hypothesis this may confer advantages in that an organism is initially better equipped than those who are less sensitive to respond to any environmental stimuli and is therefore better able to develop an expertise for the stimuli to which it is predominantly exposed and therefore conditionally adapt to the developmental environment. In terms of whether sensitivity is domain general, these results suggest pre-attentive sensitivity is initially domain general, and associated with autonomic arousal, but that increasing domain specificity of neural modules through processes such as neuroconstructivism and decreasing parity of sensitivity between domains due to intersensory integration, mean differential developmental trajectories. The same measures of sensitivity no longer correlate either between neural domains or between the neural and autonomic domains. In terms of the domain general sensitivity that is required to confer differential sensitivity to both positive and negative environments, cross sectionally at 6m, individual differences in sensitivity did correlate between domains. However, the longitudinal findings corroborate accounts of increasing domain specificity, which does not support the differential sensitivity hypothesis.

Chapter 6. Positive and negative emotional reactivity are initially associated during infancy, then diverge with increasing age

Abstract

Differential Susceptibility Theory (DST) posits that infants high in sensitivity are more affected by their environment ‘for better or for worse’ – i.e., that infants high in sensitivity should show elevated reactivity both to negative (e.g., frustrating) and to positive (e.g., playful) tasks. To test this, we used two separate behavioural tasks to measure positive and negative reactivity in infants both cross-sectionally at 6-months (N=82) and longitudinally from 6-months to 12-months (N=68). Positive and negative reactivity correlated at 6-months but not 12-months, consistent with the idea that ES is one-dimensional during early but not later development. Maternal SES moderated the relationship between negative reactivity (but not positive reactivity) at 6-months and positive (but not negative) reactivity at 12-months.

Keywords: Differential Susceptibility; Vantage Sensitivity; Diathesis Stress; infant behavioural reactivity; positive reactivity; negative reactivity; socioeconomic status

6.1 Introduction

The expression and regulation of emotion in infancy and early childhood are powerful mediators of interpersonal relationships and socioemotional adjustment, including behavioural self-control (S. D. Calkins, 1994a; Cicchetti et al., 2010; Malatesta et al., 1989; Thompson, 1994a). Emotionality refers to differences in displays of positive and negative affect in response to environmental demands (Buss & Plomin, 1975). Historically, work with infants has concentrated on negative affect, which encompasses anger proneness (Goldsmith, 1996), distress to limitations (Rothbart, 1981), fussiness–difficultness (Bates et al., 1979), irritability (Sanson et al., 1987), and negative mood (Carey & McDevitt, 1978a). Infants high in negative affect are apt to respond to environmental stressors with marked protest including behavioural reactivity and crying (Beauchaine, 2001). Longitudinal associations have been found between infant negative affect and negative developmental outcomes. High negative emotional reactivity predicts both under-control and over-control problems (Eisenberg & Spinrad, 2004; N. A. Fox et al., 2001; Gilliom & Shaw, 2004a; A. S. Morris et al., 2002a) and higher levels of both internalizing and externalizing symptoms across childhood and adolescence (Gilliom & Shaw, 2004b; Keiley et al., 2003; A. S. Morris et al., 2002b; Young Mun et al., 2001). Negative emotionality also predicts lower social competence (Murphy et al., 2004), and lower attentional control (Rothbart et al., 1994).

One mechanistic account of these longitudinal associations is that there is individual variation in the thresholds at which the body's environmental stimulus-response systems are provoked and that infants who react to their surroundings with displays of heightened negative affect are those for whom lower thresholds cause increased environmental sensitivity (ES). According to models such as the diathesis-stress model (described in (del Giudice et al., 2011)), infants with elevated ES, which manifests as increased negative reactivity, are thought to be especially vulnerable to high-risk settings, leading to poorer long-term mental and physical health outcomes (Juster et al., 2010; Lazarus, 1993).

An alternative account, called Differential Susceptibility Theory (DST) (Belsky, Bakermans-Kranenburg, & Van IJzendoorn, 2007; Belsky & Pluess, 2009; Ellis et al., 2011), challenges the disproportionate attention paid to heightened sensitivity in contextual adversity and the negative effects thereof - such as disturbances in functioning and development. Instead, DST suggests that individuals with heightened sensitivity, who are therefore more susceptible than others to negative (risk-promoting) environmental

conditions, are also more likely than others to benefit from positive (development-enhancing) environments (Belsky et al., 2007a; W. T. Boyce & Ellis, 2005; B. Ellis et al., 2005).

Consistent with DST, evidence is growing in support of the idea that infants who display more negative affect are better able to exploit the benefits of a positive environment. The higher the negative affect, the greater the behavioural and cognitive improvements in response to interventions (Blair, 2002a; Klein Velderman et al., 2006). Moreover, while children with more negative affect showed higher levels of behavioural problems and lower social competence if exposed to low-quality childcare, they showed better adjustment than their low-reactive peers when exposed to high-quality childcare (Pluess & Belsky, 2009). Cassidy and colleagues found that infants high in negative affect were relatively more likely to benefit from the positive effects of a parenting intervention (Cassidy et al., 2011). Stupica and colleagues found that infants high in negative affect who had established secure attachments to their primary caregiver proved highest on sociability at 18 and 24 months (Stupica et al., 2011). Negative affect in these studies was assessed using either parent report of temperament or assessment of observed behaviour.

Mechanistically it remains underspecified, however, why children who show increased negative reactivity are better able to exploit the benefits of a positive environment (Wass, 2018). One possibility, which is implied in DST, is that this is because emotional reactivity is a one-dimensional construct, and that children who have a heightened ability to register and process external stimuli will do so in response to both positive and negative environmental effects, so that those higher in negative reactivity to negative stimuli ought also to be higher in positive reactivity to positive stimuli. According to this explanation, negative and positive reactivity play equal roles in mediating how environments influence development, and the reason why the literature concentrates on negative affect arise in part because of the risks conferred by negative environments, but also in part for methodological reasons – because expressions of negative affect emerge earlier in development than expressions of positive affect (Rothbart, 2016; Rothbart et al., 2008) and are easier to induce experimentally in lab settings (S. v. Wass, 2021).

Relatively few researchers have, however, tested the prediction that the same children who show elevated negative reactivity should also show elevated positive reactivity. One physiological marker of ES is high baseline respiratory sinus arrhythmia (RSA), which is the extent to which the heart rate varies between beats in line with respiration. High baseline RSA, which has been robustly linked to heightened negative

reactivity in infants in response to a stressor (Porter et al., 1988), has also been found to predict positive reactivity in infants (Stifter et al., 1989). Richards and Cameron (1989) found positive associations between RSA and the approach subscale of the Infant Temperament Questionnaire (Carey & McDevitt, 1978b) at ages 14, 20, and 26 weeks. However, these studies did not present the same individuals with both positive and negative stimuli. One study identified significant associations between negative reactivity and RSA and near significant associations between positive reactivity and RSA (Fox, 1989). Another study identified positive correlations between questionnaire-based assessments of Positive Affectivity/Surgency and Negative Affectivity between 3 and 12 months (Putnam & Stifter, 2005).

However, other studies with older infants (18m) have identified weak to moderate inverse associations between positive and negative affect (Coffey, 2019; Coffey et al., 2015; Diener & Emmons, 1984; Fredrickson, 2013a). This has led some researchers to regard positive and negative affect at this age as independent constructs with distinct adaptive purposes (Coffey et al., 2015; Coffey, 2018; Fredrickson, 2013b). This is consistent with neuropsychological models of brain maturation which propose an evolutionary, vertical-integrative view on the development of communication and regulatory capacities (Feldman, 2009). According to this view, regulatory functions are processed along three core brain systems: brainstem, limbic and cortical systems. Higher systems integrate, elaborate, fine-tune, and serve an inhibitory function for hierarchically lower systems. Over time, early development within brainstem and subcortical regions becomes progressively elaborated towards higher-order social and communicative functions (Geva et al., 2000; Wass et al., 2022). Therefore, the positive associations found at 5m and inverse associations in the second year could be explained as behavioural reactivity becomes less exogenously, and more endogenously driven. From the perspective of differential emotions theory (DET) (Izard, 1977; Izard, 1991), therefore, different sets of emotions may become relatively more prominent in the different stages of life as they serve stage-related developmental processes (Abe & Izard, 2010). Added to this, temperamental research finds that positive reactivity is most often correlated with regulation, not negative reactivity later in development (Komsis et al., 2006). Therefore, this would suggest that positive and negative reactivity should associate as markers of DST in early infancy at 6-months, but this association may not continue until 12-months. Through development, continued heightened negative reactivity may act more as a diathesis.

Our first aim, therefore, was to examine the relationship between reactivity to both positive and negative environmental effects cross-sectionally at 6-months. In addition, we wanted to address another question raised by DST, namely: how does ES interact with the developmental environment? Socioeconomic status (SES) predicts a broad range of important life outcomes, including physical (Adler & Stewart, 2010) and mental health (McLaughlin, Green, et al., 2012), as well as intelligence and academic achievement (von Stumm & Plomin, 2015). Maternal education and income have been frequently used to predict a child's socioeconomic status. with maternal education one of the strongest indicators of SES in studies of child development (Hoff & Laursen, 2012). Maternal education has been linked to better developmental outcomes (Girault et al., 2019; Montroy et al., 2016). Thus, we examined how SES as one index of the developmental opportunities offered to the child moderates the relationship of ES (as measured by reactivity to positive and negative stimuli) during early infancy and both positive and negative reactivity during later infancy.

We were particularly interested however to examine the development of positive reactivity later in infancy. While there is increasing evidence to support the DST proposal of equal sensitivity to positive and negative environmental factors, Vantage Sensitivity has been proposed to counter the idea of the diathesis-stress framework that individuals high in ES are especially vulnerable to negative environmental effects by suggesting that some individuals high in ES are especially susceptible to the beneficial effects of a positive environment (de Villiers et al., 2018). Vantage sensitivity reflects heightened susceptibility to exclusively positive environmental factors or interventions as a function of individual ES characteristics (Pluess & Belsky, 2012a). High temperamental negative reactivity in 6-months girls interacted with high paternal involvement in early childcare to predict significantly more prosocial behaviour at 6.5 years, whereas girls with low negative reactivity, in contrast, evinced no such benefit from paternal involvement (Ramchandani et al., 2010). However, to our knowledge, no studies have examined whether high positive reactivity in infancy interacts with positive environmental influences in determining improved developmental outcomes.

This paper therefore has two aims. The first is to test whether emotional reactivity is a one-dimensional construct at 6-months and that the same infants who display more negative reactivity to negative stimuli ought also to display more positive reactivity to positive stimuli. To this end we used tasks from the infant version of a standard laboratory battery to assess early emotion systems in young children (Laboratory Temperament

Assessment Battery [LAB-TAB], (Planalp et al., 2017), which have been used in research on early affective development (Buss & Goldsmith, 1998a; Kochanska et al., 1998a). We presented one stimulus proven to elicit anger, namely Toy Retraction (the mother plays with an attractive toy with the infant before removing the toy and putting it out of reach but within sight for three 15-s trials) (Planalp et al., 2017). And we presented one stimulus proven to elicit positive reactivity, namely Peekaboo (an experimenter (instead of the infant's mother) appears from under a table in front of the infant and engages in three 15s Peekaboo trials) (Eckerman et al., 1999; Rochat et al., 1999; Srofe & Waters, 1976). We coded for the presence and intensity of the emotion expressed in the facial, vocal, (negative and positive reactivity) and bodily channels (motor reactivity) in one-second epochs as manifestations of positive and negative reactivity to the stimuli.

We presented the same tasks longitudinally to infants when they were 6 months and 12 months old. We predicted that at 6-months infants who show greater negative reactivity would also show greater positive reactivity. However, by 12-months, increased self-regulatory capacities, which may function differently for positive and negative emotions, and the switch from exogenously to more endogenously driven responses would see the amplitude of behavioural reactivity to positive and negative stimuli fractionate such that at 12-months infants would not be equally behaviourally reactive to positive and negative stimuli.

Our second aim was to test the hypothesis that children's home environment (as measured from data on maternal education and household income) will moderate the relationship between early life ES (as measured via behavioural reactivity) and behavioural reactivity during later infancy. We conducted four separate moderation analyses to examine how the relationships between early positive and early negative reactivity and later positive and negative reactivity are separately moderated by SES.

We predicted that home environment would moderate the relationship between ES at 6-months (as indexed by both positive and negative reactivity) and positive reactivity at 12-months in support of the Vantage Sensitivity framework such that infants who were more behaviourally reactive at 6-months would be better able to take advantage of any benefits conferred by a high SES environment to become more reactive to exclusively positive stimuli.

6.2 Method

6.2.1 Participants

Infant-parent dyads attended the BabyLab at the University of East London on two occasions – first when the infants were 6-months old and a second visit when the infant was 12-months old. The participating parent-infant dyads were recruited from local children’s centres, baby sensory classes and new-parent support groups. At timepoint 1, 82 infants (52.4% males) and their primary caregivers (98% mothers) attended (Infant mean age in weeks= 27.77 SD=0.59). At timepoint 2, 68 infants (52.9% males) returned (Infant mean age in weeks = 54.45, SD=0.75), making the attrition rate of the study 17.07%.

Demographic characteristics of the sample are shown in Table 6.1.

Table 6. 1 Demographic details of participants at 6-months (n = 82) and 12-months (n=68)

Variable	6-month visit	12-month visit
Infant age in weeks- M(SD)	27.77 (0.59)	54.45 (0.75)
Range	20.9-32.7	48.8-60.5
Gender (%)		
female	47.56	47.06
male	52.44	52.94
Income (%)		
Under £50.000	10.8	9.3
£50.000-£100.000	43	42.6
£100.000-£150.000	33.9	33.3
£150.000-£200.000	6.1	7.4
>£200.000	6.2	7.4
Maternal education (%)		
Postgraduate	45.12	47.06
Undergraduate	39.02	44.12
A level	4.88	2.94
No formal qualifications	1.22	1.47

M=Mean, SD=Standard deviation

6.2.1.i Participant exclusions

Toy retraction – 6-months: The nature of our study meant that data were unavailable from some infants for one or other of the tasks at either one or other of the time points. For toy-retraction at 6-months, N=63 infants provided usable data. N=19 infants either did not

attempt the task or the data was compromised due to experimenter error. At 12-months, of the 68 infants who attended the lab, 63 provided useable data. N=5 did not attempt the task.

Peekaboo – 6-months: useable data was provided by N=55 of the N=82 infants who attended the lab. N=27 did not attempt the task. At 12-months, of the 68 infants that attended the lab, N=30 were able to be coded. Both peekaboo and toy-retraction data were available from N=30 at 12-months.

The average age (SD) of participants who contributed both usable toy-retraction and peekaboo data was 27.08 (2.23) weeks on the day of testing. The average (SD) of participants who contributed both usable toy-retraction and peekaboo data on the second visit was 53.8 (2.99) weeks on the day of testing.

6.2.2 Equipment

Behavioural paradigms proceeded in the lab where a table, a highchair for the infant, a chair for the mother and three cameras were placed in a room with a dividing screen behind which were the data collection computers. Different age-appropriate toys were used at the 6-months and 12-months visits. At 6-months a folded foil blanket was adopted for its tactile, visual, and auditory properties. At 12-months, a pop-up, musical push-button toy was used (see Figure 6.1a). The selection was based on the cross-sectional observations reported in a pilot study.

The behavioural paradigms were videotaped with three cameras: 1) A SuperVHS Panasonic camcorder (1080p, 25fps) was placed around 1 m away from the table and focused on the infant's face and body. 2) Another SuperVHS Panasonic camcorder (1080p, 25fps) recorded the mother's face and body. 3) A webcam (480p, 30fps) mounted on a high platform provided a wide-angle view of the infant's full body, the mother, and the experimental context. Recordings from the first camera were used for coding the infant's behaviour, and the third camera functioned as a substitute where the infant's face or body was obscured in the first recording.

6.2.3 Procedure

After obtaining informed parental consent, the dyads participated in the two behavioural tasks, which were presented as far as possible in a counterbalanced order. In addition, four other tasks were presented to address separate research questions, which will be written up separately. The order of the tasks was counterbalanced across the testing sessions to reduce carry-over effects. However, sometimes a positive task was prioritized if

an infant was tired and needed calming before a negative-emotion eliciting task could be attempted.

The tasks were adapted from the standardized Laboratory Temperament Assessment Battery (Lab-TAB) (The University of Texas at Arlington, 2012; Goldsmith & Rothbart, 1999). Tasks were terminated if the infant was highly distressed or cried for more than 10 seconds or if the mother felt uncomfortable continuing the task for any reason. Parents were constantly present with their infants. Participation in the whole battery of behavioural tasks lasted approximately 30 minutes, depending on the infants' general mood.

Toy retraction task: This task was designed to evoke mild and transient frustration/anger, in a standardised setting by removing and placing the toy with which they were engaged just out of reach. Previous studies have demonstrated toy retraction to be efficient at eliciting short-term distress and frustration (Braren et al., 2019; Braungart-Rieker & Stifter, 1996; Morasch & Bell, 2012; C. A. Stifter & Braungart, 1995). The task was formed of six phases of 15s each, three free-play phases, and three trial phases (Fig 6.1b).

The mother, infant, and experimenter sat around a rectangular table. The infant was seated in a highchair opposite the mother across the table. The experimenter sat to the infant's right with a timer. The task started with the experimenter bringing an attractive toy and giving it to the infant (initial free-play phase). During this time, the mother was instructed to play with the toy with her infant freely. After 15s, the mother was cued by the experimenter to gently remove the toy from the infant and place it out of reach but still within sight of the infant for 15 s (trial phase). This sequence of playing followed by retraction was repeated twice more. Mothers were instructed to remain non-interactive, without smiling or talking during the trial phases. Three 30-second play-retraction phases consisting of 15s of free-play and 15s when the toy is retracted resulted in a 90s-long time series for the whole task.

Peekaboo task. During the peekaboo task, the infant sat in the same position at the table in a highchair. The mother sat at the narrow end of the rectangular table to the infant's left. The mother was asked to maintain a neutral expression and to refrain from interacting with the infant for the duration of the task. The experimenter greeted the infant briefly, saying: "Hello [name of infant], we are going to play peekaboo." The experimenter then crouched down under the table and remained there for 15 seconds. After 15 seconds the experimenter appeared from under the table saying: "Peekaboo, I see you [Baby's name]" and smiling and chatting to the infant (trial phase). This interaction lasted 15 seconds after which the experimenter disappeared back under the table (see Fig 6.1c).

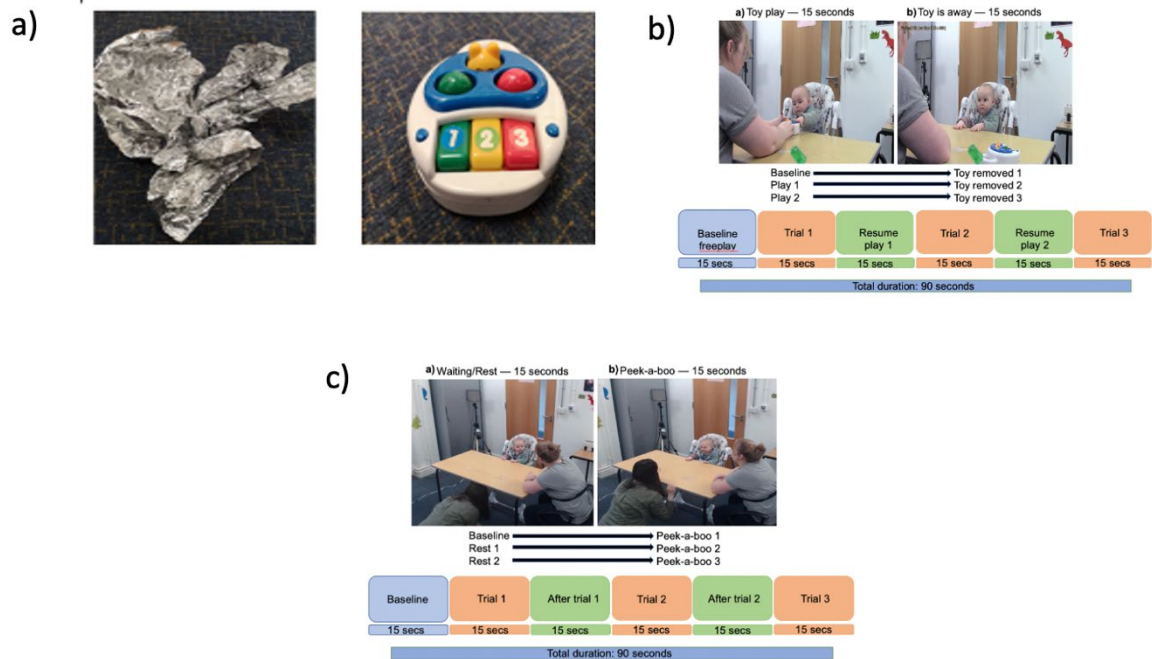


Figure 6. 1. a) Toys used in toy retraction task: at 6-months, a folded foil blanket was adopted. At 12-months, a toy that pops up and makes musical noise when its buttons are pushed was used. b) The structure of the toy retraction task. c) The structure of the peekaboo task:

6.2.4 Data processing

Coding of observed behaviour. The infant behaviour was video-coded using MATLAB (The Math Works, Inc) and the Psychtoolbox-3 (Kleiner et al., 2007). For each 1-s interval of videotape, affective and behavioural responses were rated by the same coder. The same coder was not allowed to code data from both 6-months and 12-months.

Positive and negative reactivity: Behavioural affective responses were coded separately for facial and vocal affect. The intensity of negative and positive facial affect was rated on a 4-point scale: 3 (intense), 2 (mild), 1 (low), 0 (neutral). Ratings for negative vocal affect ranged from 2 (definite whimpering, protest or crying), 1 (mild vocalisation that may or may not be negative), 0 (no or neutral vocalisation). Ratings for positive vocal affect ranged from 0 (no or neutral vocalisation), 1 (positively toned babbling, squealing, and similar vocalisations), 2 (laugh). Motor activity was coded as movements of the arms (waving them, reaching, or banging the table) and/or legs (kicking) and/or torso (leaning forwards or twisting) which were either 1 (present) or 2 (not present) (see Supplementary Materials).

Generating SES index. To provide a measure of developmental context indicated by socioeconomic status (SES), mothers also completed a demographic questionnaire at both

visits which asked for details of household income and educational status. Household income was entered as a variable on a continuous scale. Level of education was on a scale from 1-7 with 7 being the highest and 1 the lowest: postgraduate (7) graduate (6) further education (5) A' level (4) GCSE (3) No formal qualification (2) Other (1). A median split of the maternal education data created a categorical variable of mothers who had been educated to post graduate level (2) and a category who had been predominantly educated to graduate level (1). Both categories index predominantly high levels of education because the majority of our sample (84.14%) consisted of graduates and post-graduate mother as shown in Table 1.

Regression analyses revealed neither a main effect of household income on positive or negative behavioural reactivity at 6-months or 12-months or an interaction effect of household income and maternal education in predicting positive and negative behavioural reactivity at 6-months or 12-months (see Table 1. in supplementary materials). Therefore, household income was left out of the final model. Henceforth, the variable indexing maternal education will be referred to as 'SES'.

Inter-rater reliability. 10% of video records were double coded and inter-rater reliability was achieved: high absolute agreement for negative affect (ICC .98), and good agreement for positive affect (ICC .76) (Koo & Li, 2016). Following initial achievement of reliability, interrater reliability was assessed for every tenth recording to ensure a high level of agreement was maintained. In addition, coding meetings were held biweekly where the team viewed and coded a video jointly to avoid coder drift.

6.2.5 Data preparation and reduction

The raw scores of each behavioural response (positive facial, negative facial, positive vocal, negative vocal, and motor activity) obtained at every 1 sec of a task produced time-series data for each. Within these time series, there was a baseline followed by three trial and after trial/resume play pairs (see Figs 1b and 1c). To generate mean summary scores for each emotional response (e.g., vocal affect) in a task (e.g., toy retraction), each behavioural response was within-person averaged over three trial phases, each lasting 15. After obtaining summary scores of behavioural observations, normality statistics and the presence of outliers in these scores were explored by inspecting boxplots, skewness, and kurtosis values. The observed behaviours were found to show high skewness and kurtosis (>2; Field, 2009). To treat non-normality in the data, we first applied transformation methods such as log, square root, and Box-Cox. Nevertheless, none of these techniques were effective in transforming the variables to a normal distribution or reducing

their skewness and kurtosis values. This was possibly on the grounds that there was zero inflation in the appearance of some variables. Therefore, non-parametric tests such as Spearman rho were implemented wherever possible.

When the task ended early, due to incorrect timing by the experimenter or the infant being too distressed to carry on, intervals of observed emotion reactivity shorter than 15 s occurred. These missing observations within the same phase were replaced via linear interpolation using the Matlab function 'fillmissing'. The percentage of data that were interpolated by tasks were as follows: 2.20% of peekaboo task at 6-months, 1.14% of peekaboo task at 12-months, 0.10% of toy retraction task at 6-months, 0.34% of toy retraction task at 12-months. Behavioural data phases that were longer than 15s were trimmed so that second-by-second time series data obtained across participants would be equal in length. Participants who had data for at least Baseline and Trial 1 phases were included in analyses, and those phases that were entirely missing were imputed with the mean substitute of the associate condition to preserve the conditional effects, e.g., missing Trial 3 was replaced via mean of Trial 2 whereas free-play₃ was replaced via mean of free-play₂.

Missing data analysis. Due to missing data, the number of participants who had usable behavioural data differed across tasks and data collection points. For categorical variables including gender, ethnicity, maternal education, and disposable income, chi-square tests were used to investigate whether there are any differences between infants who did and did not do the toy retraction task at each age. None of these was significant for missingness at both ages ($p > 0.05$). For continuous variables that are normally distributed (age in days, birth weight), independent t-tests were utilised. Again, there were no significant differences at both ages ($p > 0.05$). Little's Missing Completely at Random (MCAR) test (Little, 1988) was used to analyse missing data patterns for the key continuous measures (observed positive and negative reactivity at 6-months and 12-months). Little MCAR test results revealed that data was missing completely at random for the toy retraction task ($X^2(95) = 111.38, p .120$) and the peekaboo task ($X^2(15) = 15.67, p .404$).

6.2.6 Statistical Analysis

Significant positive correlation coefficients were found between facial and vocal affect for toy retraction at 6-months $\rho = .8, p < .001$ and 12-months $\rho = .8, p < .001$ and facial and vocal affect for peekaboo at 6-months $\rho = .8, p < .001$ and 12-months $\rho = .4, p = .02$. Therefore, facial, and vocal affect were collapsed to create a composite score for

positive affect to peekaboo at 6-months and 12-months and negative affect to toy-retraction at 6-months and 12-months. At 6-months, motor activity was found to correlate with this composite for both toy retraction $\rho=.3$, $p=.022$ and peekaboo $\rho=.4$, $p=.002$. As motor activity is part of the behavioural activation system (BAS) (Gray, 1987), which our positive and negative reactivity scores indicate, it was therefore included in the composite scores indexing negative and positive reactivity at 6-months. Henceforth these variables will be referred to as 'positive reactivity' and 'negative reactivity'. At 12-months, motor activity ceased correlating positively with the facial and vocal affect composite (toy retraction $p=.196$ peekaboo $p=.525$) so was left out of the positive and negative reactivity scores at 12-months. Altering the measurement in this way at the two time points did not alter the findings. Positive and negative reactivity correlate at 6-months without the inclusion of motor activity in the variable $\rho = .31$ $p .03$. Positive and negative reactivity do not correlate at 12-months with the inclusion of motor activity $\rho = .21$ $p.152$.

We investigated the unadjusted bivariate associations between mean-level trial positive reactivity and negative reactivity for the two different tasks at 6-months and 12-months using the non-parametric Spearman's Rho test. Visual inspection of scatter plots revealed groupings of high and low reactors to positive and negative tasks. Therefore, X^2 tests of independence were performed to investigate the grouping of observed variables indexing high positive and negative affect in response to the two tasks at 6-months and 12-months to ascertain the extent to which, and how the observed data differed from the null hypothesis of the observations being independent.

For the second question of this study, four moderation analyses were conducted using the PROCESS macro for SPSS to see whether 6-months negative reactivity x SES and 6-months positive reactivity x SES predicted 12-months negative reactivity and/or 12-months positive reactivity. The output provides the main effects of predictor and moderator variables and their interaction effect on the outcome variables. In the case of a significant interaction, potential presence of diathesis or vantage sensitivity to the effects of SES was evaluated by inspecting the form of the interaction plot. An interaction suggestive of vantage sensitivity would see high values of the moderator (SES) predicting *better* outcomes anywhere beyond the lowest levels of the predictor whereas diathesis stress would see low values of the moderator (SES) predicting *worse* outcomes anywhere beyond the lowest levels of the predictor. Simple slopes were analysed to estimate the values of the moderator at which the gradient of the slope departed significantly from zero indicating a significant association between the predictor and outcome variables.

6.3 Results

In Analysis 1 we examine how the relationship between positive reactivity and negative reactivity in response to peekaboo and toy retraction changes from 6-months to 12-months. In Analysis 2 we examine the factors that moderate the change in reactivity to the same tasks between 6-months and 12-months.

6.3.1 Preliminary analyses – descriptive

To examine whether the tasks were performing as intended (i.e., whether the toy retraction task elicited primarily negative reactivity, and the peekaboo task positive reactivity), the mean positive and negative reactivity scores were plotted by task. Only peekaboo at 6-months evoked slightly more of the opposite valence of reactivity (negative) than the intended valence (positive) at a group level. All other tasks showed significant differences in the expected direction (more positive reactivity on the peekaboo task, more negative reactivity on the toy retraction task) (See fig. 6.2c). Furthermore, bivariate correlations show that infants who display more positive reactivity on a given task display less negative reactivity on the same task (Fig 6.3) (toy-retraction 6-months: $\rho = -.345$, $p = .004$; peekaboo 6-months: $\rho = -.180$, $p = .183$; toy retraction 12-months: $\rho = -.333$, $p = .008$; peekaboo 12-months $\rho = -.410$, $p = .024$).

Time series plots of the grand average of induced positive and negative reactivity confirmed that the tasks were working as intended insofar as higher facial and vocal affect and more motor activity were observed during the 15s trial phases than the interval phases in both tasks (Fig 6.2 a, b).

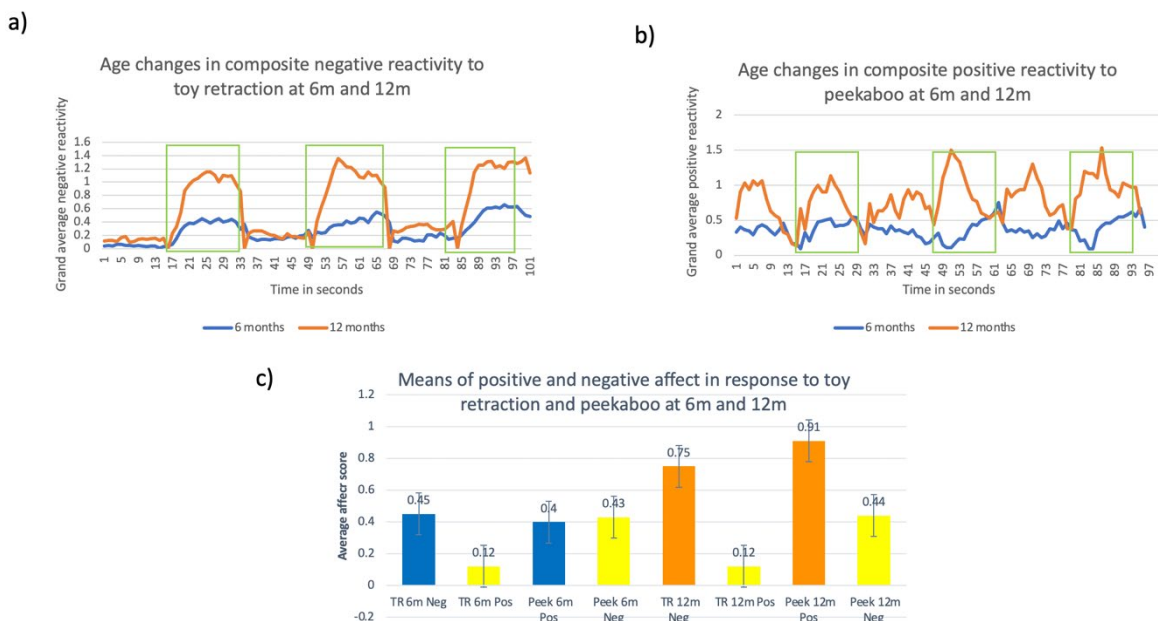


Figure 6. 2 a) time series plot of grand average negative affect during all 90 seconds of the toy-retraction task b) time series plot of grand average positive affect during all 90 seconds of the peekaboo task windows in green show timing of the 15s trial c) group means of positive and negative affect in response to toy retraction and peekaboo at 6-months and 12-months.

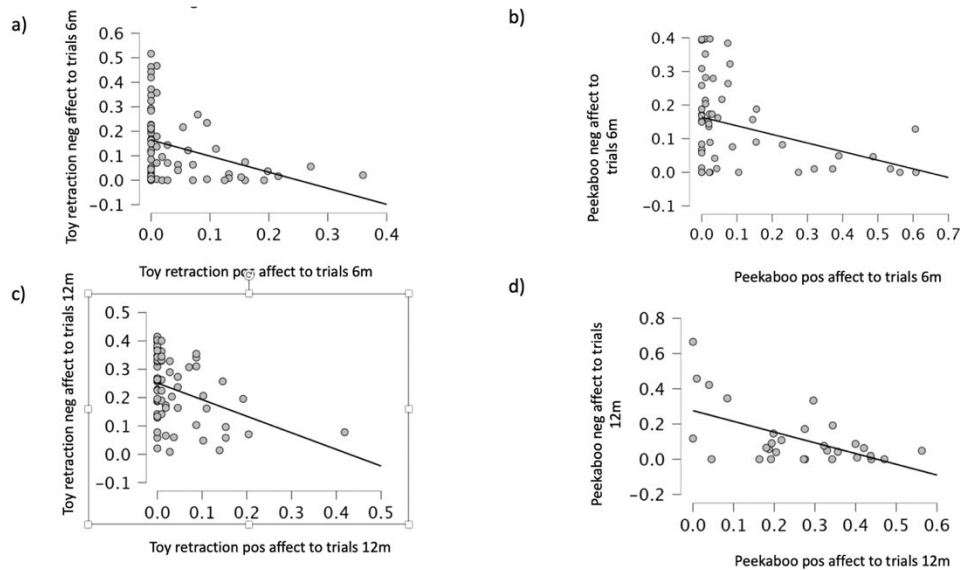


Figure 6. 3 Scatterplot showing the relationship between positive and negative affect evoked: a) toy retraction at 6-months; b) peekaboo at 6-months; c) toy retraction at 12-months; d) peekaboo at 12-months.

6.3.2 Analysis 1

At 6-months, a significant bivariate correlation was observed between positive reactivity to peekaboo and negative reactivity to toy-retraction ($\rho = .3, p = .045$) (see Fig 6.4a). To further investigate the observed association, we performed a chi squared test for independence to ascertain the extent to which, and how the observed data differed from the null hypothesis of the observations being independent. We performed a median split on the data to create four categorical variables: high positive reactivity and low positive reactivity; high negative reactivity and low negative reactivity for the 6-months and 12-months data. All expected cell frequencies were greater than 5. There was a statistically significant association between 6-months induced positive reactivity and 6-months induced negative reactivity: $X^2(1) = 6.6, p = .015$ showing that instead of there being an even spread of patterns of response, the observed values for each cell showed that infants in the high induced reactivity category were more likely to be so for both negative and positive reactivity than only positive or negative reactivity (Fig 6.4b).

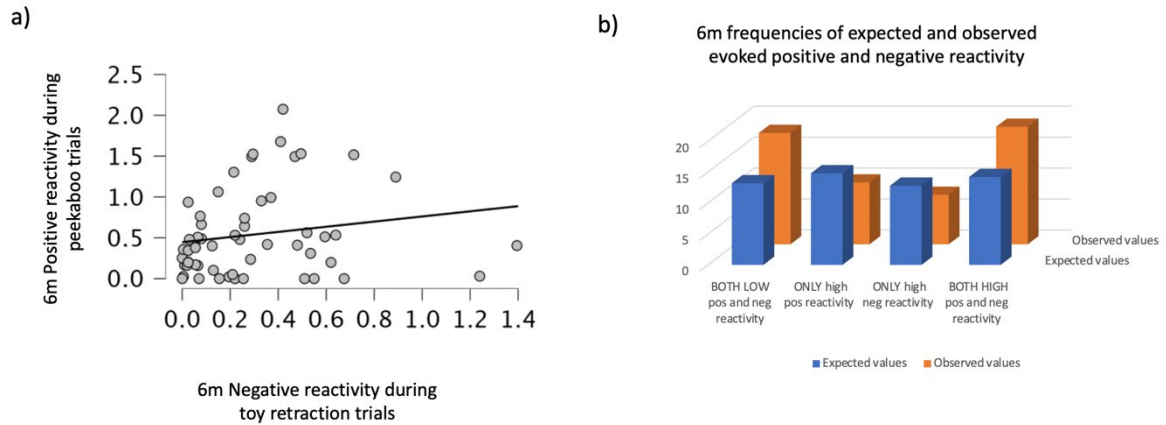


Figure 6. 4 a) scatterplot of variables indexing positive reactivity to peekaboo and negative reactivity to toy retraction at 6-months. (b) bar chart of the observed and expected values of positive and negative reactivity from the chi-squared test.

Figure 6.5 shows the results of the same analyses performed on the 12-months data. No bivariate association was found between positive reactivity in response to peekaboo and negative reactivity in response to toy-retraction $N_{29} \rho = -.003, p = .988$ (Fig 6.5a). There was no statistically significant association between 12-months induced positive reactivity and 12-months induced negative reactivity: $X^2(1) = 0.85, p = .36$. Results of the chi-squared test were also not significant (Fig 6.5b).

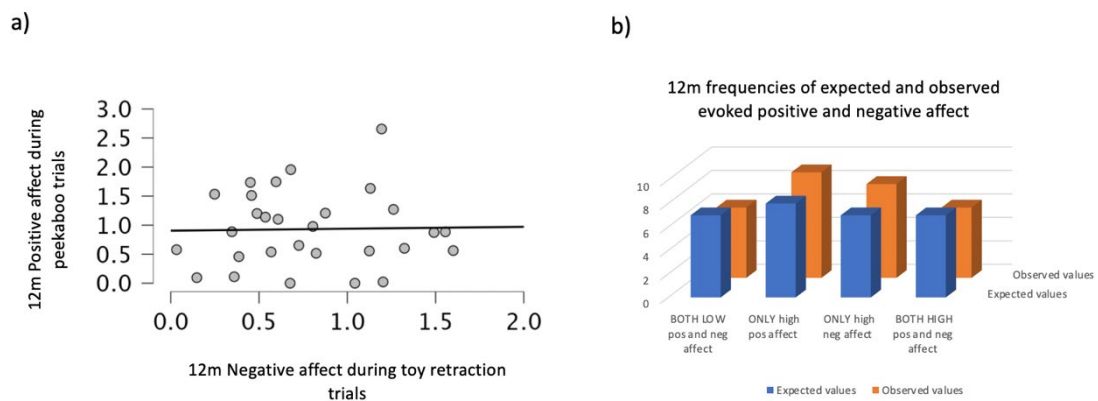


Figure 6. 5 a) scatterplot of variables indexing positive affect to peekaboo and negative affect to toy retraction at 12-months. (b) bar chart of the observed and expected values from the chi-squared test.

6.3.3 Analysis 2

Four moderation analyses using PROCESS (Hayes, 2012) in SPSS examined whether developmental context (SES), moderated the relationship between positive and negative reactivity at 6-months and 12-months. The results of the four regression interactions are presented in Table 6.2. Because these were planned comparisons, there was no correction made for multiple comparisons (Pagano, 2012). Of the four, only the interaction between negative reactivity at 6-months and SES (indexed using maternal education) in predicting positive reactivity at 12-months was significant.

Table 6. 2 Summary of the interactions between variables predicting positive and negative reactivity at 12-months

Interactions	Predicting	B	SE	p
6m Negative reactivity x maternal education	12m Positive reactivity	1.37	.69	.039
6m Positive reactivity x maternal education	12m Positive reactivity	.883	1.39	.522
6m Negative reactivity x maternal education	12m Negative reactivity	-.029	1.86	.987
6m Positive reactivity x maternal education	12m Negative reactivity	.915	.838	.274

The model containing negative reactivity at 6-months as the predictor and positive reactivity at 12-months as the dependent variable and level of SES as the moderator variable was found to be statistically significant $p = .0131$. The chi squared likelihood ratio test of unconditional interaction was $X^2 4.34$ (df 1) $p = .0370$. Analysis of simple slopes for this interaction revealed that there was no conditional effect of negative reactivity at 6-months on positive reactivity at 12-months in infants of lower SES households: $b = 0.3$, $t(4) = 1.09$, $p = .272$. However, for infants of higher SES households the slope for the effect of approach at 6-months on positive approach at 12-months was $b=1$, $t(4) = 2.0$, $p = .047$. As the moderator variable in this case was categorical, a Johnson Neyman Region of Significance (RoS) on moderator analysis was not applicable. Figure 6.6 shows that the basic assumptions for testing the presence of vantage sensitivity are met: an interaction with the regression lines crossing at the low end of the distribution of negative reactivity at 6-months and the slope of the relationship between negative reactivity at 6-months and positive reactivity at 12-months for infants of lower SES households being closer to zero. Thus, as compared to lower levels of SES, at higher levels of SES infants were reported to express higher levels of positive reactivity at 12-months when negative reactivity at 6-

months was high. On the other hand, at low levels of negative reactivity the slopes for high and low levels of SES did not differ significantly. Thus, the simple slopes analysis provided support for this observation of vantage sensitivity, revealing that negative reactivity at 6-months only predicted increases in positive reactivity at 12-months at higher levels of SES.

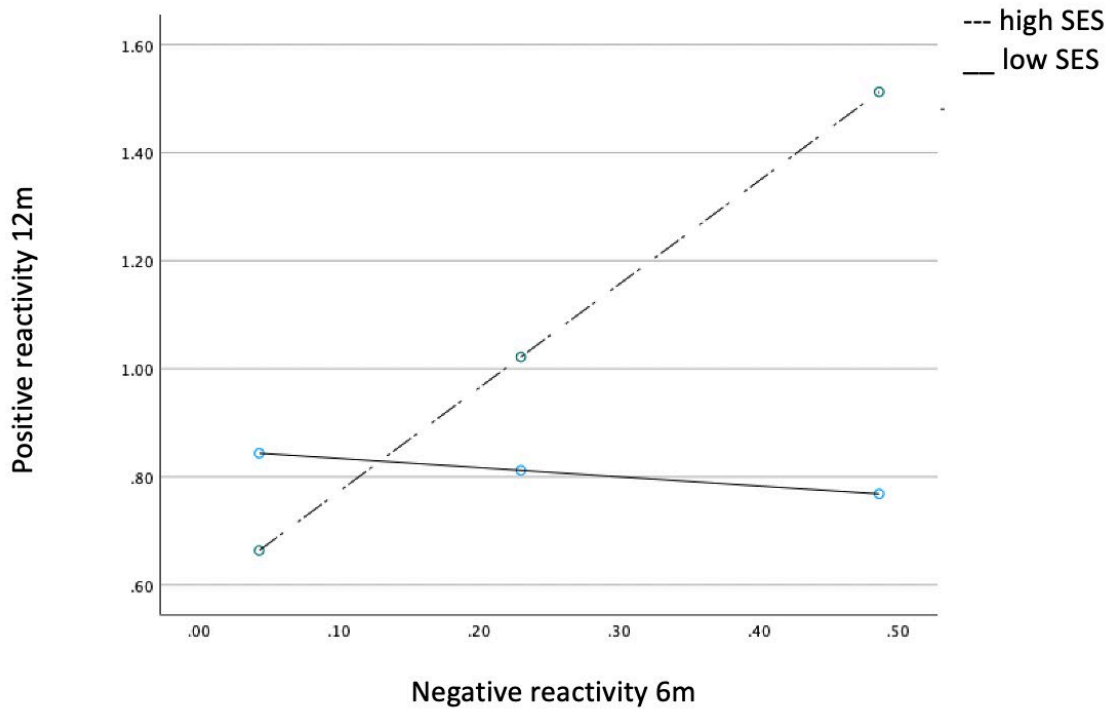


Figure 6. 6. Plot of the interaction between 6-months negative reactivity and maternal SES predicting 12-months positive reactivity.

6.4. Discussion

This study test two hypotheses. The first was that infants who display more negative affect during a task designed to elicit negative emotions would also display more positive affect during a task designed to evoke positive emotions. We predicted that an association would be observed at 6-months, but that this association would disappear by 12-months. The second hypothesis was that SES, indexed by level of maternal education, would moderate the relationship between ES indexed by behavioural reactivity at 6-months and behavioural reactivity at 12-months.

Power analyses (conducted using G*Power 3.1) (Faul et al., 2007) revealed In addition, for the chi-squared analyses G*Power calculations revealed that to detect a small effect size of 0.1 according to Cohen’s omega, with 1 degree of freedom and an 80 percent

chance of correctly rejecting the null hypothesis of no difference between the expected and observed proportions of infants showing negative and positive reactivity, 88 participants were needed. However, due to the length of the testing battery and the nature of infant research (see below) we had missing data in our analyses.

Our results showed support for hypothesis one. Overall, more positive reactivity was elicited during the peekaboo task and more negative reactivity was elicited during the toy retraction task (Fig 2c). Within a task, positive and negative reactivity was negatively correlated (i.e., children who showed more positive reactivity during a particular task tended to show less negative reactivity during that task) (Fig 3). Between tasks, however, a positive correlation was observed, such that 6-months children who showed more positive reactivity to the peekaboo task showed more negative reactivity to the toy retraction task at 6-months (Fig 4a). Chi-squared analyses performed on categorical data confirmed that the variation in frequencies of positive reactors can be explained to an extent by being a negative reactor (Fig 4b). However, at 12-months, there was no intra-individual association between positive and negative reactivity (Fig 5a). A Chi squared analysis of the categorical data of high and low positive reactivity in response to the 12-months peekaboo task and high and low negative reactivity in response to the 12-months toy-retraction task revealed no significance differences from chance (Fig 5b).

Our second hypothesis was that environmental factors would associate with behavioural reactivity at 6-months to predict either positive or negative reactivity at 12-months. Moderation analyses revealed that more negative reactivity at 6-months predicted more positive reactivity at 12-months at higher levels of SES (Table 3, Fig 6). Infants high in negative reactivity at 6-months showed more positive reactivity at 12-months; this association was stronger for higher SES households. No similar relationships were observed for predicting 12-months negative reactivity. We shall discuss these findings in turn.

Beyond the general point that neural and behavioural responses generally become more fractionated and differentiated over time (Johnson & Haan, 2023), our first finding was also not unexpected given previous findings into how emotional reactions also become more fractionated and differentiated over time (Rothbart, 1989). From birth, infants typically express signs of heightened arousal and distress through cries and facial expressions. It is thought that initially, infants mostly express these communicative displays automatically - that is, directly as a function of autonomic arousal and physiological responses to their environment (Craig, 1992; Zeskind, 2013). This predicts that, early on,

physiological states of arousal and facial and vocal affective displays should typically align (Zeskind, 2013; Sacrey et al., 2021; Rudd et al., 2022; Fox, 1989; Stifter & Jain, 1996). Over time, infants develop the ability to use displays flexibly and intentionally (Feldman, 2007a; Matthews, 2020), according to specific display rules that differ between settings. For example, a child might increasingly recognise that displaying negative affect in a given situation (e.g., toy removal) is more likely to get them what they want (the toy being returned).

Exactly which behavioural responses index ES at different periods developmentally needs further investigation. Behavioural reactivity has been found to associate with ES in infancy (Cassidy et al., 2011; Stupica et al., 2011). However, as regulatory capacities increase, negative affect may decrease. This could be evidence of increasing vantage sensitivity due to positive exposures. There is some evidence that biomarkers related to increased vantage sensitivity – such as high RSA, an index of autonomic flexibility - also predict their own increased expression during early developmental periods, in contexts of positive exposures. The association between high RSA and well-being reflects a reciprocal causality, an “upward spiral” in which high RSA facilitates capitalizing on social and emotional opportunities and the resulting opportunistic gains, in turn, lead to higher RSA. This suggests that an individual’s propensity for vantage sensitivity may increase over time, subject to conditions (Kok & Fredrickson, 2010).

The second aspect of our results is that SES (here measured using maternal education) moderated the expression of positive reactivity but not negative reactivity. As well as being one of the strongest indicators of SES in studies of child development (Hoff et al., 2012), maternal education correlates negatively with maternal intrusiveness and positively with maternal sensitivity (Diaz et al., 2019). A body of research has demonstrated that mothers who are more sensitive have infants who show more attention seeking behaviours (e.g., looking to her, smiling, reaching) and display greater positive affect, and less negative affect, across a variety of contexts (Kogan & Carter, 1996; Mills-Koonce et al., 2007; Perry et al., 2014).

Our results support vantage sensitivity as opposed to diathesis stress, insofar as developmentally, displays of more positive reactivity in the first year of life can be described as largely protective (e.g., facilitating the development of self-regulation and school readiness (Gartstein et al., 2009, 2016)).

One factor that limits the generalisability of our results is that the demographic range of our participants was relatively narrow. However, our results contrast the much

larger body of research looking only at the associations between developmental outcomes and disadvantaged developmental environments as evidence for hypotheses based on diathesis-stress. Nonetheless, an important goal for future work will be to recruit mothers with more varied education levels, as both of these have consistently been associated with maternal sensitivity in other work (Mills-Koonce et al., 2009), NICHD Early Child Care Research Network, 2004). Future studies might include a more proximal measure of maternal sensitivity to test this theory. Furthermore, behavioural measures such as the Lab-TAB are not without limitations (Hane & Fox, 2006). Although the Lab-TAB paradigms are designed to elicit targeted emotions, it cannot be determined with any certainty that infant responses are a direct function of the Lab-TAB stimuli. For example, infants may have manifested negative affect that was not anger in response to limits, but distress due instead to carry-over effects from other Lab-TAB paradigms or to the broader testing situation, including restriction in a highchair.

It bears noting that ultimately, understanding the extent to which positive and negative reactivity correlate over development will involve considering the neural structures and systems that generate emotional behaviours involved in positive and negative affect, reward, and loss. Should the plasticity of these systems across individuals be yoked? Future research could consider such mechanisms.

Nonetheless, this study has contributed to understanding the developmental trajectory of ES as indexed by behavioural reactivity to positive and negative stimuli cross-sectionally - whether individuals that are more responsive to negative exposures are also more responsive to positive ones - and longitudinally. This is required to distinguish vantage sensitivity from diathesis stress, with the former predicting disproportionate responsiveness to only positive conditions and the latter predicting disproportionate responsiveness to only negative conditions. Investigating the early development of individual differences in sensitivity is necessary to determine why some people are more responsive to both positive and negative conditions (i.e., differentially susceptible), to just supportive conditions (i.e., vantage sensitivity) or just to adversity (i.e., diathesis stress).

Chapter 7. The moderating effect of RSA on positive developmental environments and developmental outcomes

Abstract

Sociodemographic factors are associated with infant regulation and sustained attention, but whether infants with high levels of environmental sensitivity (ES) are better able to exploit the advantages conferred by a high-quality home environment remains uncertain.

This study pertained to the moderating role of ES (baseline respiratory sinus arrhythmia (RSA)) in the relationship between family environment (sociodemographic factors indexing security and protection -as opposed to risk) and sustained attention (measured using an eye tracking paradigm and duration of orienting (DofO) Infant Behaviour Questionnaire (IBQ) subscale) and regulation (measured using the IBQ composite of regulation)

We also tested the extent to which such interactions corresponded to the theoretical models of person-environment interaction: vantage sensitivity or differential susceptibility. The sample included 74 children (53% male) at advantage due to the socioeconomic status and wellbeing of their parents. At 6-months, baseline RSA was measured while the infant was calm. Socioeconomic status (SES) and maternal wellbeing were extracted from parent responses to questionnaires. At 12-months, infant self-regulation was extracted from IBQ parent responses, and sustained attention was both assessed directly with the infants and reported by parents at 12-months ($M = 54.45$ weeks; $SD = 0.75$).

Hierarchical multiple linear regressions showed very limited support for differential susceptibility but not vantage sensitivity. At low (not high) levels of RSA, low maternal anxiety predicted better IBQ REG, but was marginally non-significant. At low (not high) levels of RSA, low maternal anxiety predicted better DofO, however, at high baseline RSA, increases in maternal anxiety predicted better DofO. This contrastive interaction is not evidence of differential susceptibility. Finally, at low baseline RSA higher maternal education predicted worse infant performance on an eye-tracking measure of sustained attention.

7.1 Introduction

Individuals with an intrinsic predisposition to being more affected by the quality of their psychosocial environment - in terms of how that environment predicts developmental outcomes - should do so for better or for worse. Environmental Sensitivity (ES) pertains to endogenous factors indexing heightened sensitivity to environmental effects. ES has been measured at multiple levels of analysis from genetic and autonomic to differences in temperament and behavioural reactivity. Measures of reactivity or sensitivity to the environment are typically thought to index ES if they moderate the effect of a predictor variable (X) on an outcome variable (Y). When the effect of X (e.g., household environment) on Y (e.g., cognitive development) is different as a function of Z (e.g., autonomic activity), then moderation has taken place. Theoretically, the effect of the environment on outcomes is predicted to be greater for those with high ES than those with low ES. It is proposed that the huge variation in outcomes of children exposed to stressful developmental environments can be accounted for by large individual differences in ES (W. Boyce et al., 1995).

Initially, the predominance of studies looking at the effects of high-risk or disadvantaged childhood environments added support to the diathesis-stress hypothesis that ES constituted a heightened vulnerability to the adverse effects of such environments, with less sensitive children being more resilient in the face of adversity. However, more recently, ES researchers have drawn attention to the fact that many such studies did not look at the effect of lack of adversity or presence of advantage on the developmental outcomes of highly environmentally sensitive individuals (Hartman & Belsky, 2018b). The observation that the same individual characteristics indexing ES (e.g., infant temperament, and autonomic activity) predicted not only increased vulnerability to negative environmental features but also increased likelihood of benefitting from positive features of the environment (Pluess et al., 2015; Pluess & Belsky, 2013), suggested a general propensity for environmental sensitivity leading to worse outcomes in adverse circumstances, but better outcomes in favourable circumstances. This provides an explanation for the conservation of genes associated with maladaptive outcomes when experiencing adversity: the same genes may also associate with improved reproductive fitness, with the liability conferred under negative conditions outweighed by advantages

conferred under positive conditions (Belsky et al., 2009; Belsky & Pluess, 2013; Pluess, 2017; Uher, 2009).

Thus, the differential susceptibility hypothesis proposes that individuals high in ES are equally susceptible to both positive and negative environmental influences. Therefore, those who are rendered more vulnerable to stressors because of heightened ES, as proposed by diathesis stress models (Monroe & Simons, 1991), may also be better able to exploit the advantages, and thrive more, in a nurturing environment (Belsky & Pluess, 2009). Furthermore, studies have found that a large proportion of such variance in sensitivity is explained by environmental factors (Assary et al., 2017). Not only are those with higher ES more likely to be affected by the environment in terms of outcomes, but also, the environment may calibrate that sensitivity. Evidence supports that those with a predisposition for ES may be liable to be moulded by the quality of their developmental environment such that their sensitivity is adaptively calibrated to ensure the best outcome within that environment (W. Boyce et al., 2005; Weyn et al., 2022). However, I am unaware of evidence showing that such proposed adaptive differences become qualitative differences - determining the kind of environmental experience to which an individual becomes most sensitive. That is, an initial “neutral” genetically based propensity for sensitivity could develop into a biased sensitivity towards contextual adversity (such as increased vigilance) or contextual support (more receptive to environmental input) depending on the specific environmental conditions encountered in early development. If this were the case, it would undermine the notion of bivalency inherent to differential susceptibility theory. However, if, as evidence suggests, prolonged exposure to adversity can cause hypersensitivity of the stress response system (Beauchaine & Thayer, 2015; Ulrich-Lai et al., 2009), sympathetic hyper-reactivity (Uchino et al., 1996) and elevated HPA activation (Cacioppo, Ernst, et al., 2000), it is theoretically conceivable that exposure to positive experience may heighten sensitivity to positive stimuli. There is evidence of the physiological response of 12-months infants, with an autonomic marker of ES, differentiating between positive, attention-eliciting stimuli and negative, aversive stimuli in terms of their physiological response (S. V. Wass et al., 2018). However, the developmental context of these infants was not measured.

Pertaining to this idea, variations in individual responses to exclusively positive experiences, driven by innate or endogenous factors is proposed in the theory of Vantage Sensitivity (Pluess & Belsky, 2013). Vantage is an abbreviation for advantage, which refers to “a position, condition, or opportunity that is likely to provide superiority or an

advantage” (Pluess & Belsky, 2013). These endogenous factors that heighten people’s receptiveness to supportive experiences amplify the advantages of such experiences (Pluess & Belsky, 2013) leading to better developmental outcomes.

There is a strong link between high quality developmental environments as measured by socioeconomic status and parental wellbeing and better outcomes in terms of physical (Adler & Stewart, 2010) and mental health (McLaughlin, Costello, et al., 2012), as well as intelligence and academic achievement (Girault et al., 2019; Montroy et al., 2016; von Stumm & Plomin, 2015). Vantage Sensitivity predicts that some individuals high in ES are particularly sensitive to positive caregiving experiences in so much as they are better able to benefit from the advantages conferred by sensitive and attentive parenting than those who are less sensitive (Pluess & Belsky, 2013).

Although consensus has still not been achieved on exactly which responses reflect ES at which ages, respiratory sinus arrhythmia (RSA) has received considerable attention. RSA is heart rate variability in synchrony with respiration, by which the R-R interval on an ECG is shortened during inspiration and prolonged during expiration. RSA indexes parasympathetic nervous system (PNS) control – the branch of the autonomic nervous system (ANS) implicated in slowing heart and breathing rates, lowering blood pressure, and promoting digestion (Porges, 2001; Ulrich-Lai et al., 2009). High baseline RSA represents greater vagal control of the heart, which enables the individual to maintain homeostasis in the face of situational change by allowing attention to shift from internal processes to external demands, facilitating the use of adaptive behavioural and emotional regulatory strategies (S. D. Calkins et al., 2013). In contrast, low baseline RSA indicates reduced vagal control that may interfere with the ability to regulate behavioural and emotional state during environmental challenge resulting in hyper-arousal (Porges, 2007).

Although individual differences in baseline RSA have been shown to moderate the effects of the caregiving environment on children’s adaptation (Bagner et al., 2012; Conradt et al., 2013; Eisenberg et al., 2012; Hastings et al., 2008), the direction of this moderating effect has not been consistent across studies. Children with low baseline RSA are characterized by low attentional and emotional regulatory skills, making them more strongly dependent on and affected by external regulation provided by their caregivers (Gueron-Sela et al., 2017a; Hastings et al., 2008). Low RSA has been identified as a vulnerability factor that exacerbates the link between exposure to disruptive parental experiences and children’s internalizing problems (El-Sheikh et al., 2013; Wetter & El-Sheikh, 2012a). However, children with low baseline RSA also showed greater

improvements in disruptive behaviour following a parent–child interaction therapy program than children with high baseline RSA (Bagner et al., 2012).

However, such associations may be less straightforward during infancy. For example, studies have demonstrated that infants with high (rather than low) baseline RSA were more susceptible to specific caregiving environments (Conradt et al., 2013; Eisenberg et al., 2012; Holochwest et al., 2014a). It may be the case that infants with high RSA are more attuned and alert to their environments and are thus more strongly affected by both negative and positive caregiving experiences (Conradt et al., 2013). Another view is that infants with high baseline RSA may have an early propensity for heightened behavioural reactivity, which under supportive environments may be canalized toward positive behavioural adaptation, but under negative environments may lead to the consolidation of maladaptive coping strategies that portend behaviour problems later in development (Conradt et al., 2013).

Despite mixed findings and potential differences in autonomic influence across development, we view high baseline RSA as an index of infants' ES and awareness of their environment (Marcovitch, Leigh, Calkins, Leerks, O'Brien, et al., 2010) and thus a potential susceptibility marker to parenting in predicting developmental outcomes. In terms of desirable developmental outcomes, increasingly, research demonstrates that self-regulation predicts healthy child development (Blair and Raver, 2016, Ursache et al., 2012). In addition, self-regulation was found to moderate the negative effects of the environment in predicting poor school readiness in a sample of at-risk children (Gobeil-Bourdeau et al., 2022).

Regulation is one component of the construct of temperament, which includes both the extent to which individuals respond to their environment (i.e., reactivity) and their ability to modulate and control these responses (i.e., regulation; (Rothbart et al., 2008)). Self-regulation describes the multiple ways in which social, emotional, behavioural, cognitive, and physiological aspects of the person are organized and influence a response to a given stimulus (Posner & Rothbart, 1998; Rothbart et al., 2008).

While the capacity for self-regulation associates with psychosocial health, deficits in regulation are related to the development and expression of psychopathology (Beeghly & Tronick, 2011). Consistent with this, studies show that high behavioural reactivity and poor regulation in infancy are linked to later distress, defiance, and avoidance (S. Calkins & Degnan, 2006). In addition, behaviour problems and externalizing problems indicated by hyperactivity or negative emotionality are said to be linked to early regulatory problems

(Hemmi et al., 2011; Wolke et al., 2002). In a recent meta-analysis of 23 studies, low self-regulation in childhood was found to predict increased rates of psychopathology (Kostyrka-Allchorne et al., 2020)

Behavioural and emotional regulation can be defined as the intrinsic and extrinsic processes underlying the management of emotional arousal and adaptive behavioural responses (S. D. Calkins, 1994b; Gross, 2013; Thompson, 1994b). The origin of this model of self-regulation is found in the theoretical model of temperament proposed by Rothbart, Posner, and collaborators (Derryberry & Rothbart, 1997; Posner & Rothbart, 2000). Broadly, this model conceptualizes self-regulation as the balance and interplay between bottom-up, nonconscious, automatic reactivity and conscious, effortful, and reflective top-down regulation (Blair & Raver, 2016; Rothman et al., 2011). Research supports a neurobiological model of this relation suggesting that self-regulation relies on a bidirectional relationship between the limbic system and the prefrontal cortex (PFC) in which the top-down activity of the PFC regulates the bottom-up reactivity in the limbic system (Arnsten, 2009).

Notably, both the PFC and limbic system are susceptible to environmental influence, (Hensch & Fagiolini, 2005) 2005). Variability within the child's environmental context can bias the PFC–limbic network to be more or less reactive or reflective, thereby supporting or undermining self-regulation capacities (Blair, 2002a). Moreover, the protracted nature of PFC development highlights the importance of early life experience in promoting the development of adaptive top-down control over bottom-up reactivity. Therefore, whereas temperament models typically highlighted reactivity and regulation to be trait-like and relatively fixed, more recent developmental and neuroscience research suggests that processes related to self-regulation and reactivity are sensitive to environmental influences (Diamond, 2013). Evidence for the plasticity of self-regulation indicates that its development, especially early in life, is influenced by the context of the home and family environment and the quality of early parenting (Blair, 2010; Raver, 2004; Zeytinoglu et al., 2017). Within the theoretical framework of ES, it would follow that infants high in ES would be the most susceptible to environmental influences on the development of self-regulation.

As such, this study wanted to test the hypothesis that infants high in ES, developing in well-resourced, high-quality environments would be better able to exploit the advantages conferred by such an environment as measured by better self-regulation abilities at 12-months. However, as self-regulation it thought to develop at the end of the first year

(Gartstein & Rothbart, 2003), we wanted to look at the precursors of self-regulation that are present during the first year. During early infancy, the construct of self-regulation includes regulating through orienting towards visual, auditory, and tactile sources of comfort (Gartstein & Rothbart, 2003). Over development, the orienting response becomes more prolonged, until eventually, it is influenced by the pre-frontally mediated control networks and develops into selective sustained attention (H. A. Ruff & Rothbart, 1996). Research and theory suggest that lower-order cognitive abilities, such as attention, act as early precursors for more advanced, higher-order self-regulation processes (Posner & Rothbart, 2007; Ursache et al., 2013). For this reason, sustained attention has been cited as an antecedent to self-regulation (Brandes-Aitken et al., 2019).

Attention, like self-regulation, is a multidimensional construct. Sustained attention emerges within the first year of life and continues to develop across childhood (Amso & Scerif, 2015; Reynolds & Romano, 2016; Rose et al., 2001; H. A. Ruff & Lawson, 1990). An infant's ability to sustain attention is a core component of self-regulation and, thus, is critical to development (Casey & Richards, 1988; H. A. Ruff, 1986; Swingler et al., 2015). For instance, infants focus on and sustain their attention to stimuli in their environment to support their volitional control of behaviour (Rothbart & Rueda, 2006; H. A. Ruff & Capozzoli, 2003a). Specifically, by practising sustained attention, infants are better able to resolve internal or external conflicts and guide adaptive responses and decisions (Rothbart et al., 2011), thereby setting the stage for self-regulation.

Individual differences in early orienting and sustained attention measured by look-duration to a stimulus have been shown to predict later cognitive and behavioural functioning (Colombo & Mitchell, 2009; van de Weijer-Bergsma et al., 2008). Likewise, selective sustained attention in the first year has been found to predict parental ratings of self-regulation at age two. (Johansson et al., 2015) and elements of executive function - inhibitory control and set shifting - at 18 months of age (Frick et al., 2017). Aspects of the developmental environment that have been linked to infant regulation and sustained attention are maternal SES and maternal wellbeing infants (Richter & Reck, 2013).

One particularly salient aspect of children's environments that may affect developing self-regulation is their mothers' education levels (Miech et al., 2001). Mother education often serves as a rough, yet important, proxy of family socioeconomic status and resources (Bradley & Corwyn, 2003). Low maternal education levels have been linked to lower socioeconomic resources and higher stress levels that, over time, can affect children's

developing neuroendocrine processes (e.g., such as cortisol levels). These processes are theorized to directly shape developing self-regulatory response patterns (Blair & Cybele Raver, 2015). Maternal education also correlated negatively with maternal intrusiveness and positively with maternal sensitivity (Diaz et al., 2019) as well as mothers' warmth, responsiveness, use of rich language inputs, and ability to maintain their children's attention (Guttentag et al., 2006). These are all factors that predict individual differences in children's self-regulation levels (Grolnick et al., 2002.). Thus, we included maternal education levels as a predictor of infants' developing self-regulation patterns.

Other sociodemographic influences on infant development are number of adverse childhood experiences to which the parent was exposed and levels of anxiety. Adverse childhood experiences (ACEs) are defined as a set of exposures to abuse, neglect, and household dysfunction prior to 18 years of age. Research suggests that children of mothers who have been exposed to ACEs are at increased risk of poor health and developmental outcomes (Folger et al., 2018; Gavin et al., 2012) including social, emotional, and behavioural problems, as well as increased likelihood of parent-child relationship difficulties (Berthelot et al., 2015; McDonnell & Valentino, 2016). In addition, high levels of maternal anxiety, which is thought to be more prevalent than maternal depression (Reck et al., 2008) is a common psychosocial risk factor for regulatory disorders of young infants (Richter & Reck, 2013).

Our sample included 82 mothers. Questionnaire data revealed high levels of educational attainment, low rates of adverse childhood experiences and low anxiety. Mothers completed the infant behaviour questionnaire (IBQ) -a parent-report measure of infant temperament. The IBQ includes items designed to elicit how highly an infant rates on the factor of self-regulation. As self-regulation is thought to emerge at the end of the first year, we wanted to look at precursors to self-regulation in our sample at 12-months. Within the IBQ composite factor of regulation, there is a sub-factor specifically targeting duration of orienting (D of O), which we used as a measure of sustained attention. In addition to the parent-report measures, we also used an eye-tracking task designed to measure an infant's ability to fixate a moving target. Measurement of sustained attention in infancy is difficult, with most studies using indirect methods of assessment to elicit and infer attentional processes. For instance, sustained attention in infancy has been indexed behaviourally during looking paradigms in the laboratory. Research in this domain has found that sustained attention manifests behaviourally in the form of prolonged gaze, decreased distractibility, and object manipulation (H. A. Ruff & Capozzoli, 2003b; H. Ruff

& Rothbart, 2001). Furthermore, infants visually focused on objects for sustained periods were less prone to distraction (Oakes & Tellinghuisen, 1994)

This study tested the hypothesis motivated by vantage sensitivity theory that a putative marker of ES (baseline RSA) would moderate the relationship between the developmental environment indexed by measures of maternal wellbeing and SES and developmental outcomes measured as 12-months sustained attention and self-regulation. We calculated that to detect a small effect size $<.05$ with a significance level set at $.05$ and power $.8$ and three variables (predictor, moderator and interaction between predictor and moderator) N would need to be at least 222. As detailed below, this sample was $N82$ making the proposed analyses considerably statistically underpowered. Therefore, it was decided that as an exploratory analysis, as well as an exercise in learning, the same hypothesis would be tested using each of the variables indexing the environment and the outcome independently. While the importance of adjusting for multiple comparisons is recognised, in the absence of significant interactions after correcting for multiple comparisons, the results of any significant interactions with unadjusted p -values would be reported.

7.2 Method

7.2.1 Participants

Participants were drawn from the same sample studied in Chapters four to six of this thesis. Infant-parent dyads attended the BabyLab at the University of East London on two occasions – first when the infants were 6-months old and a second visit when the infant was 12-months old. The participating parent-infant dyads were recruited from local children's centres, baby sensory classes and new-parent support groups. At timepoint 1, 82 infants (52.4% males) and their primary caregivers (98% mothers) attended (Infant mean age in weeks = 27.46 SD=0.59). At timepoint 2, 68 infants (52.9% males) returned (Infant mean age in weeks = 54.45, SD=0.75), making the attrition rate of the study 17.07%. Demographic characteristics of the sample are shown in Table 7.1

Table 7. 1 Demographic details of participants at 6-months (n = 82) and 12-months (n=68)

Variable	6-month visit	12-month visit
Infant age in weeks- M(SD)	27.77 (0.59)	54.45 (0.75)
Range	20.9-32.7	48.8-60.5
Gender (%)		
female	47.56	47.06
male	52.44	52.94
Maternal education (%)		
Postgraduate	48.6	47.06
Undergraduate	41.09	44.12
A level	5.4	2.94
No formal qualifications	4.1	1.47

M=Mean, SD=Standard deviation

Participant missing data

For the measure of baseline RSA data was available for 74 participants. Some infants did not partake in the EEG paradigm during a part of which the ECG data was recorded (4) and for some the ECG data was too noisy for too large a proportion. For the measures of SES (maternal education) data was available for 74 participants, and for the measures indexing maternal wellbeing (GAD-7 and ACE) questionnaire data was available for 75 and 77 participants respectively. For the three 12-months outcome measures data was available for IBQ Regulation (64), Duration of Orienting (DofO) (64) and Eye tracking (64).

7.2.2 Measures

Environmental Sensitivity

RSA

ECG was recorded during an auditory oddball paradigm that was being used as part of another study with the same infants. During the paradigm infants were seated on their parent's lap in a darkened EEG booth. On a screen in front of them a silent excerpt from a popular children's television show *In the Night Garden* played concurrently with a series of

audible tones. In all, the oddball task lasted 4 minutes. ECG was recorded using a BioPac (Santa Barbara, CA) system recording at 1000Hz from three disposable Ag–Cl electrodes, placed in a modified lead II position.

Raw ECG data were analysed using Kubios software (Tarvainen et al., 2014). The interbeat intervals between R peaks are automatically detected by applying the built-in QRS detection algorithm based on the Pan–Tompkins algorithm (Pan et al., 1985). The software automatically identified noise segments (using default setting of medium) based on the raw ECG data and from the interbeat interval data (RR or pulse-to-pulse intervals). The min/max inter-beat interval was set at 300/750 ms in line with previous studies of infant HRV (S. V. Wass et al., 2021). Automatic artifact detection and rejection criteria were used to identify artifactual beats from the time series data consisting of differences between successive RR intervals (Lipponen & Tarvainen, 2019). Information on the algorithms used to process the raw ECG data in Kubios is included in supplementary materials. HRV was calculated as the root mean square of successive differences (RMSSD) between each beat across the 4-minute recording. Average RMSSD for the infants included in the analyses was 13.59 SD 5.74 range 3.68min - 32.42. RMSSD was taken to index Respiratory Sinus Arrhythmia (RSA) (Vest et al., 2018). RSA was normally distributed: skewness .872.

Developmental environment

Maternal wellbeing

GAD-7

Parents filled in a Generalized Anxiety Disorder (GAD) scale GAD-7 (Spitzer et al., 2006), a validated 7-item scale for screening for GAD and assessing its severity in clinical practice and research. Cronbach's alpha was .87. The data was positively skewed so log transformed adding a constant to account for zeros in the data.

ACE

Parents completed the Adverse Childhood Experiences (ACE) Questionnaire (Felitti et al., 1998)- a standardised 7-item questionnaire to ascertain levels of abuse and household dysfunction to which an individual was exposed before the age of 18.

Cronbach's alpha was .65 but positively skewed so log transformed adding a constant to account for zeros in the data.

Socioeconomic status

In order to provide a measure of socioeconomic status (SES), at both visits mothers also completed a demographic questionnaire which is unstandardized, but has been adapted from those used in ELAS, ELAS2 and TALBY studies at UEL BabyLab. It asked for details of household income was entered as a variable on a continuous scale. Level of education was on a scale from 1-7 with 7 being the highest and 1 the lowest: postgraduate (7) graduate (6) further education (5) A' level (4) GCSE (3) No formal qualification (2) Other (1).

Outcomes

12-months Infant regulation.

At 12 months of age regulation was assessed with the short form of the Infant Behavior Questionnaire-Revised (IBQ-R; Gartstein Rothbart, 2003; Putnam, Helbig, Gartstein, Rothbart, & Leerkes, 2014), a widely used parent report measure of different facets of infant temperament. The 91-item questionnaire measures the occurrence of different infant behaviours within the past two weeks on a scale from 1 (never) to 7 (always). It has shown satisfactory reliability at 0.70 and acceptable validity (Thomas et al., 2017). From the IBQ-R, the composite Regulation scale was used as one dependent variable in the analyses. Regulation consisted of the subscales: low intensity pleasure; cuddliness; duration of orienting and soothability. The internal consistency of items included in the Regulation scale was $\alpha = .698$. To explore the slightly low alpha for regulation, we examined 'scale if item deleted' and found that removing one item 'how often during the last week did the baby enjoy listening to a toy in a crib?' would raise the alpha to 0.719. The average Regulation for the infants included in the analyses was 4.70 (SD = 0.577; range = 3.60-6.17).

12-months Infant sustained attention

IBQ duration of orienting subscale

We also find that the internal consistency of one of the subscales - duration of orienting – of the factor of Regulation was sufficient ($\alpha = .72$) if one of the items was removed. The removed item was as follows: 'how often during the last week did the baby play with one toy or object for 10 minutes or longer?' All other items relating to this subscale asked for duration of orienting of between 2 to 10 minutes. The average score for duration of orienting was 4.60 (SD = 1.11; range = 1.50-6.17).

Eye-tracking task

At 12-months infants took part in several eye-tracking tasks. A Tobii T120 eyetracker (Tobii AG, Stockholm) was used. Stimuli were presented using custom-built scripts using Matlab and Psychtoolbox, interfacing with the eyetracker via the Matlab Tobii SDK. One of the tasks targeted sustained/focused attention. Infants were seated in their parent's lap in front of a screen. Parents were requested to look away to ensure the eyetracker captured the infant's gaze. A modified version of a task used to assess sustained attention was used (see (Rose et al., 2017) for further details). A target (a subtending butterfly) was presented on the screen. When the infant fixated the target, the butterfly "flew" across the screen accompanied by music. When the infant looked away the target remained static on screen. On refixing the target, it recommenced moving until it reached the right side of the screen whereupon it grew, and congratulatory music played. Each infant was presented with 3 blocks of the task interspersed among other eyetracking tasks. Each block contained two gaze-contingent transitions from the left to the right-hand side of the screen (Wass et al., 2011).

Data was analysed using a Matlab script to produce variables of interest. The dependent variable was the infant's ability to sustain their attention to the target, indexed by the proportion of the trial duration spent looking to the target so that it would continue moving across the screen. The mean (SD) [range] was 57.63 (16.09) [18.59 92.25] and was normally distributed: skewness -.123 kurtosis -.554.

7.2.3 Statistical analyses

For positively skewed data containing zeros (ACE and GAD-7) a constant (+1) was added to make the minimum value 1 after which it was log₁₀ transformed. Negatively skewed data (maternal education) was reflected and then log₁₀ transformed. All variables were standardized using z-scores. As previously stated, unadjusted bivariate relations between predictors and outcome variables were studied using Pearson's correlations. Independent contributions of the three predictor variables on the three outcome variables were examined using linear regression analyses.

Interaction effects between the measure of ES (RSA at 6-months) and the variables reflecting maternal wellbeing (GAD-7 and ACE) and SES (maternal education) on the outcome variables indexing sustained attention (eyetracking and IBQ DofO subscale) and

regulation (IBQ REG scale) at 12-months were studied using regression analyses with the PROCESS tool made for SPSS by Andrew F. Hayes (www.afhayes.com). In all, nine moderation analyses were conducted.

No imputation of missing data was made, due to the relatively low numbers of missing values.

Where no significant interactions were found between the variables indexing ES and developmental context, no further analyses were conducted on this data. Possible reasons for insignificance will be explored in the Discussion.

In case of a significant interaction, potential presence of differential susceptibility or vantage sensitivity to the effects of the developmental context will first be evaluated by inspecting the form of the interaction plot, i.e., whether there is a crossover interaction suggestive of differential susceptibility (Belsky et al., 2007) or vantage sensitivity (Jolicoeur-Martineau et al., 2019)

More formal evaluation of the crossover will then be then carried out using simple slopes to ascertain the direction and strength of the effect of X on Y at high and low levels of the moderator variable (± 1 SD from the mean)

Shortcomings of this technique for testing for the presence of differential susceptibility over diathesis stress have been identified (Roisman et al., 2012). Therefore, the suggested further analyses will be carried out. The first shortcoming was that a simple visual inspection of the interaction plot for evidence of a crossover is problematic as all interactions would eventually cross over if extrapolated to a wide enough range of X. As such, regions of significance (RoS) on X now establish the values of the predictor variable below which *and* above which the regression lines of the moderator variable begin to differ with respect to the outcome (Bakermans-Kranenburg & van Ijzendoorn, 2015; Preacher et al., 2006; Roisman et al., 2012). Differential susceptibility is implied when the estimated SD values fall within ± 2 SD of the mean of the predictor (Aiken et al., 1991; Bakermans-Kranenburg & van Ijzendoorn, 2015; Roisman et al., 2012). In addition, the interaction plot is considered to reflect diathesis-stress when the lines are significantly different only in the observable range (± 2 SD of the mean) of the developmental environment measure reflecting adversity (e.g., low maternal education or high GAD-7 scores); vantage sensitivity when the lines are significantly different only in the observable range of the environmental quality measure reflecting support and enrichment (e.g., high maternal education or low GAD-7 scores); and differential-susceptibility when the lines are significantly separated at both ends of the environmental quality measure (Jolicoeur-

Martineau et al., 2019). Therefore, two further indicators are proposed to evaluate the applicability of the differential susceptibility or vantage sensitivity model in addition to the regions of significance analysis (Roisman et al., 2012). Proportion of interaction (PoI) provides a calculation of the proportion of the total interaction that is represented to the right of the crossover point. In a typical differential susceptibility model, this value will be closer to 0.50 rather than extreme values (i.e., 0 or 1), which would indicate that the interaction can only account for either increasing or decreasing values of the predictor which would be support either a vantage sensitivity or diathesis-stress model. Proportion affected (PA) provides an estimate of the proportion of cases in the data that are above the crossover point and therefore differentially affected by the moderator. Again, support for differential susceptibility is obtained if the value is closer to 0.50 rather than extreme values.

7.3 Results

The results of the regression analyses are depicted in Table 7.2. The three interactions between household environment and ES which significantly predict the outcome variables indexing regulation and sustained attention will be detailed below.

Table 7. 2. summary of regression analyses between interactions at 6-months predicting infant developmental outcomes at 12-months * $p < .1$ ** $p < .05$

	12m Regulation				12m Duration of Orienting				12m Sustained Attention			
	<i>B</i>	<i>SE</i>	β	<i>p</i>	<i>B</i>	<i>SE</i>	β	<i>p</i>	<i>B</i>	<i>SE</i>	β	<i>p</i>
RSA x GAD-7	.226	.129	.231	.077*	.309	.123	.319	.015**	-.153	.138	-.147	.271
RSA x ACE	.006	.115	.100	.962	.089	.112	.101	.444	-.101	.113	-.117	.374
RSA x Mat Ed	-.039	.161		.812	-.219	.139	-.208	.120	.280	.135	.270	.042**

Maternal anxiety (GAD-7) on duration of orienting (D of O) moderated by infant ES

The interaction between maternal education and RSA in predicting sustained attention at 12-months was significant beta = .319 $t = .215$ $p = .015$. Figure 7.1 shows the interaction between maternal anxiety at 6-months, levels of RSA predicting infant duration of orienting at 12-months. The shaded areas in grey represent the RoS on X, that is, the lower and upper bounds of values for maternal education outside of which the two regression lines differ significantly. The plot shows that one assumption for testing the

presence of differential susceptibility is met: a crossover interaction with the regression lines crossing closer to the middle of the distribution of maternal anxiety than at high levels of anxiety (indicating vantage) or low levels (indicating diathesis). However, another assumption is not met as neither slope is close to zero. At low (-1SD) and high (1SD) levels of RSA the valence of the association between maternal anxiety and sustained attention runs in opposite directions and both are significant: At low baseline RSA, exposure to low levels of maternal anxiety predicts higher DofO scores: Simple slope at $Z = -1$ is -0.45 , $t(54) = 10.70$, $p < .001$. However, at high levels of RSA, exposure to higher levels of maternal anxiety at 6-months predicts better DofO scores at 12-months: Simple slope at $Z = 1$ is 0.21 , $t(54) = 4.47$, $p < .001$. Evidence for a contrastive interaction such as this is not considered consistent with differential susceptibility effects (Belsky et al., 2007b). Therefore, no RoS on X or proportion of interaction calculation (PoI), indicating the proportion of the interaction to the right of the crossover point, or proportion affected (PA) values are reported.

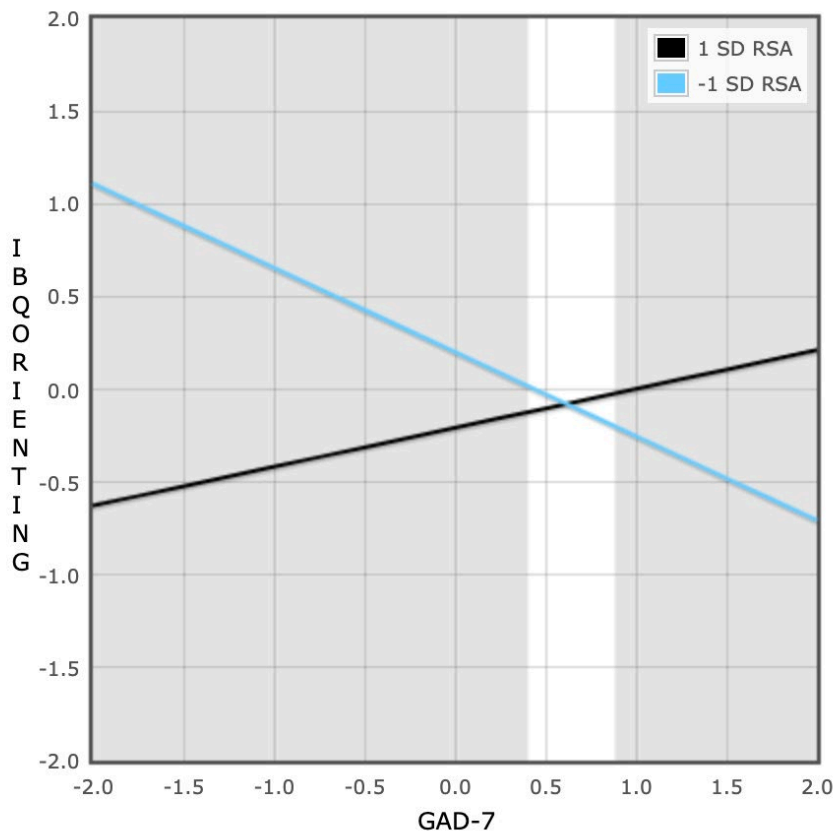


Figure 7. 1. Regression lines of the interaction between maternal anxiety at 6-months, levels of RSA predicting infant duration of orienting at 12-months.

Maternal Education level on sustained attention moderated by infant ES

The interaction between maternal education and RSA in predicting sustained attention at 12-months was significant $\beta = .270$ $t = 2.10$ $p = .042$. Figure 7.2. Shows that the assumptions for testing the presence of differential susceptibility are met: a crossover interaction with the regression lines crossing closer to the middle of the distribution of maternal anxiety and the slope for infants at high levels of HRV being close to zero: Simple slope at $Z = 1$ is -0.07 , $t(53) = 1.49$, $p = 0.143$.

As compared to infants with high baseline RSA, infants with low baseline RSA fixated on the target for a greater proportion of the trial when maternal education was low but for a lesser amount of time when maternal education was high. Simple slope at $Z = -1$ is -0.59 , $t(53) = 13.88$, $p = <.001$.

The RoS on X analysis provided support for the technical observation of differential susceptibility as the lower and upper bounds of RoS were $X = -0.034$ and $X = 0.492$ respectively (i.e., within the conventional limit of ± 2 SD indicating differential susceptibility; Roisman et al., 2012). This finding indicated the difference between the low and high RSA regression lines became statistically significant after scores of maternal education exceeded 0.492 SD above and -0.034 SD below the mean of maternal education. The PoI and PA were 0.40 and 0.42 respectively, further supporting a differential susceptibility account of the current data.

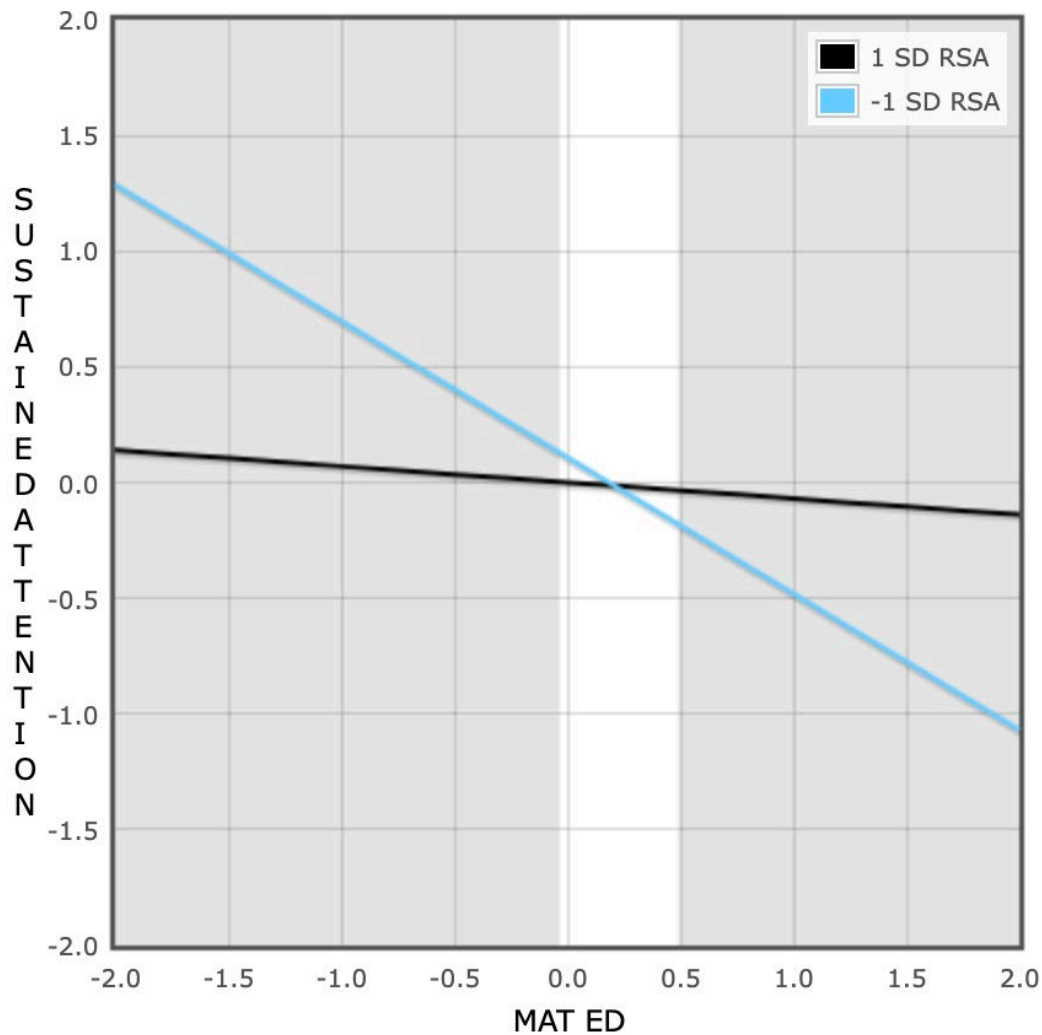


Figure 7. 2. Regression lines of the interaction between maternal education and levels of baseline RSA on predicting infant sustained

Maternal anxiety (GAD-7) on IBQ regulation moderated by infant ES

The interaction between maternal anxiety and RSA in predicting regulation at 12-months was marginally non-significant: $\beta = .232$ $t = 1.80$ $p = .077$. Figure 7.3 shows that the assumptions for testing the presence of differential susceptibility are met: a crossover interaction with the regression lines crossing closer to the middle of the distribution of maternal anxiety and the slope for infants at high levels of RSA being closer to zero. As compared to infants with high RSA (simple slope at $Z = 1$ is 0.09 , $t(54) = 2.00$, $p = 0.056$), infants with low RSA were reported to demonstrate lower levels of regulation when maternal anxiety was high but greater regulation when maternal anxiety was low: simple slope at $Z = -1$ is -0.37 , $t(54) = 8.73$, $p < .001$. The RoS on X analysis provided support for the technical observation of differential susceptibility as the lower and upper bounds of

RoS were $X = 0.050$ and $X = 0.668$ respectively (i.e., within the conventional limit of ± 2 SD indicating differential susceptibility; Roisman et al., 2012). This finding indicated the difference between the low and high RSA regression lines became statistically significant after scores of maternal anxiety exceeded 0.668 SD above and from below 0.050 SD above the mean of maternal anxiety. The PoI and PA were 0.37 and 0.34 respectively, further supporting a differential susceptibility account of the current data.

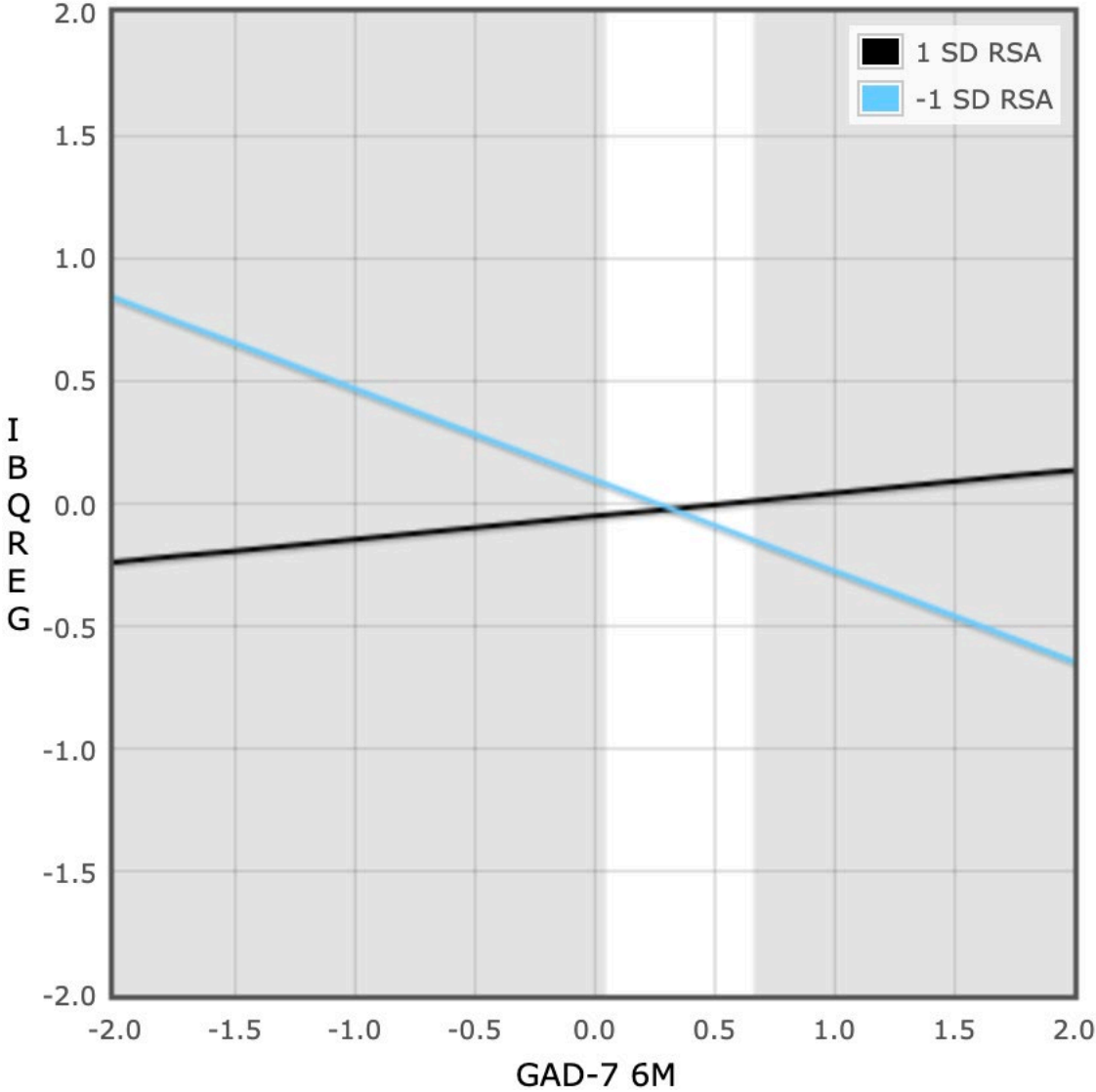


Figure 7. 3. Regression lines of the interaction between maternal anxiety and levels of RSA predicting infant regulation.

7.4 Discussion

This study set out to test the hypothesis that higher levels of maternal wellbeing and SES would predict better regulation and sustained attention at 12-months for infants higher in ES in line with Vantage Sensitivity theory. To do so we used a sample of high SES mothers with low scores on GAD-7 and ACE questionnaires indicating high maternal wellbeing. We predicted that that a putative marker of ES (baseline RSA) would moderate the relationship between the developmental environment indexed by measures of maternal wellbeing and SES and developmental outcomes measured as 12-months sustained attention and self-regulation, such that infants with high baseline RSA, would be better able to take advantage of the benefits of such a developmental environment, resulting in higher scores on measures of regulation and sustained attention at 12-months.

Before any meaningful discussion of this set of results, it should be stated that, although respectable in terms of infant research, this sample was not large enough to detect the small effect size anticipated. G*power calculations (Faul et al., 2007) revealed that to detect a small effect size of .02 according to Cohen's conventions (i.e., 2%, 18%, and 54% small, medium, and large effects sizes respectively) with a significance level set at $<.05$ and power .8 and three variables (predictor, moderator and interaction between predictor and moderator), N would need to be at least 550. Therefore, this study was considerably statistically underpowered for these analyses. Regions of Significance analyses used in this study have been found to perform poorly when $N \geq 250$ (Jolicoeur-Martineau et al., 2019).

After adjusting for multiple comparisons using the Benjamini-Hochberg correction to control the false discovery rate, no significant interactions were found. Therefore, the results of three interactions between ES and the developmental environment in predicting regulation and sustained attention at 12-months, which were significant ($p < .05$) before correcting for multiple comparisons, were explored, and presented above.

The first finding was that at lower (not higher) levels of baseline RSA, lower maternal anxiety predicted better 12-months DofO IBQ scores. This would seem to suggest that infants with low baseline RSA were more susceptible to the benefits of low parental anxiety. However, the slope of the gradient for infants with high baseline RSA predicted that for every one unit increase in GAD-7 scores, infants' DofO scores also increased by .2 of a unit. As the slopes for high baseline RSA and low baseline RSA both significantly predicted scores on DofO from levels maternal anxiety, but in different directions, this could not be considered evidence of differential susceptibility, which stipulates that only those with high ES (here measured as high baseline RSA) are more affected by variations in the environment.

The second finding was that while at high levels of baseline RSA the level of maternal education did not predict performance on a sustained attention task, at low levels of RSA it did. However, the direction of the prediction was unexpected: For every unit increase in maternal education, sustained attention performance decreased by .6 of a unit.

The third finding was marginally non-significant. However, the slope for low baseline RSA indicated that for every one unit increase in maternal anxiety, IBQ REG scores decreased by .37 of a unit. As the slope for high baseline RSA was closer to zero, this result does support the hypothesis that in this sample low baseline RSA indexes ES that associates with differential susceptibility to the environment: at low levels of baseline RSA infants score better on DofO at low levels of maternal anxiety and worse than can be expected at high baseline RSA when maternal anxiety is high. Unfortunately, this finding was only marginally significant.

No evidence was found in support of vantage sensitivity. Vantage sensitivity would have required the lines to be significantly different only in the upper observable range of the environmental quality measure (e.g., low anxiety or high maternal education), thereby reflecting support of enrichment (Jolicoeur-Martineau et al., 2019). This would mean that there is little difference in the outcome at either low or high ES at lower levels of the predictor but that outcomes improve more at high levels of ES than low levels of ES at higher values of the predictor. Instead, the form of the plotted significant interactions supported differential susceptibility whereby the outcome differed significantly for worse at high levels of ES at lower ends of the predictor and for better for high ES at higher values of the predictor.

A notable feature of this sample is that there was limited variation in the measured quality of the developmental environment. Almost 90% of the mothers included were educated to graduate level, with more than half of those educated to postgraduate level. In addition, the data on maternal wellbeing was positively skewed indicating low levels of anxiety and low exposure to adverse childhood experiences among the mothers in the study. This potential limitation was exploited as a strength of the study. As high-quality developmental environments are linked to good developmental outcomes (Samdan et al., 2020) we wanted to see whether at higher levels of ES, infants were better able to benefit from any advantages conferred by the environment than at low levels of ES. The model was used to counter the weight of studies looking only at the opposite end of the spectrum of environmental quality whereby only the effects of risk and adversity on the developmental outcomes of highly sensitive individuals are probed.

In the study presented in Chapter six of this thesis, which used the same sample of participants, lower maternal education (up to graduate level) did not moderate the effects of ES at 6-months on behavioural reactivity at 12-months. However, high maternal education (postgraduate) did. Infant negative reactivity which has been reliably found to index ES (Blair, 2002a; Klein Velderman et al., 2006; Smith et al., 2016), which we observed in the lab, predicted higher infant positive behavioural reactivity at 12-months only at the higher level of maternal education. While associations have been found between higher maternal education and high-quality parenting (Diaz, 2019), future studies should examine more proximal measures of parenting sensitivity to gain insight into what mediates the relationship between maternal education and improved developmental outcomes. Such measures should be based on observations rather than parent-reports. In a meta-analysis of 84 longitudinal studies that reported on a parenting-by-temperament interaction predicting child adjustment, parenting-by-temperament interactions were more pronounced when parenting was assessed using observations compared to questionnaires (Slagt et al., 2016). Furthermore, parental reports measuring infant regulation failed to show significant findings with parenting behaviour at any given time (Samdan et al., 2020).

However, even within these ostensibly high-quality developmental contexts, we found variation in developmental outcomes as a function of ES more in line with differential susceptibility. In contrast with our prediction, it was low, not high baseline RSA which seemed to represent greater susceptibility to environmental effects. We predicted that high baseline RSA would represent greater ES at the age of 6-months in line with previous findings for infants of this age. High RSA in the first year has functioned as a susceptibility factor (Conradt et al., 2013; Eisenberg et al., 2012; Holochwost et al., 2014b). In new-born infants, high baseline RSA reflects greater physiological reactivity as well as flexibility in responding (Porges et al., 1973; Porges et al., 1974). In older infants, those with higher RSA showed larger heart rate decelerations during sustained attention (Richards and Casey, 1991; Richards, 1987; Richards, 1985). As such, infants with higher RSA are thought to be more alert and engaged with their surroundings and therefore more likely to be affected by them.

However, in toddlers and children, low baseline RSA is associated with greater susceptibility to the effects of the environment, most notably parental sensitivity (El-Sheikh et al., 2013; Wetter & El-Sheikh, 2012a). Children with low RSA had significantly lower developmental outcomes when exposed to low levels of maternal sensitive parenting compared to children with high RSA. As high RSA is associated with better self-regulation

(Gueron-Sela et al., 2017a; Hastings et al., 2008), children with low baseline RSA are more reliant on external regulation from caregivers, which renders them more susceptible to environmental effects, (Hastings et al., 2008) both for better when parental quality is high (Bagner et al., 2012), and for worse when parental wellbeing is low (Wetter & El-Sheikh, 2012b).

One possible limiting factor of our study is that we measured baseline RSA and not RSA reactivity. RSA reactivity is the extent to which vagal suppression of heart rate is withdrawn leading to increased heart rate to support active coping during environmental challenge (S. D. Calkins & Keane, 2004). This was because although RSA withdrawal has been linked to various social– emotional outcomes (Calkins & Keane, 2004; Graziano et al., 2013; Vasilev et al., 2009), findings on the relations between RSA withdrawal and children’s cognitive functioning and control are mixed (Graziano et al., 2013), possibly nonlinear (Marcovitch, Leigh, Calkins, Leerks, O’Brien, et al., 2010) and may depend on task context or task-specific demands (Sulik et al., 2015). However, it has been theorized that as well as being an index of ES, the extent to which RSA decreases in response to stimuli, also indexes regulation. In very simple terms, RSA indexes PNS activity, and heart rate (HR) is a measure of Sympathetic Nervous System (SNS) activity (McCabe et al., 2000). Although the association between SNS and PNS cannot be regarded as a zero-sum system, in many cases the SNS and PNS function in opposition (Samuels & Szabadi, 2008) and the correlation between measures of HR and RSA is negative. Therefore, at times of lower RSA, HR, as measured by beats per minute (BPM), increases. Based on animal models it is thought that the relationship between autonomic arousal and attention is U-shaped such that at high arousal, individuals are hyper-vigilant and responsive to external stimuli, at low levels of arousal individuals are inattentive and unresponsive, but that at intermediate levels of autonomic arousal selective attention and self-regulation are optimal (Aston-Jones & Cohen, 2005). As HR is an index of arousal, it could be that in our sample, at 6-months, infants with lower baseline RSA, were more aroused and therefore alert to their environment. Of note, the Aston Jones model defines high and low levels of arousal only relative to the arousal level within individuals. They do not explicitly deal with between-participant variance and whether individuals with higher or lower arousal levels relative to other individuals tend to show different attentional profiles (S. v. Wass, 2018a).

Furthermore, indirectly consistent with our findings, infants with high baseline HR (and therefore lower baseline RSA) demonstrated fewer withdrawn behaviours if they had been exposed to positive engaging parenting during infancy (Wagner et al., 2016).

However, in the same study, RSA was not found to moderate the associations between parenting in infancy and later internalizing behaviour problems suggesting that, during infancy, overall autonomic functioning may have greater implications for the development of internalizing behaviours than do parasympathetic influences alone.

Despite the small sample size and consequent difficulty in detecting effects, this study has contributed to understanding of the importance of self-regulation. High RSA, which constitutes superior physiological flexibility and regulation constituted a protective factor against the effects of environmental adversity on children's outcomes (e.g., El-Sheikh, Harger, & Whitson, 2001; El-Sheikh & Whitson, 2006). Whereas children with low RSA were found to be more vulnerable, exhibiting more behavioural problems and poorer health in the context of high marital conflict, children with high baseline RSA were less negativity affected by marital conflict (ElSheikh & Whitson, 2006; El-Sheikh et al., 2001). The importance of sensitive parenting especially for infants and children whose internal regulatory resources are lacking - and are therefore more reliant on caregivers for regulation - cannot be overstated. Furthermore, scaffolding children's self-regulatory capacities can act as a buffer against the adverse effects of sub-optimal family environments (Gobeil-Bourdeau et al., 2022; Gueron-Sela et al., 2017b). A possible interpretation of the evidence presented in the literature is that higher baseline RSA reflects the degree to which cardiac activity is modulated to meet changing situational demands, and thereby facilitates restoring homeostasis - indexing better self-regulation (Bylsma et al., 2013). Furthermore, evidence has shown that lower baseline RSA rendered infants more susceptible to the effects of the developmental context on developmental outcomes (Gueron-Sela et al., 2017b). The authors suggested that infants with lower baseline RSA are more reliant on external regulation and therefore more dependent on the quality of their environment for developing self-regulation. A future direction for research into ES would be to investigate the developmental trajectory of the PNS in relation to both the developmental context and developmental outcomes.

Chapter 8. General Discussion

This final Chapter summarises the theoretical motivation for research into ES in infancy and the three empirical studies conducted for this thesis. The methodological strengths and limitations of the work are then discussed, followed by an interpretation of the study findings in the context of the broader literature. Recommendations for future research are presented. Finally, ethical questions raised during this research into individual differences in environmental sensitivity will be considered.

8.1 Synopsis

In the general introduction Chapter, perspectives on the evolution and development of individual differences in environmental sensitivity and its implications were outlined. The three independently developed, but complementary theories which together constitute the field of Environmental Sensitivity were detailed and the models explaining the effects of individual differences in ES were described. Despite having different perspectives on the maintenance and distribution of differences in ES in the population, BSC, DST and SPS are united in predicting that high ES can have a bivalent effect on developmental outcomes. While acknowledging that high ES can constitute a vulnerability, predisposing individuals to fare worse than less sensitive individuals in adverse conditions, as proposed by diathesis stress models, there is mounting evidence that high ES in individuals also predisposes them to be more susceptible to the benefits of nurturing, supportive environments, and thereby experience fewer adverse outcomes (and even more positive outcomes) than those less sensitive. Cross-over or disordinal interactions support the core differential susceptibility hypothesis of the three theories. Vantage sensitivity develops the idea of the potential benefit of high sensitivity by focusing on the wider range of reaction to exclusively positive life experiences enabled by heightened ES.

The evolutionary explanations for the maintenance of individual differences in ES were outlined as well as the proposal that in developmental environments which are particularly adverse or particularly advantaged, an individual's environmental response system adaptively calibrates - for individuals with a genetic predisposition - to ensure the best outcomes within that context, whether that be survival or thriving.

Finally, the questions which informed the research aims of this project were outlined: Is there a general factor of ES within which different mechanisms driving individual differences in sensitivity covary?

To what extent does reactivity at different levels of analysis associate over the first year of life? To countenance that ES may have a bivalent effect it appears a prerequisite to hold that ES is a one-dimensional construct. In which case, do infants who react with greater intensity to negative stimuli also react with greater intensity to positive stimuli? To have a bivalent effect on long-term outcomes, to what extent does increased sensitivity to immediate effects constitute greater susceptibility to the effect of the environment on long-term developmental outcomes both for better and for worse? Is, as according to the theory of conditional adaptation, the ES of infants calibrated to respond most to the elements of their environment which will enable them to survive or thrive within that environment?

Chapter three set out the evidence for the measures thought to reflect ES at different levels of analysis from neural and autonomic to behavioural reactivity and temperament. Associations between measures thought to index ES have been found, but no studies had looked at associations between several measures within an individual both cross-sectionally and longitudinally while measuring elements of the developmental environment. The research aims were set out in four main hypotheses motivated by the developmental framework of ES.

Hypothesis one predicted that measures of infant reactivity to both positive *and* negative environmental stimuli indicated by: higher baseline RSA during EEG and behavioural paradigms, and RSA reactivity during behavioural reactivity paradigms; the intensity of reactivity to lab-based positive *and* negative tasks; scores on IBQ scales of negative affect *and* surgency; neural sensitivity to auditory oddball and emotional-face processing paradigms would correlate at 6-months - indicating a general level of ES. Hypothesis two was exploratory. We tested whether the associations between the same measures of ES at 6-months endured at 12-months. To test the model of vantage sensitivity, hypothesis three predicted that factors indicating the quality of the developmental environment would moderate the relationship between infant heightened reactivity to positive or negative stimuli at 6-months and 12-months. Hypothesis four predicted that infants with high sensitivity to environmental effects at 6-months, with low exposure to early-life stressors would have better sustained attention at 12 months than infants with measures indexing low ES.

Bivariate correlations between variables indexing ES at 6-months revealed correlations between different measures within different levels of analysis, and to both positive and negative stimuli. At a neural level of analysis, measures of neural sensitivity to visual and auditory stimuli correlated at 6-months but did not associate at 12-months. At a behavioural level of analysis, measures of behavioural reactivity to positive and negative stimuli associated at 6-months but not 12-months. The evidence for associations for indices of ES (between neural measures) to both positive and negative stimuli (for behavioural measures) at 6-months but not 12-months was explored and developed in studies one and two which formed Chapters five and six of this thesis. Furthermore, in Chapter five, evidence was presented in support of hypothesis three. The change in the relationship between positive and negative behavioural reactivity from 6-months to 12-months is moderated by the developmental environment suggesting that highly supportive developmental environments associate with the development of heightened responsiveness to positive stimuli. In Chapter seven, the results of a study looking at whether heightened ES moderated the effects of different aspects of the developmental environment on developmental outcomes were presented.

8.2 Summary of findings

The three empirical chapters which detail the studies emanating from the preliminary analyses of the data found limited support for the four initial hypotheses. In partial support for hypothesis one, associations were found within levels of analysis and in reactivity to both positive and negative stimuli at 6-months.

These same associations were not found at 12-months. In response to the exploratory hypothesis two, in which we were agnostic as to whether associations found at 6-months would endure at 12-months, and based on evidence, the fractionation which occurred is interpreted and discussed in both Chapter five and Chapter six. In support for hypothesis three, the developmental environment was found to moderate the relationship between ES at 6-months and 12-months indexed by behavioural reactivity to positive and negative stimuli. The second result of the study in Chapter six could also be interpreted as support for hypothesis four, that heightened negative reactivity at 6-months, which has been robustly found to indicate heightened susceptibility to the environment, predicted more positive reactivity at 12-months at higher levels of maternal education. While the study in Chapter seven found some marginally non-significant evidence in support of hypothesis

four, the measure which represented increased susceptibility to the environment was low (and not high as predicted) baseline RSA.

The first study, presented in Chapter five, developed the association between measures of neural sensitivity to auditory and visual stimuli over temporal and occipital regions respectively. Furthermore, autonomic arousal correlated with neural sensitivity at 6 months but not at 12 months. Based on previous findings, we had predicted that to support the theory that ES is domain general, there would be an association between autonomic and neural activity such that measures of autonomic arousal and neural sensitivity to differences in auditory stimuli as well as differences in visual stimuli would covary. The results suggested that neural perceptual sensitivity is domain-general across auditory and visual domains and is related to autonomic arousal at 6 months but not at 12 months of age. I had predicted that these measures would correlate to test the concept that ES is a unitary construct, instantiated at multiple levels of analysis, which is implied by the theories of DST, BSC and SPS. However, the discontinuation by 12-months of associations found at 6-months was interpreted within a neuroconstructivist framework and with respect to the concept of interactive specialisation. By 12 months of age, mechanisms denoting perceptual sensitivity to the low-level features of stimuli, which were initially not specific to particular neural domains (auditory and visual modules in the brain), become more so as a result of processing different kinds of input (Karmiloff-Smith, 1998). More experience of visual processing may have led to the development of top-down endogenous attention mechanisms that process visual information in a way that no longer associates with bottom-up auditory perceptual sensitivity.

The second association found during preliminary analyses was developed in the second empirical study of this thesis in Chapter six. The association between behavioural reactivity to positive and negative stimuli, is consistent with the idea that ES is one-dimensional. However, at 12-months, the emotional reactivity profiles differentiated between infants who reacted with more negative reactivity and those who displayed more positive reactivity. Maternal socioeconomic status (SES) moderated the relationship between environmental sensitivity (as measured by negative reactivity) at 6-months and positive but not negative reactivity at 12-months. Infants high in environmental sensitivity (ES) at 6-months displayed more positive reactivity at 12-months at higher levels of maternal SES. We concluded that early in development, those infants who show high negative reactivity also show high positive reactivity. However, by 12-months again, this had fractionated. This fractionation was interpreted as evidence of conditional adaptation,

with infants who showed high environmental sensitivity better able to benefit from any advantages conferred by SES.

The third empirical study – Chapter seven, was a more conventional investigation of the interaction effects of sensitivity (measured using baseline respiratory sinus arrhythmia (RSA)) and the environment on a developmental outcome variable (measured using an eye tracking paradigm and scores on the duration of orienting (DofO) IBQ subscale) and regulation (measured using the IBQ scale of regulation). Due to the homogeneity of the developmental environment, indexed by the advantaged socioeconomic status and wellbeing of parents, the extent to which such interactions corresponded to either of the theoretical models of person-environment interaction: vantage sensitivity or differential susceptibility was tested.

Several exploratory hierarchical multiple linear regressions showed limited support for differential susceptibility but not vantage sensitivity. At low (not high) levels of RSA, low maternal anxiety predicted better IBQ REG, but higher maternal anxiety predicted lower IBQ REG scores than infants with high RSA, but the prediction was only marginally significant. At low levels of RSA, low maternal anxiety predicted better DofO, however, at high baseline RSA, increases in maternal anxiety predicted better DofO. As this was a contrastive interaction it is not evidence of differential susceptibility. Finally, at low baseline RSA higher maternal education predicted worse infant performance on an eye-tracking measure of sustained attention.

In the remainder of this discussion, I will address several methodological strengths and limitations of the studies contained in this thesis. I will then go on to discuss the main findings overall within the context of the wider literature as well as the importance of elucidating the construct of ES both from a research perspective and in terms of its application in developmental settings. To do this, I will suggest future directions for research in this area before turning to ethical considerations for the field.

8.3 Methodological strengths

Before detailing the limitations of this thesis, the main methodological strengths are outlined. The first is that it compared different levels of analysis regarding mechanisms driving individual differences in sensitivity. By comparing acknowledged markers of ES at different levels of analysis, I hoped to elucidate the mechanisms underlying ES and move towards a better understanding of whether it is a single factor construct. Evidence underscores the complementing nature of social and biological levels of analysis. Both

biological processes that associate with or influence behaviour (Hill, 2002; Porter et al., 1988) as well as the social influences on biological processes that are often viewed as outside the social domain including genetic constitution, gene expression, disease, and autonomic, neuroendocrine, and immune (Seeman et al., 1997). This research underscores the unity of psychology and the importance of retaining multilevel integrative research on the mechanisms linking social and biological events and processes (Cacioppo et al., 2000).

Another strength was the inclusion of measures of reactivity to both positive and negative stimuli. Negative reactivity has been found to both associate with (in observational studies) (Kim & Kochanska, 2012; Raver et al., 2013) and influence (in experimental studies) (Berg et al., 2014) better or worse developmental outcomes depending on the quality of the environment or the nature of interventions. However, it is unknown whether heightened reactivity to positive events leads to altered long-term outcomes in the same way that heightened reactivity to negative events is (S. V. Wass, 2018). Greater short-term stress reactivity to adverse events leads to hypersensitization of the stress response to negative events and increased allostatic load leading to worse developmental outcomes (Armbruster et al., 2012.; Ulrich-Lai et al., 2009) . But, if stress-reactivity is a one-dimensional construct, there is no theoretical reason why increased reactivity to positive stimuli should not lead to hypersensitization of ‘positive’ attention-related physiological changes through repeated exposure. This study hoped to provide empirical evidence that is lacking in this area.

The incorporation of both a cross-sectional and longitudinal design was intended to address the question of whether children who show greater moment-to-moment reactivity to stressors or stimuli are also more susceptible to long-term environmental influences on development. Furthermore, relatively weak correlations between lab-based assessments of temperament and parent-reports of temperament in the literature may be reflective of the difference between a state at the time of testing or a trait, more indicative of habitual responses. In addition, any associations between RSA and reactivity could be either short-term, within individual changes, such that individuals who are in a temporarily calm state at the time of testing show different behavioural responses, or as static, time-invariant features of individual differences. Efforts were made to address this in the current study by taking measurements both cross sectionally- RSA was measured during both the EEG and behavioural paradigms - and longitudinally at both the 6-months and 12-months visits. The longitudinal design of the study was to distinguish reactivity that was reflective of a state during the testing session, or a more stable characteristic whereby measures of reactivity at

6-months were associated to reactivity at 12-months. Baseline measures of RSA correlated across the different tasks, but not reactivity measures. However, low test-retest reliability of reactivity measures is to be expected during the first twelve months of life, as reactivity is developmentally canalized (Kagan, 1994).

Finally, this thesis contributes to countering the relative lack of systematic examinations of variability in response to positive experiences as a function of endogenous factors. It is considered imperative that tests of the differential susceptibility hypothesis secure adequate variance in environmental conditions (Belsky et al., 2007; Ellis et al., 2005). However, while it is well established that risky environments are especially problematic for susceptible individuals, far fewer studies have targeted the potential benefits of exposure to positive contexts for susceptible individuals. Thus, while a broad range of environmental qualities is a minimum condition to reveal differential susceptibility, to reveal vantage sensitivity, one could adopt the inverse of the practice of looking only at conditions of environmental stress (or a lack of such) used in studies of developmental psychopathology. Introducing the concept of vantage sensitivity, Pluess stipulated the lack of a requirement for environmental conditions ranging from negative to positive (Pluess & Belsky, 2012). Therefore, the relative homogeneity of the current sample in terms of SES and maternal wellbeing was exploited as a strength of the study. As high-quality developmental environments are linked to good developmental outcomes (Moore et al., 2017; Wolff et al., 1997), I wanted to see whether at higher levels of ES, infants were better able to benefit from any advantages conferred by the environment than at low levels of ES. I will now turn to the methodological limitation of this study.

8.4 Methodological limitations

In the following section I will outline the methodological limitations of this study. Firstly, for some of the analyses undertaken, power calculations revealed the need for samples with more participants. This was due to the relatively small effect sizes that we anticipated. I draw attention to the problems of ascertaining to which specific elements of the developmental context highly sensitive individuals are the most susceptible. I then consider fatigue effects before turning to the issue of ecological validity.

8.4.1 Sample size

Power analyses (conducted using G*Power 3.1) revealed that to achieve power of .80 (80 percent chance of correctly rejecting the null hypothesis) at the $p < .05$ level, to detect bivariate correlations with an effect size of around .3, we would need a minimum sample size of $N=84$. To allow for adjusted p values (at the $p < .01$ level), due to multiple comparisons, we would need a sample size of 127. We initially aimed for a sample of at least $N=100$ infants to provide enough statistical power to detect significant results. Over six months we welcomed 82 6-months-old infants and their parents to the lab. For the analysis of correlations this was sufficient. Furthermore, because Bayesian analyses do not assume large samples, as is the case with maximum likelihood estimation, typically smaller data sets can be analyzed without losing power while retaining precision (Van De Schoot et al., 2015). The probability of finding (or not) the same association in the population is computed rather than the more restrictive calculation of the likelihood of falsely rejecting the null hypothesis. However, as in the frequentist context, an increase in sample size appears to reduce the variance of the posterior distribution estimated in a Bayesian model.

In addition, for the chi-squared analyses G*Power calculations revealed that to detect a small effect size of 0.1 according to Cohen's omega, with 1 degree of freedom and an 80 percent chance of correctly rejecting the null hypothesis of no difference between the expected and observed proportions of infants showing negative and positive reactivity, 88 participants were needed. However, due to the length of the testing battery and the nature of infant research (see below) we had missing data in our analyses.

For the moderation analyses in Chapter seven, G*power calculations revealed that to detect a small effect size of .02 with a significance level set at $<.05$ and power .8 and three variables (predictor, moderator and interaction between predictor and moderator), N would need to be at least 550. Therefore, this study was considerably statistically underpowered for these analyses. Regions of Significance analyses used in this study have been found to perform poorly when $N \geq 250$ (Jolicœur-Martineau et al., 2019).

8.4.2 Adequate measurement of the developmental environment

This study would have benefited from a direct measure of parental sensitivity either as a self-report measure, or preferably through measurements of observed interaction between parents and infants. Measures of the stress response of the parents were taken, including ECG data for autonomic activity and cortisol for HPA axis activity. However, due to technical complications, these were not available for inclusion

in the analyses. Therefore, measurement of the developmental environment was limited to scores on self-report questionnaires.

The importance of taking measurements at multiple levels of analysis on more than one occasion to assess ES was fundamental to the research undertaken and described in this thesis. However, the importance of precise assessments of the developmental environment and outcome measures was also an utmost consideration. In reviews of studies into the interaction between genes and environment on developmental outcomes, the method of assessment of environmental adversity was an important determinant of the outcome of the study (Uher et al., 2008;2010). Detailed interview-based approaches were associated with significant GxE findings, whereas non replications used self-report questionnaires. Unstable or unreliable measures of the environment can lead to the error components of the genetic and environmental parts of the G x E equation strongly diverging which increases the risk for both Type 1 and Type 2 errors when testing for moderation (Ellis, Boyce, et al., 2011). Therefore, as well as measuring ES at different levels of analysis, in studies on differential susceptibility, all elements should be assessed reliably and validly by aggregation of data across settings and measures.

In study two, level of maternal education was found to moderate the relationship between negative reactivity at 6-months and positive behavioural reactivity at 12-months. However, it is unclear by what process the relationship between 6-months negative reactivity and 12-months positive reactivity was stronger at higher levels of maternal education. Based on previous literature, it was suggested that maternal sensitivity was positively correlated with level of education. As well as being cited as one of the strongest indicators of SES in studies of child development (Hoff et al., 2012), maternal education correlated negatively with maternal intrusiveness and positively with maternal sensitivity (Diaz et al., 2019). Furthermore, in a study into the differential susceptibility of infants with high and low levels of baseline RSA, reared in poverty, it was not levels of poverty, but the nature of attachment (secure or disorganised) which had the largest association with the developmental outcomes of infants with high baseline RSA (Conradt et al., 2013). Therefore, the quality of parenting a child receives has been shown to be more directly predictive of outcomes than other measures of SES. However, in the same way that multiple risk factors tend to co-occur (financial hardship may well associate with marital conflict) the inverse must, to some extent, be true with higher levels of education leading potentially to more opportunities and greater financial stability. Physiological

susceptibility may enable infants to be more attuned to—and affected by—a sensitive caregiver who aids the infant to self-regulate despite being raised with fewer economic resources (Miller et al., 2011).

8.4.3 Fatigue effects

During both visits to the laboratory at 6-months and 12-months infants participated in a battery of EEG, Eye-tracking, and play-assessments while their parents filled in questionnaires. It is worth noting that these research visits ran over the course of several hours. The research team were aware of the need to be as flexible as possible to accommodate naps, feeding and comfort-breaks for infant participants. Nevertheless, fatigue may have influenced parent and infant behaviour, as well as parent responses on questionnaires. This was particularly relevant during the tasks assessing behavioural reactivity, which were usually the last battery of the visit. This may have partly explained the lack of association between measures of lab-observed behaviour, which may have been more indicative of a state at the time of testing and parent-reported temperament, likely to be more indicative of a trait. That said, while we were unable to control any variables which may have affected behaviour prior to arrival at the lab such as quality of sleep or the journey to the university, once the protocol commenced, conditions were controlled and relatively consistent across visits and participants.

8.4.4 Ecological validity

Considerable effort was made to ensure the visits to the lab felt as relaxed and informal as possible. Most participants had been recruited from baby-music and baby-sensory groups local to the University of East London. Therefore, the sample was characterised as urban and having been exposed to a variety of settings and stimuli. However, the study was conducted entirely in a laboratory setting, with researchers present throughout visits. The use of a variety of measurement apparatus in a controlled and unfamiliar setting may have influenced both infant and parental behaviour. However, as noted above, the lab environment allowed control over the experience ensuring relative consistency across participants.

8.4.5 Gold standard measure of infant sensitivity

The studies in this thesis have attempted to capture sensitivity indirectly. An alternative approach is to measure sensitivity more directly with the help of questionnaires. Questionnaires have been developed that attempt to capture the typical behaviours of sensitive adults and children. Currently the Highly Sensitive Person (HSP) (Aron & Aron 1997) and the Highly Sensitive Child (HSC) scales (Pluess et al., 2018) are self or parent-report questionnaires that have been developed to measure behavioural sensitivity, indexing sensitivity as a function of lowered threshold of reactivity to stimulation and greater depth and breadth of processing of sensory and emotional stimuli (Assary, 2021). These questionnaires are subjective and come with the problems inherent to self-reporting. The Highly Sensitive Child-Rating System (HSC-RS) (Lionetti et al., 2019) has been developed as an objective observer-rated measure of sensitivity in young children. Evidence that high scores on this measure reflect a greater propensity for children to be more affected by their experiences comes from experimental studies of school-based interventions (Nocentini et al., 2018; Pluess & Boniwell, 2015) and parenting quality (Slagt et al., 2018; Lionetti et al., 2019). So far, no gold standard measure of infant ES exists.

The Infant-Toddler Sensory Profile (ITSP) (Dunn et al., 2002) is the most common parent-reported measure of infants' sensory processing. The 128/48-item questionnaire provides a measure of infants' sensory processing manifestations in four quadrants (i.e., sensory seeking, low registration, sensory avoiding and sensory sensitivity) for four sensory domains (i.e., visual, auditory, tactile, and vestibular) (Piccardi et al., 2021). It looks at active and passive strategies from which an infant's neurological threshold for sensory perception can be deduced.

8.5 Interpretation and integration of main findings

I will discuss the findings of the three empirical studies and the extent to which they support (or not) the four hypotheses of this thesis with regard to wider literature.

8.5.1 Hypothesis one – Sensitivity to immediate environmental effects is a domain-general unitary construct.

In order to ascertain whether or not sensitivity to immediate environmental effects was instantiated at different levels of analysis, we collected data on neural sensitivity to auditory and visual stimuli, baseline autonomic measures as well as the extent to which these fluctuate in response to stimuli, measures of behavioural reactivity to positive and

negative tasks and parent-report measures of infant temperament. Unadjusted bivariate correlations of these measures revealed the correlation within levels of analysis at 6-months, and between neural sensitivity and autonomic state. There were no correlations between the sensitivity and reactivity measures.

We initially intended to conduct a factor analysis to discover the hypothesized underlying variable of ES. However, when performing factor analysis, the advice is to try to use at least 100 participants in the analysis, and to have five times as many participants as variables. Furthermore, it is only worth performing factor analysis if the variables are correlated with one another. If they are not, there would be no patterns of correlations to analyse (Dancey & Reidy, 2007). Therefore, we were not able to proceed with this analysis.

The two studies contained in the empirical chapters five and six indicate the domain-generality of sensitivity at 6-months. In study one, the finding that detection of difference correlated across the visual and auditory modalities at 6-months was interpreted as a domain-general level of sensitivity across neural domains, in terms of the early stages of visual and auditory processing. This has been considered evolutionarily adaptive – in terms of automatic discernment of relevance and to facilitate making novel and serendipitous associations with environmental cues in an uncertain environment (Chiappe & MacDonald, 2005). Study two looked at behavioural reactivity to positive and negative stimuli. For those infants for whom the tasks evinced a behavioural response (as opposed to those for whom there was no observable response) they were more likely to react to both the negative and positive reactivity inducing tasks than to just one or the other. The results were consistent with the hypothesis of bivalent immediate reactivity at 6-months in that the same infants reacted positively to a positive task and negatively to a negative task.

Despite the correlations between measures of different modalities within levels of analysis, there were no correlations between the sensitivity measures and reactivity measures at 6-months or at 12-months. While previous studies in infancy have linked heightened neural sensitivity with increased behavioural reactivity (Marshall et al., 2009), and higher RSA with more emotionally reactivity (C. Stifter et al., 1996; C. A. Stifter & Fox, 1990), other studies have failed to find coherence between experiential “subjective emotional stress experience” and physiological response systems in terms of arousal (Campbell & Ehlert, 2012; Lupien et al., 2022). However, Dunn’s four quadrant model of sensory processing (Dunn, 1997) suggests that individuals with passive tendencies may internally respond in the way that at the active end of the continuum, individuals adopt

strategies to actively control the type and amount of sensory input in their environments, which may be more overtly manifest (Dunn, 2007).

While negative affect has been consistently found to be a marker of ES, in that it has repeatedly been found to moderate the relationship between the developmental environment and outcomes, Pluess (2018) has acknowledged that uncertainty remains over which component of the typically multidimensional component of ‘difficult temperament’ reflects ES and susceptibility to environmental effects. A more nuanced approach to the concept of negative reactivity calls into question whether stress reactivity even to negative events is similarly a one or multi-dimensional construct (S. V. Wass, 2018).

The fact that the infants who were more negatively reactive when the toy was retracted were the same infants who were more positively reactive to the peekaboo task could reflect a reaction to the social element of both tasks rather than distinguishing between the negative and positive elements of the trials themselves and reacting with opposite valence but equal intensity to both. During the toy retraction task, the mother was instructed to play with the toy with their infant. When the toy was removed, the mother was told to maintain a neutral expression and refrain from interacting. In this way there are similarities with the still-face paradigm in which a caregiver suddenly becomes unresponsive while still present after a period of social interaction. We did not code for positive affect during the between-trial episodes of the toy-retraction task, but it would be interesting to see whether positive affect between trials, when the infant was interacting with the mother correlated with either positive affect during the peekaboo-trials or negative affect during the toy-retraction trials. In this way, the correlation could be interpreted as covariance of approach behaviours.

Motivational systems theory (Gray, 1987) conceptualises positive approach, but also frustration, anger, and impulsivity as part of the Behavioural Approach System (BAS), whereas fear is related to the Behavioural Inhibition System (BIS). Support for this conceptualisation has come from studies looking at associations between behavioural affect and frontal asymmetry using EEG. In contrast to right frontal asymmetry during rest, which is associated with behaviours facilitating withdrawal (K. A. Buss et al., 2003; S. D. Calkins et al., 1996), left frontal EEG asymmetry during rest is associated with a tendency to demonstrate behaviours facilitating approach (Carver & Harmon-Jones, 2009; Pizzagalli et al., 2016), such as approach motivated anger (Harmon-Jones, 2004) as well as the expression of certain positive emotions (N. A. Fox, 1991). Furthermore, infants with more left frontal asymmetry during rest were found to be more susceptible to the positive effects of sensitive parenting than those with right-frontal asymmetry (Diaz, 2019). Infants who

engaged in more fast-paced and vigorous play, and whose parents were observed as being more sensitive to their needs, demonstrated a relative left frontal activation response during toy retraction (Underwood & Garstein, 2022). This suggests that our study captured a correlation between approach behaviours. Furthermore, it is approach behaviours, rather than either or both positive and negative affect, which facilitate increased engagement with the environment, and thus constitute markers of heightened susceptibility to environmental effects.

Motor activity was included in the composite of negative affect which interacted with the developmental environment to predict 12-months positive reactivity in study two of this thesis. In general, infants who are higher on approach based temperamental tendencies such as anger and exuberance are also more active. Activity level, although not overtly emotion-related, is a traditional temperament dimension included in the surgency dimension of the IBQ. Evidence suggests that motor activity reflects multiple systems: reactivity (Filippi et al., 2020; N. A. Fox et al., 2015) both positive (Putnam et al., 2014) and negative (Kagan et al., 1994), and both up-regulation and down-regulation of reactivity (Crockenberg & Leerkes, 2004). Ekas et al. (2013) noted that there were relatively few studies examining behaviours associated with up-regulation, such as banging arms and kicking legs, and this remains the case. Motor activity has also been positively associated with markers of ES (Underwood & Gartstein, 2022). This strengthens the case that approach behaviours are more prevalent in supportive environments, and could make infants more susceptible to the positive elements of the environment.

In contrast, behaviourally inhibited children with an attention bias to threat or novelty are at increased risk for developing anxiety disorders (N. Fox et al., 2007). This could be evidence of the domain-specificity of sensitivity insofar as individuals develop heightened sensitivity towards different elements of the environment which influence developmental outcomes. The propensity to display increased vigilance to novelty among behaviourally inhibited children may prevent effective regulation of emotional responses to novel situations and may sustain or exacerbate social and affective maladjustment (E. Fox et al., 2001, 2005).

For both the sensitivity measures (neural) and reactivity measures (behavioural) there were interesting relations with autonomic measures. In terms of the autonomic measures themselves, baseline and reactivity measures correlated in the expected direction: higher baseline correlated with greater reactivity. Heart rate correlated negatively with RSA.

The second branch of the findings in Chapter five was that autonomic arousal (indexed by higher heart rate) was associated with a larger difference in response amplitude of the visual N290 component to fearful and neutral faces one component thought to be more linked to emotion recognition and a smaller difference in the response amplitudes of the visual P4 component and the auditory P3 component thought to reflect bottom-up stimulus driven sensitivity in the 6-month-old infants. Follow up analyses showed that autonomic arousal, indexed by HR, was associated with a larger N290 component in response to fearful faces. Higher heart rate indexes more SNS activity, which indexes vigilance to threat and could explain why it associates with a larger neural response to fearful faces.

8.5.2 Hypothesis two – Measures of sensitivity to immediate environmental effects are stable across development.

We did not find support for this hypothesis. One of the strengths of this study was its longitudinal nature which provided the opportunity to track changes in sensitivity across development, while concurrently measuring the developmental environment. Our results provided support for the theory that perception is initially broadly tuned and through development becomes refined so as to be best adapted to the environment in which development takes place.

While the autonomic baseline measures correlated between 6-months and 12-months, as did the scores on the parent-report measures of temperament, most of the autonomic reactivity measures did not. Furthermore, neither the neural sensitivity nor the behavioural reactivity measures correlated from 6-months to 12-months. This is in line with other researchers' lack of findings of test re-test reliability of reactivity in infants (Kagan, 1994). Other studies have been unable to find associations between reactivity measures even in the same testing session. When multiple lab experimental stressors are administered to a single cohort, consistent inter-individual differences in stress reactivity were not observed (Obradović et al., 2011). Repeated assessments of stress reactivity have shown that test–retest reliability only becomes moderate in middle childhood (Alkon et al., 2003), and does not reach high levels until adolescence (Allen & Matthews, 1997). Consistent with the animal literature on early plasticity of stress response systems (Hofer, 1994; Meaney, 2001), this increasing test–retest reliability over childhood suggests that in line with the notion of conditional adaptation conceptualized in BSC theory, reactivity is a

developmentally “canalized” characteristic, which is significantly influenced by early experience.

The results of both the study of neural sensitivity and that of behavioural reactivity in chapters five and six respectively were interpreted as representing fractionation of response with development. The neural associations at 6-months were not found at 12-months. We interpreted this with regard to neuroconstructivism and increasing domain specificity of initially domain relevant modules. An initially broadly tuned perceptual sensitivity becomes increasingly domain specific such that the size of the same components no longer associates. While the correlation found at 6-months is not sufficient to support a claim of domain-general sensitivity, it does elucidate the development of perceptual sensitivity in infants and that there does seem to be a subset who are more sensitive to both visual and auditory stimuli at 6-months and that different levels of autonomic arousal associate with early neural processing of stimuli.

The development of neural sensitivity, from being general across neural domains to being domain specific, that we found, is in line with accounts that hold that initially separate sensory systems become integrated through repeated experience of concurrent information provided by the different sensory modalities (Birch & Lefford, 1963, 1967). Intersensory integration of different modalities comes at the expense of a level of sensitivity that is domain general. Our findings corroborate accounts of a level of sensitivity that is initially domain general at 6-months -whether perceiving multi-modal or unimodal stimuli - and thereafter develops differentially in the different domains at 12-months.

Much work has been carried out to ascertain the most sensitive periods for brain and behavioural development (Gabard-Durnam & McLaughlin, 2020; Frankenhuys & Walasek, 2020). The developmental processes that contribute to plasticity in early life include both experience-expectant and experience-dependent mechanisms (Kolb & Gibb, 2014). Experience-expectant processes regulate the types and timing of environmental experiences that are needed for specific cognitive, emotional, and social capacities to develop in a typical manner (McLaughlin & Gabard-Durnam, 2021; Hensch, 2018). Research examining variation in the timing of removal from institutions and placement into a family has revealed a sensitive period in the first two years of life for the development of a secure attachment to a caregiver (Smyke et al., 2010). Experience-dependent plasticity during development allows neural structure and function to be influenced more readily by lived experiences that occur during these early phases of life (Kolb & Gibb, 2014), potentially shifting longer-term developmental trajectories (Ellis et al., 2022). However, further

investigation is required into which domains of developmental outcomes are sensitive to which elements of the environment and which point in development. In conclusion, recent research in the area suggests that while ES may start out as domain-general, in that all infants show heightened sensitivity and reactivity to all elements of their environment, it develops in a domain-specific manner through experience-expectant and experience-dependent mechanisms.

In the following section, I shall look at conceptions of the environment and how this motivates research

8.5.3 Hypothesis three: Heightened sensitivity will associate with more highly positive or negative developmental environments.

I did not find any significant associations between measures denoting the quality of the developmental environment and infant sensitivity measures. However, the demographic and environmental measures were not normally distributed and were highly skewed in the direction of high socioeconomic status and parental wellbeing. The lack of heterogeneity of environmental context may have made it difficult to detect correlations.

Relevant to a discussion on where heightened sensitivity to the environment is likely to emerge is that unlike the behavioural reactivity measures, which did not correlate from 6-months to 12-months, parent-report measures of temperament did correlate longitudinally. This suggests either that habitual responses to the environment are relatively stable by 6-months or that parents' perception of their infants' responses are consistent. Factor analyses of the IBQ scores of infant temperament revealed positive loadings on factors of items describing 'easy' temperaments such as soothability and low-intensity pleasure and negative loadings on factors of items denoting 'difficult' temperaments such as fear, sadness, and distress to limitations. This predominantly positive perception of their infants' temperaments is noteworthy in terms of its contribution to the quality of the developmental environment of the infants in this study. Perceptions of difficult infant temperament during early infancy predicted poorer mother-to-infant bonding during the first 9 months of infancy (Takacs et al., 2020).

One conceptualization of the adverse developmental environment is that of cumulative risk (Evans et al., 2013). This approach assumes that adversity can be separated into discrete forms such as neglect, abuse or poverty and these have additive effects on developmental outcomes. Criticisms of this approach are that it does not assume that

different kinds of adversity produce distinct changes in different domains of development such as behavioural or neural (Ellis et al., 2022). Furthermore, it does not explain how environmental effects become instantiated which is necessary to know which elements of the environment affect which developmental outcomes. This consideration is equally applicable to conceptualisations of supportive environments. Which elements are necessary at which developmental stage for which outcomes? Throughout the literature, supportive environments associate with better self-regulatory capacities. Research has found that during infancy, markers of low self-regulation such as low baseline RSA are also associated with prefrontal hypoactivity and predict hypervigilance and inefficient allocation of attentional and cognitive resources (Thayer & Brosschot, 2005). Well-regulated infants are therefore possibly better able to be receptive to development enhancing aspects of the environment, which are conducive to optimal long-term functioning.

Attention should now focus on understanding by which mechanisms the effects of adverse or supportive environments become instantiated and why contextually induced development operates the way that it does. These two questions are essential to understanding which dimensions of the environment matter (Ellis et al., 2022) and whether this varies between individuals, with some being more affected by certain elements and others by others.

The finding contained in Chapter five that larger neural responses to fearful faces correlated with higher autonomic arousal could indicate greater activation of the SNS in response to threat. More frequent activation of the SNS has been found to exacerbate an attention bias that alters critical affective neurocircuitry to threat and enhances and maintains anxious behaviour in the child (Fox et al., 2007).

Neuroimaging studies in adults have shown that fearful facial expressions, elicit strong activation of the amygdala (J. S. Morris et al., 1996) even when the expressions are spatially unattended (Vuilleumier et al., 2001). This functional imaging work is particularly interesting in that the enhanced activation of the amygdala in response to threat-related stimuli has been shown to modulate modality-specific sensory cortical areas (Armony et al., 2001). This is consistent with the idea that in infants, sub-cortical orienting involving the amygdala modulates activity in face-sensitive cortical regions before the arrival of visual information through the cortical route (Johnson, 2005). The implications of these findings are that in adults also, the amygdala is activated directly by the presence of threat-related stimuli and that cortical areas are then modulated via re-entrant projections from the amygdala to the cortex (Amaral & Price, 1984). This mechanism would serve to prioritize

the processing of emotionally significant stimuli (Anderson & Phelps, 2001; Vuilleumier, Richardson, Armony, Driver, & Dolan, 2004) at higher levels of arousal.

In terms of ERPs, an enhanced N170 response to fearful faces in adults might reflect recurrent feedback from the amygdala to the visual extrastriate region, which heightens the perceptual processing of fearful faces (Pegna et al., 2008). The N290 is thought to be the infant precursor of the adult face-sensitive N170 response (Haan et al., 2003). There is evidence that an early general sensitivity to threat can be exacerbated if this sensitivity proves adaptive in the developmental environment. In this way domain-specific sensitivity which prioritizes the processing of potentially threatening elements of the environment may develop due to adaptive calibration. In line with this, greater wave amplitudes when processing angry faces were found among maltreated children (Cicchetti et al., 2005; Pollak et al., 1996, 2003).

Because of the undeniable necessity and importance of research into developmental pathways to psychopathology, research into enhanced responses to facial expressions of positive emotion in individuals developing in nurturing contexts, which could be evidence of vantage sensitivity, is lacking.

8.5.4. Hypothesis four: Highly sensitive individuals will benefit more from a positive developmental environment than less sensitive individuals.

In the same way that adverse developmental environments may adaptively calibrate sensitivity to threatening elements, supportive environments may adaptively calibrate sensitivity to best exploit the available resources. A limitation of the study on neural sensitivity in chapter five - regarding pre-attentive processing of difference - is that it lacks an outcome measure and therefore we cannot ascertain whether greater bottom-up perception of auditory difference constitutes differential susceptibility to environmental effects on long-term outcomes.

However, in Chapter six, I found that the relationship between negative affect at 6-months and positive affect at 12-months was stronger at higher levels of maternal education. Early in infancy, evidence suggests that negative affect constitutes greater susceptibility to the effects of the environment on outcomes. It could be that in a well-resourced and supportive environment which could be indicated by higher levels of maternal education it was those infants whose behavioural manifestations of negative affect

were met with sensitivity, were better able to learn to self-regulate and develop more pro-social behaviours by 12-months (Waal & Preston, 2017).

One question regarding vantage sensitivity is whether supportive environments are co-extensive dimensionally with adverse environments. The Benevolent Childhood Experiences (BCE) scale (Narayan et al., 2018) has been developed to ascertain the extent of support along the same lines as the adverse childhood experiences (ACE) checklist. However, these will not elucidate which elements of the developmental context are most beneficial at which stage, how and why. These are all questions relevant to further research on vantage sensitivity.

8.6 How do the findings of this thesis inform our understanding of sensitivity and the measurement thereof?

Recent work has highlighted the necessity to progress from understanding merely *what* the effects of early developmental experiences and environmental exposures of adversity and support are on child development. Attention should now focus on understanding by which mechanisms the effects become instantiated (Ellis et al., 2022). However, it is now more common to acknowledge that individuals may differ systematically in their susceptibility to environmental influences (Belsky & Pluess, 2009).

Findings from both observational and experimental (Berg et al., 2014) studies prove consistent with the proposition that negative emotionality is a behavioural indicator of enhanced developmental plasticity, “for better and for worse.” This suggests that rather than a development risk factor, negativity should be regarded as an “opportunity” factor (Hartman & Belsky, 2018). It should be noted that in a meta-analysis of research on Parenting x Temperament interaction, the “for better and for worse,” differential-susceptibility-related effect was restricted to investigations that assessed negative emotionality in infancy, not later in life. When, meta analytically, negativity was examined as a moderator of parenting effects at older ages, results did prove more consistent with diathesis–stress thinking (Slagt et al., 2016).

Interestingly, we found an interaction effect of negative reactivity and maternal SES on the development of more positive reactivity at 12-months. This could be interpreted as more evidence in support of the robust finding that it is in fact negative reactivity (and not positive reactivity, with which it correlated at 6-months) which indexes heightened susceptibility to the effects of the environment in young infants. As with all indices of heightened sensitivity, negative reactivity can constitute a diathesis. More negative mood

has been associated with lower flexibility and adaptation in response to stressors in pre-term infants (Langkamp et al., 1998). These low self-regulation capacities may make preterm infants highly dependent on external regulation provided by their caregivers. Whereas a supportive environment can successfully regulate physical and emotional arousal, a stressful unsupportive environment may not be able to effectively modulate infants' arousal, preventing exploration and social interaction. For infants with more effective regulation capacities (often associated with less negative affect) sub-optimal environmental support may be less detrimental (Gueron-Sela et al., 2015).

Similarly, and related to negative reactivity, evidence suggests that high baseline RSA is a marker of susceptibility in early infancy. Because of higher reactivity, infants with higher RSA may be more likely affected by variations in environmental input (Beauchaine, 2001), which may lead to negative or positive developmental outcomes depending on the quality of the environment (Conradt et al., 2013; Eisenberg et al., 2012; Obradović et al., 2010). For this reason, I predicted that high baseline RSA would moderate the relationship between the developmental environment and developmental outcomes – indexed by measures of self-regulation and sustained attention.

However, low baseline RSA has been linked to reduced internal regulatory resources (Skowron et al., 2014). This has been associated with increased reliance on external sources of regulation. For children, low baseline RSA associated with a differential effect of sensitive parenting during toddlerhood on executive functioning, suggesting that a supportive caregiving environment is particularly important when internal regulatory resources are lacking (Gueron-Sela et al., 2017). As such, greater reliance on external regulation is a weakness leading to detrimental long-term effects when states of arousal are not effectively managed by a caregiver. Low RSA indicates states of SNS dominance associated with disinhibited defensive circuits, which can be pathogenic when sustained for long periods.

In summary, the findings of the studies contained in this thesis suggest that in early infancy, heightened sensitivity is general to all levels of analysis and represents a predisposition towards a wide range of reaction in terms of developmental outcomes and functioning (Manuck, 2009). However, depending on the environments that are encountered, this can be calibrated towards better self-regulation, which buffers against the risks associated with negative environments and enables better exploitation of positive experiences. However, more reliance on external regulators, can be either detrimental leading to hyperactive stress responses and increased allostatic load or protective -

strengthening self-regulatory capacities and enabling increased responsiveness to beneficial environmental input.

All this points to the importance of measuring the developmental environment in a more fine-grained way as specified in models such as the harshness-unpredictability model (REF) or the threat-deprivation model (REF) or an integrated model which looks at both proximal and distal cues to threat or deprivation based forms of harshness and unpredictability ((Ellis et al., 2022) as well as similar models for supportive environments. Furthermore, Although DST and BSC are developmental evolutionary theories, it has recently been highlighted that for many years a simplistic general trait-like view of susceptibility to environmental influences has been widely entertained if not embraced in the field (Belsky et al., 2022). Studies of differential susceptibility referred to different putative ‘plasticity markers’ whether focused on genes, temperament or physiology as moderating in similar ways the association between many different environmental effects and developmental outcomes.

The possibility has been more recently described as “differential, differential susceptibility,” suggesting that individuals who are susceptible to one environment may be less susceptible to another (Belsky et al., 2021). The view that ES is domain specific with different modalities being differentially calibrated by different elements of the developmental context leading to different outcomes in different domains of functioning is increasingly supported. Therefore, more research into which mechanisms affect which domains of functioning is required.

8.7 Practical implications of study findings

Overall, identifying those with higher levels of sensitivity and susceptibility to the environment has implications both for research and for child protection. I shall address each in turn.

Despite the evidence for significant inter-individual differences in ES, psychological research often tests hypotheses by comparing average effects of an intervention or condition across the sample and accepting the null hypothesis if there is no change for the whole group post intervention or if the variance within a group exceeds the variance between groups. This ignores that effects may vary between people as a function of their specific degree of environmental sensitivity. Hence variability within groups will be to some extent because some will be more susceptible to the effects of an independent

variable. Such studies are at risk of underestimating effects for highly sensitive individuals and overestimating effects for less sensitive ones (Ellis et al., 2011).

This prediction has already been confirmed in various experimental interventions on parenting and childcare, as already evidenced in preceding chapters. Quite modest or even absent intervention effects within a mixed sensitivity group are juxtaposed with modest to strong effects for susceptible subgroups of children or their parents (e.g., Bakermans-Kranenburg, van IJzendoorn, Mesman, et al., 2008; Bakermans-Kranenburg, van IJzendoorn, Pijlman, et al., 2008; Cassidy et al., 2011). Thus, intervention effectiveness cannot be indexed by the average effect across all participants without considering their differential susceptibility to the intervention. (Ellis et al., 2007b). Therefore, increasing knowledge of ES may eventually guide the (a priori) identification of subsets of participants most open to intervention. This will enable practitioners and policymakers to obtain more realistic estimates of the effectiveness of preventive or curative efforts. The ability to easily identify individuals high in ES could facilitate the design of programmes and policies specifically tailored to the needs of children and adults at all levels of ES.

Bridging the gap between research and practical application, decades of research has implicated the role of different emotional, behavioural, or cognitive attributes in moderating environmental effects on development. Parenting and other environmental factors are posited to vary in their developmental influence as a function of the characteristics of the child (Wachs and Gandour, 1983; Bronfenbrenner, 1993). Therefore, a long history of research on parenting x temperament interactions suggests that children are not equally susceptible to rearing and other contextual experiences (Boyce, 2016). Nevertheless, much work has persisted in focusing on contextual effects (such as amount of time spent in non-parental childcare (Bradley et al., 2007)) that are assumed to apply equally to all children and thus fails to consider the possibility that whether, how, and to what degree early experiences influence child-development may critically depend upon individual characteristics (Ellis & Boyce, 2011).

Theories of ES assume that children are not equally susceptible to the effects of childcare. Early experience may calibrate reactivity to either the negative or positive elements of the environment. One way in which an adverse environment can heighten sensitivity to threat is through the HPA axis and amygdala activation. Activation of the amygdala triggers the release of glucocorticoids. Children repeatedly exposed to stressors may be at high risk for frequent activation in the amygdala that promotes patterns of use-dependent connectivity which are detrimental to attention and executive cognitive

processes. Specifically, patterns of connectivity may be promoted which increase the influence from anxiety and fear on attentional and executive processes rather than fostering executive processes to regulate amygdala activation and fear (Blair, 2002b). Furthermore, the prefrontal cortex plays an important role in the control of fear and anxiety. In studies of conditioned fear in rats, work on the fear system, has shown that its operation and its attendant consequences for cognition need not require the conscious experience of fear but likely reflect vigilance to possible threat and the directing of cognitive resources to the maintenance of the vigilant state (LeDoux, 2003).

Evidence has shown that the reactivity of the HPA axis is particularly susceptible to the quality of the caregiving experienced in infancy. Whereas a cortisol response is reliably elicited under stressful experiences for adults and children, there is evidence that from around 6-months, infants undergo a stress hypo-responsive phase, during which cortisol is not elevated in response to stressors. It may function to protect the developing brain from circulating glucocorticoids (M. R. Gunnar & Cheatham, 2003). It is thought that adequate parental care buffers stress reactivity (Gunnar et al., 2002). Among rodents and humans, sensitive parenting is necessary to maintain this stress hypo-responsive period (Levine, 2002). Maternal separation caused a cortisol response in infants with disorganised attachment, but not those with organised attachments (Hertsgaard et al., 1995).

The fact that the first two years of life have been found to be a window of heightened plasticity for brain development and organisation (Fox et al., 1994) thereby rendering all individuals highly susceptible to environmental influences at this time means that it is critical that those environments calibrate development towards optimal long-term outcomes in terms of cognitive, social, and emotional development.

Research has found that during infancy, markers of low self-regulation such as low baseline RSA render infants more reliant on caregivers for regulation. While this can grant more agency to parents who are well regulated themselves, for parents with depressive symptoms or high anxiety, this can lead to a continuing cycle of dysregulation. Higher postpartum depression (PPD) symptoms predicted higher maternal depressive symptoms at 36 months, especially among mothers whose infants had lower resting RSA. The interactive effect of PPD symptoms and infant RSA on 36-month depressive symptoms was partially mediated by lower parenting self-efficacy. Lower infant RSA may exacerbate the detrimental effects of PPD symptoms on subsequent maternal well-being via damage to mothers' beliefs in their ability to parent effectively (Somers et al., 2019).

Interventions such as the Video-feedback Intervention to promote Positive Parenting and Sensitive Discipline (VIPP-SD) have proved effective in enhancing sensitive parenting which are key to positive parent-child relationships (Juffer et al., 2017). These would be especially effective for those infants whose level of environmental sensitivity makes them especially susceptible to all environmental effects early in development. Intervention at this early stage could buffer them against sensitivity to the detrimental effects of adversity later in life (Keers et al., 2016).

From a societal impact perspective, SPS has gained substantial popularity in the public and media, with programmes being developed and professionals trained to coach and support highly sensitive employees, leaders, parents, and children (Greven et al., 2019).

8.8 Future directions

Efforts to overcome the limitations of this thesis should begin with replication. This would ideally involve conducting high-powered studies by increasing the sample size. This could be done by extending the data collection at the different ages to allow for greater numbers to be tested. This would eventually involve running testing sessions for 6-months and 12-months-old concurrently as the first 6-months infants started to return at 12-months. However, use of the same battery for both ages would facilitate this. Ideally participants would be drawn from a greater diversity of developmental environments in order to be able to more comprehensively test the differential sensitivity hypothesis.

As already discussed in the limitations section, a more proximal measure of parenting might yield more clarity on exactly which components of the developmental environment interact with ES to affect developmental outcomes. Interventions such as the attachment and biobehavioral catch-up programme (Dozier et al., 2017), infant-parent psychotherapy (Cassidy et al., 2011; Dehghani et al., 2014) and the group attachment-based intervention (Steele et al., 2019) are undoubtedly beneficial for all children. But may be especially valuable for those who whom stressful early life experiences have caused them to have hypersensitive stress response systems. A meta-analysis of the first 25 randomised controlled trials of Video-feedback Intervention to promote Positive Parenting and Sensitive Discipline (VIPP-SD) (Juffer & Bakermans-Kranenburg, 2018), showed substantial combined effect sizes for parenting behaviour and child attachment (Van Ijzendoorn et al., 2022).

To build on the findings of this thesis, researchers could use models with multiple waves of data collection. For example, as good relations have been maintained with participants in this study, there is always the possibility that developmental outcomes could be measured to see how they associate with measures of ES and the developmental context.

Finally, as mentioned by Ellis et al. (Ellis, Belsky, et al., 2011) the meaning and context of specific parental behaviours, as well as the value placed on specific developmental outcomes, may vary between different cultural groups and across different ecological niches (Deater-Deckard et al., 1996; Hinde et al., 1990). Furthermore, neurobiological susceptibility may differ between ethnicities. One gene x environment interaction was found to apply to Caucasians but not African Americans (Widom & Brzustowicz, 2006). This highlights the cultural specificity of the environment, the susceptibility factor, and the developmental outcome that together constitute the differential susceptibility equation. Therefore, while ethnically homogeneous samples should thus be preferred in G E investigations, they should not be restricted to Caucasian samples in Western countries. The generalizability of GE interaction effects reflecting differential susceptibility to populations of different cultures and races is not self-evident, but should each time be empirically established (Ellis, Belsky, et al., 2011).

8.9 Ethical considerations

Two ethical considerations which had been concerning me throughout this research had been addressed by researchers in the field over a decade ago. The first concerns the fact raised in section 8.4 of this Chapter that a direct implication of DST is that intervention effects will be much larger for those individuals more susceptible to environmental input (Bakermans-Kranenburg et al., 2008). Being able to identify subsets of participants most open to intervention will provide more realistic estimates of the effectiveness of preventive or curative efforts. While this could facilitate the design of programmes and policies specifically tailored to the needs of individuals high in ES, it could also lead to the possibility of excluding individuals on the grounds of being less likely to benefit from interventions. Ellis et al. (Ellis, Belsky, et al., 2011) highlight that as ES is better conceptualised as a continuous dimension than in categorical terms of susceptible or not, less susceptible individuals may simply need intensification of intervention efforts before obtaining results like those achieved with more susceptible individuals. Alternatively, it

could be that less susceptible individuals are simply unresponsive to the range of interventions employed so far.

My second concern was that identifying highly sensitive individuals should not imply a “making the vulnerable more durable” solution (i.e., fixing what is “wrong” with sensitive people). It is important that the focus should not be on ‘within-person’ attempts at change, or increasing resilience, but instead on focusing on ‘environmental’ effects that do no harm to anyone at the least and foster thriving at best. One perspective of resilience is framed in terms of reaction norms (Manuck, 2009), whereby some individuals have a wide range of reaction in terms of their developmental outcomes and functioning, depending on the environments they encounter. So-called resilient children, if afforded especially supportive rearing environments, might be the least likely to benefit. The discovery of susceptible individuals renders possible a perspective in which making social environments safe and supportive for even the most sensitive people makes the world better for all people (Ellis, Belsky, et al., 2011).

Finally, focusing on the ‘bright side’ of ES should not in any way detract from the risks associated with susceptibility to the effects of the environment, the ‘dark side’ (Bakermans-Kranenburg & van Ijzendoorn, 2011). Rather, it should direct attention towards interventions and modifications to make developmental environments better for all and highlight the importance of sensitive and appropriately responsive parenting and on supporting parents to be able to offer this to all children.

Concluding comment

“It is easier to build strong children than to repair broken men” the abolitionist, journalist, and reformer Frederick Douglass (1819–1895) proclaimed in the mid-19th century. While this undoubtedly holds true and is in accordance with insights from modern neuroscience and biomedical research, suggesting that the foundation for health and positive adaptation across the lifespan is laid early in life (Heim et al., 2019), perhaps a complementary ideal would be to try to build systems which will not break people regardless of their “strength”. Systems in which all can survive... and thrive.

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Appendices

Appendix A. Ethics documentation



University of
East London

Pioneering Futures Since 1898

Dear Katie

Application ID: ETH1819-0059

Project title: Doctoral Research Project

Lead researcher: Mrs Katie Daubney

Your application to University Research Ethics Committee was considered on the 27th of February 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 University 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'.

The approval of the proposed research applies to the following research site.

Research site: UEL BabyLab Stratford Campus

Principal Investigator / Local Collaborator: Mrs Katie Daubney

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

Fernanda Silva

Administrative Officer for Research Governance

Research, Research Degrees and Ethics Subcommittee (RRDE)

Email: researchethics@uel.ac.uk

Docklands Campus
University Way
London E16 2RD

Stratford Campus
Water Lane
London E15 4LZ

University Square Stratford
Salway Road
London E15 1NF

+44 (0)20 8223 3000
srm@uel.ac.uk
uel.ac.uk





University of
East London

Pioneering Futures Since 1898

Dear Katie,

Application ID: ETH2223-0101

Original application ID: ETH1819-0059

Project title: Environmental Sensitivity: A Multi-Domain Investigation of its Development in Infancy

Lead researcher: Mrs Katie Daubney

Your application to Ethics and Integrity Sub-Committee (EISC) was considered on the 10th January 2023.

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 4 years from the approval date.

If you have any questions regarding this application please contact your supervisor or the administrator for the Ethics and Integrity Sub-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/consultancy project you must complete 'An application for approval of an amendment to an existing application'.

The approval of the proposed research/consultancy project applies to the following site.

Project site: **UEL BabyLab Stratford Campus**

Principal Investigator / Local Collaborator: Mrs Katie Daubney

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/consultancy 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 projects are conducted in compliance with the consent given by the Ethics and Integrity Sub-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 Pereira Da Silva

Administrative Officer for Research Governance

Appendix B. Subscales included in the Negative affect and Surgency scales of the Infant Behaviour Questionnaire (IBQ)

Table ?? qualitative description of the dimensions comprising the negative reactivity scale from *Infant Behaviour Questionnaire-Revised-Short Form*

Scales	Definitions
Distress to limitations	Fussing, crying, or showing distress while (a) in a confining place or position; (b) in caretaking activities; (c) unable to perform a desired action. ("When the baby wanted something, how often did s/he become upset when s/he could not get what s/he wanted?")
Sadness	Lowered mood and activity related to personal suffering, physical state object loss, or inability to perform a desired action; general low mood. ("When tired, how often was your baby show distress?")
Fear	Startle or distress to sudden changes in stimulation, novel physical objects, or social stimuli; inhibited approach to novelty. ("How often during the last week did the baby startle to a sudden or loud noise?")
Falling reactivity	Rate of recovery from peak distress, excitement, or general arousal; ease of falling asleep. ("When put down for a nap, how often did your baby settle down quickly?")

Table ?? qualitative description of the dimensions comprising the surgency scale from *Infant Behaviour Questionnaire-Revised-Short Form*

Scales	Definitions
Approach	Rapid approach, excitement, and positive anticipation of pleasurable activities. ("How often during the week did your baby move quickly towards new objects?")
Smiling and laughter	Smiling or laughter from the child in general caretaking and play situations. ("How often during the last week did the baby laugh aloud?")
High pleasure	Amount of pleasure or enjoyment related to high stimulus intensity, rate, complexity, novelty or incongruity. ("When tossed around playfully, how often did the baby laugh?")
Activity level	Gross motor activity, including movement of arms and legs, squirming and locomotor activity. ("During feeding, how often did the baby squirm or kick?")
Perceptual Sensitivity	Amount of detection of slight, low intensity stimuli from the external environment. ("How often did your baby notice fabrics with a scratchy texture?")
Vocal Reactivity	Amount of vocalisation exhibited by the baby in daily activities. ("How often during the last week did the baby squeal or shout when excited?")

The current study used the composites of negative reactivity (comprised of the dimensions of sadness, distress to limitations, fear, and low falling-reactivity) and surgency (comprised of the dimensions of approach, smiling and laughter, high pleasure, activity level, perceptual sensitivity and vocal reactivity) (see Table?? And ?? for qualitative descriptions) as measures of parent reported temperamental positive and negative affect. The internal consistency of the negative affect scale was $\langle .59$ (rising to $.73$ without the fear subscale) at 6-months and $\langle .59$ at 12-months. The alphas for the four subscales which comprise negative affect, ranged from $.5$ to $.77$ at 6-months and $.58$ to $.62$ at 12-months. The internal consistency of the positive affect scale was $\langle .77$ at 6-months and $\langle .85$ At 12-months. The alphas for the six subscales ranged from $.55$ to $.77$ at 6-months and $.46$ to $.85$ at 12-months.

Appendix C. Information on the algorithms used to process the raw ECG data in Kubios

In the automatic artefact correction algorithm, artefacts are detected from dRR series, which is a time series consisting of differences between successive RR intervals. The dRR series provides a robust way to separate ectopic and misplaced beats from the normal sinus rhythm. To separate ectopic and normal beats, time varying threshold (T_h) is used. To ensure adaptation to different HRV levels, the threshold is estimated from the time varying distribution of the dRR series. For each beat, quartile deviation of the 90 surrounding beats is calculated and multiplied by factor 5.2. Beats within this range cover 99.95% of all beats if RR series is normally distributed. However, RR interval series is not often normally distributed, and thus, also some of the normal beats exceed the threshold. Therefore, decision algorithm is needed to detect artefact beats. Ectopic beats form negative-positive-negative (NPN) or positive-negative-positive (PNP) patterns to the dRR series. Similarly long beats form positive-negative (PN) and short beats negative-positive (NP) patterns to the dRR series. Only dRR segments containing these patterns are classified as artefact beats. Missed or extra beats are detected by comparing current RR value with median of the surrounding 10 RR interval values ($medRR$). A missed beat is detected if current RR interval ($RR(i)$) satisfies condition $RR(i) - medRR(i) < 2T_h$ (1) and an extra beat is detected if two successive RR intervals ($RR(i)$ and $RR(i+1)$) satisfy condition $|RR(i) + RR(i+1) - medRR(i)| < 2T_h$. (2) Detected ectopic beats are corrected by replacing corrupted RR times by interpolated RR values. Similarly, too long and short beats are corrected by interpolating new values to the RR time series. Missed beats are corrected by adding new R-wave occurrence time and extra beats are simply corrected by removing extra R-wave detection and recalculating RR interval series

Appendix D. Coding manual for behavioural tasks

Terminology

Certain terminology is used in describing the components of the manual. Sometimes the stimulus is presented over multiple trials. To facilitate coding, the longer episodes are typically divided in shorter intervals called epochs (for our purposes, these are one second epochs). Within each epoch, several infant responses, such as smiling, reaching, or crying, are coded. Sometimes simply the presence or absence of a response is noted; however, more often parameters of the response, such as duration and intensity are rated.

Peekaboo task: This task includes three trials; you will see the experimenter doing peek-a-boo three times with 15s intervals in between.

Toy Retraction task: This task includes three trials. For each trial the mother moves the toy to the edge of the table where it is in sight but out of reach of the infant and leaves it there for 15s before resuming play with the toy for 15s.

The coding of both tasks will include the three 15s trials (when the toy is removed) and the 15s free play sessions before and between the trials

Set-Up

Open the script for the relevant task on the desktop e.g., “SlyviaCoding_Peekaboo.m”

Enter the subject number you want to code (In the script, somewhere around line 23 or 24, you will see SubNo=...)

Click the green “Run” button on the top (see fig. 1)

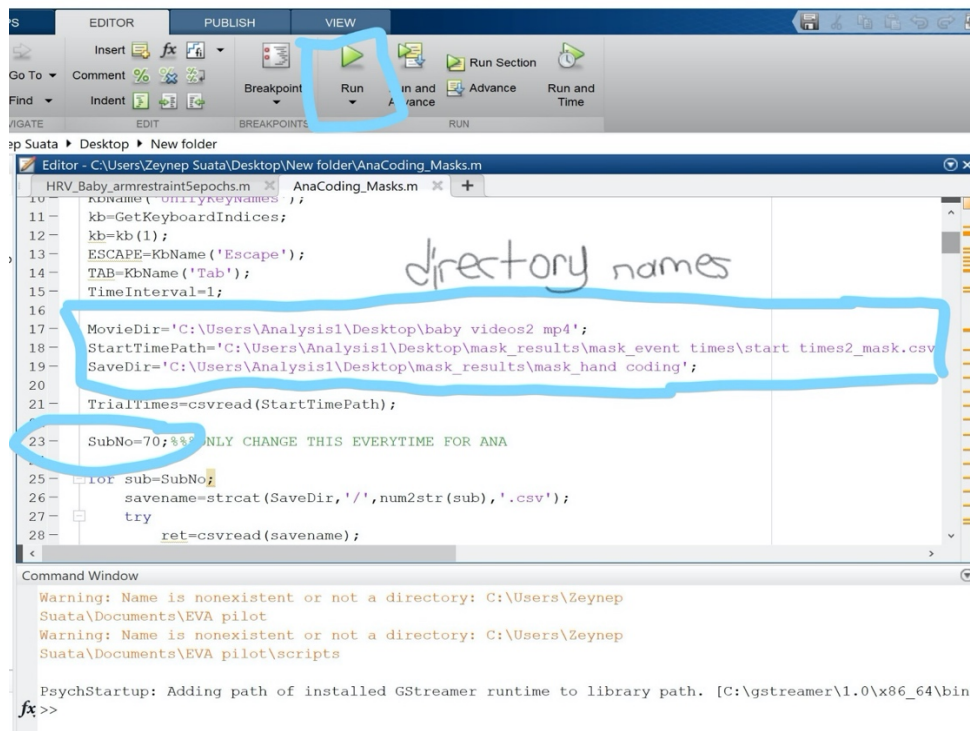


Figure 1. MATLAB open with coding script open. Highlighted are the directories where the videos are, the times that the task starts, and the folder where the coded files are to be stored

A small window showing the video will come up on the left upper side, and the experiment will start.

Possible errors you may face at this stage:

If the subject number you put does not exist in the videos file (“baby videos2 mp4”) or saved with a different name-> check the script and the folder (e.g., you put 70, but it was saved as 0270)

If one of the directories’ names is slightly wrong, i.e., the folder name or the excel file of times-> check the script and laptop for the correct directories

Sometimes MATLAB crashes->in that case try restarting MATLAB

If you cannot solve the problem, please get in touch with me quickly.

Several questions come up in order, and you will need to press a specified button as an answer:

Peekaboo Task

Question 1*: ‘Infant distraction (1), not doing (2), repeat (9), or quit (10) or recode previous epoch (11)?

Distraction means looking away from stimulus. Before the task starts, there may not be an explicit stimulus. Thus, the infant might not be distracted from something unless you see there is an object that baby is attending to and could be distracted by even before the actual task. If the infant is just looking around the room or under the table before the experiment starts, this is not distraction, especially when the experimenter is under the table. If these behaviours happen during the experiment, then it is distraction.

Press 9; if you would like to replay the epoch

If you press 10, you can jump to the next trial of the tasks and eventually quit the coding questions. This option only will appear at the end of the first question at each epoch/second.

Press 11; if you would like to go back and recode the previous epoch/second before. This option only will appear at the end of the first question at each epoch/second.

Distraction is looking away from the stimulus (e.g., infant looking around the room, at another stimulus or the camera etc.). However, if the baby is looking at the mother, that is only looking at the mother. There is no distraction.

If the baby does both distraction behaviours and looks at the mother (e.g., the infant looked at the walls, and then mother in one epoch clearly); then you can code for both.

Question 2*: ‘Looks to mother (1), not doing (2) or repeat (9)

This is when the infant looked at the mother’s face as social referencing. If the infant definitely looks elsewhere at the mother such as hands during the task, that is distraction. If it is not very clear where the infant is looking (e.g., not clear whether looking at face, hair, shoulder...), you can still code it as looks to mother.

Question 3*: ‘Reaching/touching mother (1), not doing (2) or repeat (9)

This is when the infant is trying to touch/reach mother, or if the infant touches the mother.

Question 4*: ‘Self-soothing (1), not doing (2) or repeat (9)

The infant uses a body part to engage in repetitive manipulation (e.g., sucking thumb, fingering clothing, and twirling hair). Thumb sucking is very apparent self-soothing behaviour. Sometimes you can see twirling or playing with hair, make sure this is occurring most of that second/segment, if you think it is happening. You should see at least two seconds for it to be self-soothing

Question 5: ‘Infant motor activity present (1), not present (2) or repeat (9)

Positive motor acts include the following: banging hands on the table; clapping hands; waving arms in excitement; definite leaning forward towards the experimenter.

Question 6: ‘Infant positive facial affect - neutral/no affect, (2) low pos (3) mild pos (4) intense pos (5) cannot see (8) or repeat (9)

Intensity of facial joy: Peak intensity of positive facial affect is noted in each epoch using AFFEX (see appendix A) and rated on the following scale:

2= No facial region shows codable negative affect or no smiling at all.

3= Small smile, with lips slightly upturned, and no involvement of cheeks or eyes.

4= Medium smile, with lips upturned, perhaps mouth open, slight bulging of cheeks, and perhaps some crinkling about the eyes.

5= Large smile, with lips stretched broadly and upturned, perhaps mouth open, definite bulging of cheeks and noticeable crinkling of eyes.

8=Baby face cannot be seen at all (If whole face is covered!) Do not be tempted to go for this if you could didact from the voice or from the previous segment about baby's facial expression.

Question 7: 'Infant negative facial affect - neutral/no affect (2), low neg (3), mild neg (4), intense neg (5), cannot see or (8), repeat (9).

Intensity of facial fear/anger/sadness: Peak intensity of negative facial affect is noted in each epoch using AFFEX (see appendix A) and rated on the following scale:

2= No facial region shows codable negative affect or no smiling at all.

3= Only one facial region shows codable movement, identifying a low intensity negative emotion, or expression is ambiguous.

4= Only 2 facial regions show codable movement, or expression in one region is very clear.

5= An appearance change occurs in all 3 facial regions, or coder otherwise has impression of strong negative facial affect.

8=Infant face cannot be seen at all (If whole face is covered!)

Remember that infants can react differently to the same situations (see figure. 2 for examples of positive and negative facial affect and motor activity)

Question 8: 'Infant negative vocalization - no voc (2), mild/unclear protest (3), definite neg protest (4), or repeat (9)?

Intensity of distress vocalizations: Peak intensity of distress vocalizations is noted in each epoch and rated on the following scale:

2= No vocalisation

3= Mild or unclear vocalization that may be difficult to identify as hedonically negative.

4= Definite whimpering 1 second duration.

Question 9: 'Infant positive vocalization - no voc (2), Positively toned babbling, squealing, and similar vocalisations (3), laugh (4), or repeat (9)?

2= No vocalisation

3= Positively toned babbling, squealing, and similar vocalisations

4= laugh

Toy Retraction Task

Question 1*: 'Infant distraction (1), not doing (2), repeat (9), or quit (10) or recode previous epoch (11)?

Distraction means looking away from stimulus. Before the task starts, there may not be an explicit stimulus. Thus, the infant might not be distracted from something unless you see there is an object that baby is attending to and could be distracted by even before the actual task. If the infant is just looking around the room or under the table before the experiment starts, this is not distraction, especially when the experimenter is under the table. If these behaviours happen during the experiment, then it is distraction.

e.g., if the infant looks at the camera but not the toy when it is removed to the edge of the table, then, this is distraction.

e.g., if the infant looks at the toy when it is removed to the edge of the table then, this is not distraction.

Press 9; if you would like to replay the epoch

If you press 10, you can jump to the next trial of the tasks and eventually quit the coding questions. This option only will appear at the end of the first question at each epoch/second.

Press 11; if you would like to go back and recode the previous epoch/second before. This option only will appear at the end of the first question at each epoch/second.

Distraction is looking away from the stimulus (e.g., infant looking around the room, at another stimulus or the camera etc.). However, if the baby is looking at the mother, that is only looking at the mother. There is no distraction.

If the baby does both distraction behaviours and looks at the mother (e.g., the infant looked at the walls, and then mother in one epoch clearly); then you can code for both.

Question 2*: 'Looks to mother (1), not doing (2) or repeat (9)

This is when the infant looked at the mother's face as social referencing. If the infant definitely looks elsewhere at the mother such as hands during the task, that is distraction. If it is not very clear where the infant is looking (e.g., not clear whether looking at face, hair, shoulder...), you can still code it as looks to mother.

Question 3*: 'Reaching/touching mother (1), not doing (2) or repeat (9)

This is when the infant is trying to touch/reach mother, or if the infant touches the mother.

Question 4*: 'Self-soothing (1), not doing (2) or repeat (9)

The infant uses a body part to engage in repetitive manipulation (e.g., sucking thumb, fingering clothing, and twirling hair). Thumb sucking is very apparent self-soothing behaviour. Sometimes you can see twirling or playing with hair, make sure this is occurring most of that second/segment, if you think it is happening. You should see at least two seconds for it to be self-soothing

Question 5**: 'Infant motor activity present (1), not present (2) or repeat (9)

Motor activity includes the following: banging hands on the table; clapping hands; waving arms in excitement; definite leaning forward towards the toy or tension release. The latter is when the infant is engaged in high energy behaviour with no apparent instrumental focus (e.g., screaming but not in a negative way or fast kicking of the legs with excitement). The key is these behaviours are quick and intense, but not like struggling in a negative way.

Infants seems to calm down after tension release. Tension release is not very common, but sometimes happens - so it is good to be aware of it!

Question 6*: 'Infant not engaged with toy (1), mild interest (2), fully engaged (3), or repeat (9)

The infant's level of engagement with the toy is noted. Also, look duration/staring at the toy is important for this one.

1= Indifferent to the toy (not looking; not interested)

2= Neutral reaction to toy, looks at toy with mild interest. (Looking at the toy for some time)

3= Fully engaged with toy; likes toy, engrossed in toy. (If looking at the toy for the whole epoch which is one second)

**** When considering engagement with the toy, remember that staring, leaning, and reaching are equally important, especially for infants who may not have the motor skills

required to reach for a moving toy. Consider the intensity of the stare, is it a blank stare or is the child mentally engaged/concentrated? An infant should not automatically lose engagement points just because they do not reach.

If the infant is only holding/playing with the toy or only looking at the toy; code it as 2-mild interest.

If the infant is neither playing nor looking; it is going to be 1-no interest.

If the infant is both looking and playing, it is 3.

E.g., Mother took the toy away, and the infant is not looking at the toy. Then, this is 1.

E.g., Mother and infant are playing; and the infant is playing with the toy; but not looking at the toy. This is 2.

Question 7: 'Infant positive facial affect - neutral/no affect, (2) low pos (3) mild pos (4) intense pos (5) cannot see (8) or repeat (9)

Intensity of facial joy: Peak intensity of positive facial affect is noted in each epoch using AFFEX (see appendix A) and rated on the following scale:

2= No facial region shows codable negative affect or no smiling at all.

3= Small smile, with lips slightly upturned, and no involvement of cheeks or eyes.

4= Medium smile, with lips upturned, perhaps mouth open, slight bulging of cheeks, and perhaps some crinkling about the eyes.

5= Large smile, with lips stretched broadly and upturned, perhaps mouth open, definite bulging of cheeks and noticeable crinkling of eyes.

8=Baby face cannot be seen at all (If whole face is covered!) Do not be tempted to go for this if you could didact from the voice or from the previous segment about baby's facial expression.

Question 8: 'Infant negative facial affect - neutral/no affect (2), low neg (3), mild neg (4), intense neg (5), cannot see or (8), repeat (9).

Intensity of facial fear/anger/sadness: Peak intensity of negative facial affect is noted in each epoch using AFFEX (see appendix A) and rated on the following scale:

2= No facial region shows codable negative affect or no smiling at all.

3= Only one facial region shows codable movement, identifying a low intensity negative emotion, or expression is ambiguous.

4= Only 2 facial regions show codable movement, or expression in one region is very clear.

5= An appearance change occurs in all 3 facial regions, or coder otherwise has impression of strong negative facial affect.

8=Infant face cannot be seen at all (If whole face is covered!)

Remember that infants can react differently to the same situations (see figure. 2 for examples of positive and negative facial affect and motor activity)

Question 9: 'Infant negative vocalization - no voc (2), mild/unclear protest (3), definite neg protest (4), or repeat (9)?

Intensity of distress vocalizations: Peak intensity of distress vocalizations is noted in each epoch and rated on the following scale:

2= No vocalisation

3= Mild or unclear vocalization that may be difficult to identify as hedonically negative.

4= Definite whimpering 1 second duration.

Question 10: 'Infant positive vocalization - no voc (2), Positively toned babbling, squealing, and similar vocalisations (3), laugh (4), or repeat (9)?

2= No vocalisation

3= Positively toned babbling, squealing, and similar vocalisations

4= laugh

Question 11**': 'Infant approaching toy (1), not approaching (2), or repeat (9)

During frustration tasks, approach is defined as the infant's attempts to retrieve the toy that was taken away from them. Again, it could be leaning forward to get the toy back. This may be accompanied by banging the table sometimes. Clearly pointing at the toy or to the mother to get the toy back is also an approach behaviour.

*- These measures were not included in the composites of behavioural reactivity used in the study in Chapter five.

** - These measures were collapsed to form the composite of motor activity used in the study in Chapter five.

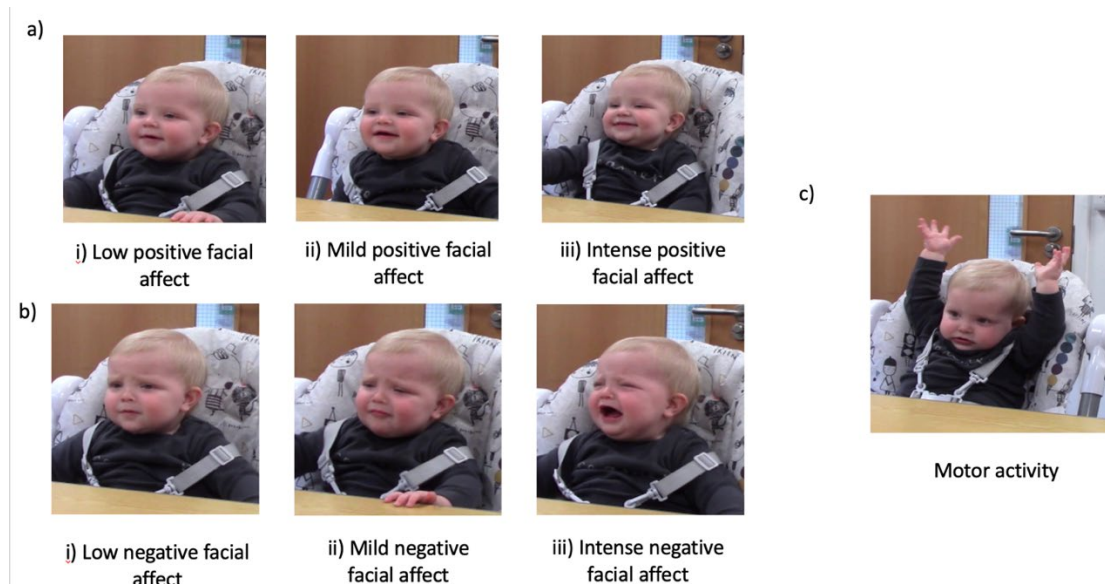


Figure 2. examples of positive and negative facial affect and motor activity

Some Practical Notes

Once the coding finished, the small window should automatically disappear. If not, you can type sca into the command window to close the small video window.

If you start a subject's coding, you are better to finish it because the script does not allow you to come back to where you left. It will recommence from the beginning. Be aware, if you press a letter rather than a number during coding, the script stops working, and asks you to recommence. If this happens, you can start from the trial that you left, so you would not code all the trials in case an error occurs (see fig. 2 line 45; for trials=1:3 %%you can change the trial number if you make an error). This will be explained more during your training.

```

41
42 MovieName=strcat(MovieDir,'/',num2str(sub),'.mp4')
43 [mov dur fps, h w framecount] = Screen('OpenMovie', EXPWIN, MovieName);
44
45 for trials=1:3%you can change the trial number if you make an error
46     if trials==1
47         StartTime=TrialTimes((TrialTimes(:,1)==sub),2:3);
48         EndTime=TrialTimes((TrialTimes(:,1)==sub),4:5);
49     elseif trials==2
50         StartTime=TrialTimes((TrialTimes(:,1)==sub),6:7);
51         EndTime=TrialTimes((TrialTimes(:,1)==sub),8:9);
52     elseif trials==3
53         StartTime=TrialTimes((TrialTimes(:,1)==sub),10:11);
54         EndTime=TrialTimes((TrialTimes(:,1)==sub),12:13);
55     end

```

Figure 3. lines of the coding script that can be used to return to the previous trial in case of a mistake

If you change your mind while coding regarding the previous segment, use the “recode previous segment key”.

If a short segment of the task is obscured from view by problems with the camera or unusual movements, it is permissible to make reasonable inferences as to the infant's behaviour from the previous epochs and behaviour.

Otherwise, please make a note of the subject number and let the team know.

If you think a behaviour happens for more than half of one segment you can code it. If any behaviour happens just at the end of that segment (or is about to happen) and extends through the next segment, code it into the next segment but not in the previous one.

As you go along, check inside the folder “hand coding” from time to time to see whether your coding is all saved. You should see the excel files named with the subject number and trial number in there (e.g., 70_2.csv).

In some coding, such as facial affect measures, the individual characteristics of the infant must be considered. That is, the fullest smile that one infant can show may be less intense than the fullest smile of another infant. Although there are obvious dangers in making too great an allowance for such individual differences, they should be a background factor in coding.

Unusual behaviours by the infant or mother or mistakes by the camera operator or experimenter should be noted briefly with subject number and the name of task.

APPENDIX A: AFFEX FACIAL EXPRESSION DEFINITIONS

Emotion	Movements In Forehead/Brows Regions	Movements In Eyes/Nose/Cheeks Regions	Movement In Mouth/Lips/Chin Regions
Anger	Inner corners are lowered and drawn together. Bulging or vertical furrows between the eyes may be visible due to this movement.	Eyes may look tense or squinted. Cheeks may be raised. Folds under eyes may deepen.	Mouth looks tense, very squarish. Alternatively, mouth closed with lips pressed together.
Fear	Entire brow should be raised and drawn together. Brows may also look straighter across than usual. Faint horizontal furrows may be present in forehead.	Upper eyelids raise making the eyes appear wider. Eyes have tense appearance.	Lip corners are drawn back. Mouth is usually less open.
Sadness	Inner corners move upward and together resulting in bulging/furrows in middle of forehead.	Cheeks may look lower than usual or have a droopy appearance. Alternatively, cheeks may be raised, and eyes squinted.	Lip corners should be pulled down. Bottom lip may be pushed out by the chin which may be wrinkled.
Joy	Most likely remain neutral.	Cheeks raise Furrow below the eyes deepens. “Crow’s feet” will extend from the outer corners of the eye. Eyes may appear squinted.	Lip corners are raised. Nasolabial fold deepens.
Interest	Entire brow is raised. Alternatively, brows are drawn together and slightly lowered.	Eyes look wider than usual due to raised brows. Alternatively, eyes may be squinted, and cheeks raised.	Mouth may open.

Note on the potential for an "illusion of sadness"

There are several occasions when an illusion of sadness may appear. Sadness should not be coded in these situations:

The first situation is when brows are drawn tightly down and together. In this case, it is common for the inner most corners of the brows to bulge up in the middle falsely giving the appearance of sadness. This is most likely due to the large amount of fat in the infant face.

The second situation is when the outer corners of the brows are lowered falsely giving the appearance that the inner corners have raised. In this case, be sure to observe the actual movement of the brows. In sadness, the inner corners need to be raised and drawn together. Simply observing a still frame of this expression is not sufficient to distinguish between true sadness and the illusion of sadness.

Finally, an illusion of sadness may occur when children inhale deeply during a bout of crying. In this situation, the lip corners will be drawn down by the inhaling action giving the impression of sadness.

These descriptions were adapted from C.E. Izard's The Maximally Discriminative Facial Movement Coding System

