

1 **NEURAL DETECTION OF CHANGES IN AMPLITUDE RISE TIME IN**  
2 **INFANCY.**

3  
4 Áine Ní Choisdealbha<sup>1</sup>, Adam Attaheri<sup>1</sup>, Sinead Rocha<sup>1</sup>, Perrine Brusini<sup>1\*</sup>, Sheila A. Flanagan<sup>1</sup>,  
5 Natasha Mead<sup>1</sup>, Samuel Gibbon<sup>1</sup>, Helen Olawole-Scott<sup>1</sup>, Isabel Williams<sup>1</sup>, Christina Grey<sup>1</sup>,  
6 Panagiotis Boutris<sup>1</sup>, Henna Ahmed<sup>1</sup>, & Usha Goswami<sup>1</sup>.

7  
8 <sup>1</sup> Centre for Neuroscience in Education, Department of Psychology, University of Cambridge

9 \* Now at University of Liverpool

10

11 **Data availability statement:** Data are available at <https://osf.io/v96xe/>.

12

13 **Funding statement:** This project was funded from the European Research Council (ERC) under  
14 the European Union's Horizon 2020 research and innovation programme (grant agreement No.  
15 694786).

16

17 **Conflict of interest disclosure:** The authors declare no conflict(s) of interest in relation to this  
18 study.

19

20 **Ethics approval statement:** The project from which these results were found was approved by the  
21 Psychology Research Ethics Committee of the University of Cambridge, U.K., in accordance with  
22 the Declaration of Helsinki.

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79

## NEURAL DETECTION OF CHANGES IN AMPLITUDE RISE TIME IN INFANCY.

### Research highlights

- Mismatch responses to changes in amplitude rise time seen at seven and eleven months.
- Longitudinal data show a shift from positive MMR to negative MMN with age.
- The right fronto-central MMR is sensitive to the size of the change in rise time.
- Neurophysiological measurements show robust responses across a range of rise times.

### Abstract

Amplitude rise times play a crucial role in the perception of rhythm in speech, and reduced perceptual sensitivity to differences in rise time is related to developmental language difficulties. Amplitude rise times also play a mechanistic role in neural entrainment to the speech amplitude envelope. Using an ERP paradigm, here we examined for the first time whether infants at the ages of seven and eleven months exhibit an auditory mismatch response to changes in the rise times of simple repeating auditory stimuli. We found that infants exhibited a mismatch response (MMR) to all of the oddball rise times used for the study. The MMR was more positive at seven than eleven months of age. At eleven months, there was a shift to a mismatch negativity (MMN) that was more pronounced over left fronto-central electrodes. The MMR over right fronto-central electrodes was sensitive to the size of the difference in rise time. The results indicate that neural processing of changes in rise time is present at seven months, supporting the possibility that early speech processing is facilitated by neural sensitivity to these important acoustic cues.

**Keywords:** rise time, ERP, MMN, infancy, auditory

### 1. Introduction

To acquire language, a child must be able to segment an incoming auditory stream into its separate phonetic, syllabic, lexical and other components, and to attach symbolic meaning to acoustic word forms. Infants utilise a range of acoustic cues to aid language learning. The neural literature shows that they are sensitive to rapidly-arriving pitch information (Hämäläinen, Ortiz-Mantilla & Benasich, 2019), changes in duration (Richardson et al., 2003), F0 changes, and features like voice onset time (Guttorm et al., 2005; Guttorm et al., 2010; Leppänen et al., 2010; van Zuijen et al., 2013). The incoming stream of speech contains multiple such acoustic features that offer cues to its

80 linguistic structure. In this study, we focus on “rise times” (rates of change) in the modulations in  
81 intensity (amplitude) that carry important linguistic information. Infant sensitivity to rise time has  
82 not previously been studied at the neural level.

83         Speech meets the human ear as a sound pressure wave whose shape (“amplitude envelope”)  
84 contains temporal patterns that fluctuate over many different timescales. Rise times function as  
85 acoustic edges marking the onset of new phonological units. They are mechanistically important for  
86 speech comprehension (Ding & Simon, 2014; Doelling et al., 2014). They trigger alignment  
87 between brain rhythms and speech rhythms, supporting neural encoding of the speech envelope  
88 (Giraud & Poeppel, 2012, for overview). The speech envelope is represented neurally throughout  
89 infancy (Kalashnikova et al., 2018; Jessen et al., 2019; Attaheri et al., 2021; Ortiz Barajas, Guevara  
90 & Gervain, 2021). Reduced perceptual sensitivity to amplitude rise times has been linked to both  
91 developmental dyslexia (difficulties in phonological processing) and Developmental Language  
92 Disorder (DLD, difficulties with syntax and grammar, e.g. Goswami et al., 2002; Pasquini,  
93 Corriveau & Goswami, 2007; Richardson et al., 2004). Individual differences in infants’ ability to  
94 detect changes in rise time could affect the fidelity with which linguistic information in the speech  
95 envelope is represented, helping to explain individual differences in later language outcomes.  
96 Behavioural evidence shows that perceptual sensitivity to differences in the rise times of non-  
97 speech sine tone stimuli is linked to receptive and productive vocabulary at three years of age  
98 (Kalashnikova, Goswami & Burnham, 2018, 2019). In the current study, we also used tone stimuli  
99 but recorded EEG, because neural data may reveal greater sensitivity to changes in rise time.

100

101         From one perspective, we might view speech as built of units like phonemes and syllables  
102 placed together to construct larger units of meaning like words and sentences. However, it may be  
103 more fruitful to view speech processing as perceiving a tree-like structure of amplitude modulations  
104 within the pressure wave in which larger patterns provide hierarchically-organised form to smaller  
105 components (Lieberman & Prince, 1977). This proposed linguistic hierarchy is reflected acoustically  
106 in the amplitude modulation (AM) structure of the speech envelope, in which the slowest  
107 modulations provide a nested structure for faster ones (Leong & Goswami, 2015). For young  
108 infants who cannot yet comprehend speech but nonetheless preferentially attend to it (Vouloumanos  
109 & Werker 2004; Spence & DeCasper, 1987), speech rhythm may provide a predictive temporal  
110 framework upon which to build their language acquisition. Rise time is a key acoustic component of  
111 perceived rhythm (Greenberg, 2006), and rhythm has long been recognised as a precursor of  
112 language acquisition (Mehler et al., 1988; Nazzi et al., 1998). Accordingly, sensitivity to rise time  
113 may play a key role in infants’ ability to utilise speech rhythm patterns during language learning.

114

115 Prior infant ERP studies of other language-relevant acoustic features document a number of  
116 changes over the first year of life. Auditory ERPs in infants become larger from birth for repeated  
117 sounds (Kushnerenko et al., 2002b; Lippé et al., 2009) and ERPs become either larger or smaller for  
118 change detection responses depending on the polarity of the ERP response (Choudhury and  
119 Benasich, 2011; Kushnerenko et al., 2002a; Ortiz-Mantilla et al., 2016). Early research on the  
120 auditory mismatch response (MMR), a measure of change detection, found a positive peak in the  
121 infant difference wave about 250ms post-stimulus, rather than the anticipated mismatch negativity  
122 (MMN; Dehaene-Lambertz & Dehaene, 1994). A MMN is seen as a more mature response than the  
123 positive MMR (Friedrich, Weber & Freiderici, 2004), with its emergence linked to age and  
124 language exposure (Garcia-Sierra et al., 2011), stimulus type (Cheng et al., 2015), and the size of  
125 contrast between stimuli (Cheng & Lee, 2018). Accordingly, morphological changes to rise time  
126 MMRs would be expected over the first year of life.

127

128 We used an ERP-based mismatch paradigm during a longitudinal infant project  
129 (“BabyRhythm”), conducted when infants were seven and eleven months of age. Following the  
130 behavioural report by Kalashnikova, Goswami and Burnham (2018), we examined whether infants  
131 could discriminate a standard stimulus with a short rise time (15 ms) against stimuli with longer rise  
132 times. Our aim was to investigate whether the neural thresholds for detection of changes in rise time  
133 differ from those seen when an overt behavioural response is required. Behavioural measures  
134 provide information about an infant’s perception of a stimulus, but it is possible that before this,  
135 developmental changes in auditory processing may be occurring at a neural level. Infants track the  
136 amplitude envelope from birth (Kalashnikova et al., 2018; Jessen et al., 2019; Attaheri et al., 2021;  
137 Ortiz Barajas, Guevara & Gervain, 2021) and thus, given that rise time discrimination plays a role  
138 in adult speech tracking, we would expect that neural mechanisms of rise time detection should be  
139 present in the infant brain. Plakas and colleagues (2013) used an ERP approach to study rise time  
140 detection in young children, and found a MMN to a single amplitude rise time sine tone oddball  
141 among typically-developing children at 41 months of age. In the present study, we also measure  
142 MMNs, but instead of presenting a rise time oddball of a fixed length, we vary the rise time oddball  
143 on an interval scale. By manipulating the length of the rise time oddball, we can examine, on both  
144 an individual and a group level, the limits of infants’ rise time discrimination capability. Our  
145 primary hypothesis was that infants would exhibit a mismatch response to amplitude rise time  
146 oddballs. We anticipated that this response would become smaller as the difference in rise time  
147 between the standard and the oddball (henceforth, rise time difference) became smaller.

148

149 We examined three additional factors which make a novel contribution to the infant rise time  
150 literature. First, we hypothesised that the mismatch response would be less positive for older  
151 infants, reflecting the transition from MMR to MMN. Interactions between rise time difference and  
152 age could be expected at the neural level, as there is behavioural change in rise time sensitivity  
153 between seven and ten months for infants not at risk for dyslexia (Kalashnikova, Goswami &  
154 Burnham, 2018, 2019). Second, we were interested in whether infants' detection of changes in rise  
155 time would be facilitated by a stimulus more acoustically similar to speech, speech-shaped noise  
156 (SSN). SSN is used in Dutch studies of rise time discrimination by children (e.g. Law et al., 2017)  
157 because it has similar temporal features to speech. Accordingly, we varied whether the stimuli were  
158 presented as sine tones or SSN. We anticipated that rise times of the SSN stimuli, given their  
159 temporal speech-like features, may be more easily discriminated by infants. Differences in neural  
160 detection of stimuli with speech-like features, relative to tone stimuli, may also be informative in  
161 relation to the role of rise time detection in speech tracking and possible variations with age.

162

163 Finally, we compared responses across the fronto-central electrodes. These electrode groups  
164 were identified for their role in rise time mismatch detection in older children by Plakas and  
165 colleagues (2013) and Peter, Kalashnikova and Burnham (2016). Sensitivity to temporal acoustic  
166 features can differ by hemisphere. More rapid temporal transitions, related to phonemic  
167 information, appear to be preferentially processed in the left hemisphere (Boemio et al., 2005).  
168 Slower auditory modulations, those associated with prosodic and syllabic processing, may be  
169 preferentially processed in the right hemisphere, which is also associated with rhythm perception  
170 (Sammler et al., 2015). In the current study, we take a scalp-level approach due to the difficulty in  
171 attaining accurate source-localised results in infants, especially across different ages (Lew et al.,  
172 2013; Noreika et al., 2020). Nonetheless, topographical results may show differences between  
173 electrode groups by picking up different levels of activity from different sources or due to  
174 developmental change. Topographical results may also inform comparisons with related research  
175 with older children. Temporal sampling theory has hypothesised that atypical processing of slower  
176 modulations in speech may be right-lateralised, and this has been found to be the case in neural  
177 speech tracking studies with older children with dyslexia (di Liberto et al., 2018).

178

## 179 **2. Methods**

180

### 181 **2.1 Participants**

182 Participants were infants enrolled in a longitudinal, multi-measure study of early auditory  
183 processing and language acquisition. Infants were recruited as a community sample and their

184 parents provided informed consent. At the age of seven months, 113 infants were enrolled in the  
185 study, and 109 infants took part in the rise time study. At the age of eleven months, 100 infants  
186 received the rise time stimuli. Missing sessions are accounted for in the supplementary materials.  
187 During preprocessing and data cleaning, technical issues were diagnosed and resulted in the  
188 exclusion of two seven-month-old and four eleven-month-old EEG sessions due to missing triggers  
189 in the EEG data, and one seven-month-old session due to no sound being played in the EEG booth  
190 during recording. The data included in the current analyses are from 74 infants at seven months and  
191 96 infants at eleven months, among whom 64 infants contributed data at both ages. The average  
192 ages at the time of recording were 7 months, 3 days (SD = 5 days) and 11 months, 2 days (SD = 5  
193 days). The study was approved by the Psychology Research Ethics Committee of the University of  
194 Cambridge, U.K. REDCap (Research Electronic Data Capture; Harris et al., 2009, 2019) database  
195 software was used to store and manage information about the data.

196

## 197 **2.2 Stimuli**

198 The standard stimulus with which infants were presented had a rise time of 15 milliseconds. The ten  
199 oddball stimuli had longer rise times ranging from 161.1ms to 292.7ms, in steps of 14.6ms. In each  
200 lab session, infants were played all auditory stimuli – standards and oddballs – exclusively in the  
201 form of either a sine tone or SSN. Of the infants included in the analysis, 37/74 received SSN and  
202 37/74 received sine tone stimuli at seven months. At eleven months 50 heard the SSN and 46 heard  
203 the sine tone stimuli. Of the 64 included infants who attended both sessions, 15 heard the sine tone  
204 both times, 24 heard the SSN both times, and 25 heard a different stimulus type each time.

205

## 206 **2.3 Procedure**

207 EEG data were recorded at a rate of 1000Hz via a 64-channel EGI Geodesic Sensor Net and GES  
208 300 amplifier (Electrical Geodesics Inc., Eugene, OR, USA) with four facial electrodes removed.  
209 Infants were seated in a soundproof acoustic chamber, in a high-chair or occasionally on a parent's  
210 lap. They were seated approximately 65cm away from a presentation screen. Auditory stimuli were  
211 played through speakers placed either side of this screen (Q Acoustics 2020i), via an amplifier  
212 (Cambridge Audio Topaz AM5 Stereo).

213

214 The auditory stimuli were played in blocks. There were five blocks with 48 auditory stimuli  
215 each, of which 16.67% were oddballs. The first oddball presented was the deviant with the longest  
216 rise time, that is, the one with the largest difference from the standard stimulus' rise time. There  
217 were four to nine standard stimuli between the oddballs, and every fifth oddball decreased in rise  
218 time from the previous one.

219

220 To keep infants occupied during the 5-minute EEG recording, a silent black-and-white  
221 cartoon played on the presentation screen. This EEG-based rise time detection paradigm was  
222 presented at the start of a longer data collection session including auditory and audiovisual EEG,  
223 eye-tracking and motion-capture paradigms. Videos and auditory stimuli were presented using  
224 scripts written in Matlab with Psychtoolbox (Brainard 1997; Kleiner, Brainard & Pelli, 2007).

225

#### 226 **2.4 EEG preprocessing**

227 Data were filtered via EEGLab (Delorme & Makeig, 2004), with a highpass filter of 0.2 Hz and a  
228 lowpass filter of 45 Hz. The data file for each participant was inspected to identify persistently bad  
229 channels (e.g. broken electrodes, poorly fitting channels exhibiting extreme fluctuations in  
230 amplitude). Of the 60 channels on the infant cap, two were always identified for rejection (channels  
231 23, 55) as they rarely fit flush to the infant's skin. On average, 3.9 additional persistently bad  
232 channels were identified per recording, with a standard deviation of 3.01 channels. During infant  
233 EEG testing sessions, channels may become noisy – transiently or persistently - due to the infant  
234 touching their head, shifting position, or engaging in gross movement. Data cleaning was therefore  
235 performed on epoched data in a number of steps – first, identifying bad channels epoch by epoch,  
236 and rejecting and interpolating these transiently bad channels alongside the persistently bad  
237 channels; second, running both automated and manual procedures for identifying epochs with  
238 artefacts remaining after bad channel interpolation; and third, rejecting epochs based on agreement  
239 between the automated and manual bad epoch identification procedures. Epochs ran from 160ms  
240 before the onset of the stimulus to 800ms after, with the 160ms before stimulus onset used as  
241 baseline. Further details on these steps are given in the supplementary materials.

242

243 When the cleaned and epoched data were split into standard and oddball epochs, there were  
244 on average 169.05 (SD = 30.21) epochs in response to standard stimuli and 31.78 (7.15) to oddball  
245 stimuli. Table 1 gives the mean number of epochs per stimulus in each age group as well as the  
246 range (further explanation of “matched standards” is given in the section below). After the rejection  
247 of epochs with artefacts, the data were re-referenced to the whole head, with the exclusion of 9  
248 peripheral channels near the neck, ears and forehead.

249

250

251

252

253

254

255

256

257 **Table 1:** Mean and standard deviation of epochs per rise time stimulus per age, by stimulus type,  
 258 after removal of noisy epochs.

Oddball rise time length in ms	293	278	263	248	234	220	205	190	176	161
<b>7 months mean oddball epochs per sine ERP (SD, min - max)</b>	3.22 (1.25, 0-4)	3.3 (1.1, 0-4)	3.35 (0.79, 1-4)	3.08 (0.98, 0-4)	3.08 (1.04, 1-4)	3 (1.13, 0-4)	3.3 (0.88, 1-4)	3.08 (0.95, 1-4)	2.86 (1.27, 0-4)	3.03 (0.99, 0-4)
<b>7 months mean standard epochs per sine ERP (SD, min-max)</b>	3.05 (1.27, 0-4)	3.19 (1.1, 0-4)	3.35 (0.95, 0-4)	3.27 (0.8, 2-4)	3.11 (0.84, 1-4)	3.05 (1.03, 1-4)	3.27 (0.87, 1-4)	2.97 (1.07, 0-4)	2.86 (1.16, 0-4)	2.97 (1.07, 0-4)
<b>11 months mean oddball epochs per sine ERP (SD, min-max)</b>	3.28 (0.83, 1-4)	3.2 (0.98, 0-4)	3.35 (0.92, 1-4)	3.43 (0.83, 1-4)	3.35 (1.02, 0-4)	3.15 (1.25, 0-4)	3.24 (0.9, 1-4)	3.48 (0.78, 1-4)	3.28 (1.09, 0-4)	2.87 (1.24, 0-4)
<b>11 months mean standard epochs per sine ERP (SD, min-max)</b>	3.3 (0.96, 0-4)	3.3 (0.92, 0-4)	3.41 (0.88, 1-4)	3.2 (0.86, 1-4)	3.3 (0.99, 0-4)	3.33 (1.03, 0-4)	3.17 (0.93, 1-4)	3.09 (1.21, 0-4)	3.29 (0.83, 1-4)	3.09 (1.35, 0-4)
<b>7 months mean oddball epochs per SSN ERP (SD, min - max)</b>	3.51 (0.87, 0-4)	3.43 (0.87, 0-4)	3.41 (0.9, 1-4)	3.49 (0.73, 2-4)	3.3 (0.85, 1-4)	3.3 (0.97, 0-4)	3.19 (0.97, 0-4)	3.11 (1.05, 0-4)	3 (1.08, 0-4)	2.86 (1, 0-4)
<b>7 months mean standard epochs per SSN ERP (SD, min-max)</b>	3.35 (0.95, 0-4)	3.43 (0.9, 1-4)	3.27 (1.07, 1-4)	3.43 (0.73, 2-4)	3.41 (0.8, 1-4)	3.16 (1.04, 0-4)	3.19 (1.04, 0-4)	3.03 (1.09, 0-4)	3.03 (1.07, 0-4)	3 (1.13, 0-4)
<b>11 months mean oddball epochs per SSN ERP (SD, min-max)</b>	3.14 (1.01, 0-4)	3.26 (1.03, 0-4)	3.08 (1.12, 0-4)	3.16 (0.98, 0-4)	3.24 (1.04, 0-4)	3.12 (1.12, 0-4)	2.9 (1.28, 0-4)	3.04 (1.28, 0-4)	3.08 (1.32, 0-4)	2.72 (1.21, 0-4)
<b>11 months mean standard epochs per SSN ERP (SD, min-max)</b>	3.1 (0.99, 0-4)	3.22 (1.07, 0-4)	3.22 (0.91, 1-4)	3.08 (1.03, 0-4)	3.24 (1.1, 0-4)	3.16 (1.23, 0-4)	3.1 (1.13, 0-4)	2.98 (1.15, 0-4)	2.82 (1.4, 0-4)	2.88 (1.3, 0-4)

259

260

## 261 2.5 Data analysis

262 The average ERP in response to each stimulus was calculated over three subgroups of electrodes  
 263 corresponding to FC3, FCz and FC4 and their neighbours<sup>1</sup>. Due to the greater number of standard  
 264 than oddball stimuli, the standard stimulus ERP was derived from the epoch preceding an oddball  
 265 stimulus. These epochs were determined in advance of data cleaning, to ensure that both rise time

1 FC3: EGI electrode numbers 14, 15, 19; FCz: 4, 7, 54; FC4: 53, 56, 57.

266 oddball and standard epochs had a similar probability of being missing. The average ERP in  
267 response to these standard stimuli was subtracted from the average ERP in response to the  
268 corresponding oddball stimulus. The window of interest for the analyses was 300 to 460ms post-  
269 stimulus. This is a typical mismatch response window for infants (e.g. Dehaene-Lambertz &  
270 Dehaene, 1994; Friedrich, Weber & Freiderici, 2004) while also allowing for the longest stimulus  
271 rise time (293ms) to have concluded. Cluster-based permutation testing was applied post-hoc to  
272 confirm the appropriateness of these electrode groups and of the time window for analysis (see  
273 supplementary information).

274

275         Difference waves with a mean amplitude in the window of interest exceeding the mean  
276 (across all infants, regions of interest, and oddball rise time lengths)  $\pm$  3 times the standard  
277 deviation were excluded as outliers. This equated to 1.34% of all data points. A set of comparison  
278 difference waves (henceforth, the “matched standards”) were computed by subtracting each of the  
279 standard ERPs used to calculate the mismatch peak from another standard ERP. This was done to  
280 ensure that results reflected differences in processing of standard and oddball stimuli, and not the  
281 fact that ERPs in response to any stimuli may differ from one another by chance, especially when  
282 computed from a limited number of trials as in this study. A similar approach, referred to as  
283 “dummy standards”, was used in research by Bishop and Hardiman (2010), who also wanted to  
284 ensure that results were not driven by false positives.

285

286         Following outlier exclusion, the difference wave data from the mismatch window and the  
287 baseline window was entered in linear regression models to find whether there was, overall, a  
288 significant mismatch peak; whether it differed from the matched standard peak; if it was affected by  
289 stimulus type (sine tone or SSN); how it changed with age; how it differed by electrode location;  
290 and how it varied depending on how similar or different the oddball stimulus was to the standard.

291

292         We compared difference wave amplitude in the baseline window to that in the window of  
293 interest as another means of examining whether there was a mismatch peak in the data. Amplitude  
294 in the baseline window approximates zero, and thus a significant difference between difference  
295 wave amplitudes in the baseline window and those in the window of interest suggest the presence of  
296 a mismatch peak in the data; if the difference wave in the window of interest also approximates  
297 zero, this suggests that no peak is present. The use of the baseline window to ascertain the presence  
298 of a peak is also used in Foxe and Simpson (2002).

299

300 Statistical analyses were run using the lme4 and lmerTest packages in R (Bates, et al., 2007).  
301 Regression analyses allow for the inclusion of both categorical independent variables (such as age)  
302 and continuous ones (such as the difference in rise time between the standard and the oddball).  
303 Furthermore, the application of a Linear Mixed-effects Model (LMM) allows for the inclusion of  
304 the data that we do have for a given infant even if they missed an appointment or had data from one  
305 electrode subgroup excluded due to outlier values. For the same reason, a mixed effects approach  
306 has been previously used in infant ERP research (Stahl et al., 2010), including in auditory  
307 paradigms (Begum-Ali et al., 2021) and specifically a mismatch paradigm (Zhao & Kuhl, 2021).

308

309 Please note also that rise time difference is treated as continuous by the LMM. This is  
310 because differences in rise time length are differences of scale, not category. Designating rise time  
311 as a continuous variable ameliorates the potential issue of some oddball intervals having at least one  
312 infant who did not contribute any valid epochs (Table 1), as the linear trend across rise time  
313 differences can still be computed. Including more epochs in each calculated ERP (e.g. by collapsing  
314 rise time difference into two categories of “long” and “short”) might reduce the noise in each  
315 difference wave, but would also mean that each difference wave would be computed from non-  
316 identical stimuli. Providing more data-points along the rise time difference continuum per  
317 participant to the LMM and including a random intercept on participant identity means that the  
318 model can work around the noise we might otherwise aim to remove by averaging over more  
319 epochs.

320

321 Finally, we explored whether each infant, at each age, had exhibited a mismatch response to  
322 each of the oddball stimuli. This was done by finding, for each individual infant, the 95%  
323 confidence interval of the amplitude of the difference waves, across all oddball stimuli, in the  
324 baseline period. If the mean amplitude of the window of interest in a particular oddball’s difference  
325 wave exceeded the upper or lower bounds of this interval, this was characterised as a mismatch  
326 response. We could then determine at which point in the experiment, in response to which oddball  
327 stimulus, the infants stopped exhibiting a mismatch response. We expected this to allow us to infer  
328 each individual’s detection threshold, providing an individual differences measure to regress against  
329 neural entrainment and language acquisition data from other timepoints in the BabyRhythm project.

330

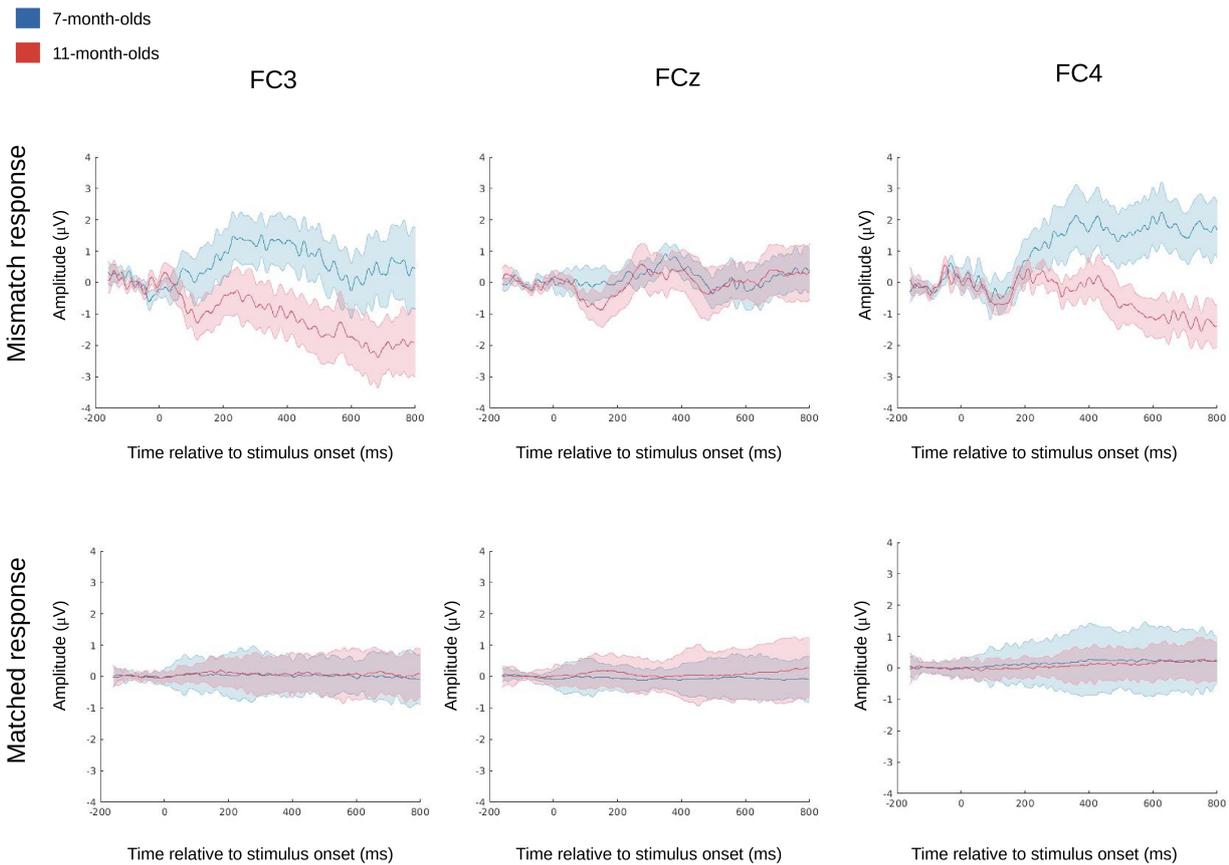
### 331 **3. Results**

332

#### 333 *3.1 Difference wave results*

334 The mean amplitude of the difference wave in the window of interest (300 to 460ms post-stimulus)  
 335 was  $0.414\mu\text{V}$  (SD = 3.467) averaged across all oddballs. At seven months, this value was  $1.06\mu\text{V}$   
 336 (SD = 3.114) and at eleven months it was  $-0.084\mu\text{V}$  (SD = 3.655). An initial model (Equation 1)  
 337 was run to determine whether there was, overall, a peak in the window of interest that differed from  
 338 the baseline window:

339 Equation 1:  $\text{Difference Wave}_i = \beta_{0i} + \beta_1\text{Window}_i + \beta_2\text{Age}_i + \beta_3\text{Window}*\text{Age}_i + u_{0i} + \varepsilon_i$ , where  $i =$   
 340 participant identity.



341 **Figure 1:** Average difference waves at seven (blue) and eleven (red) months of age, over electrode  
 342 groups. Top row shows the mismatch response between ERPs to standard and oddball stimuli,  
 343 bottom row shows the “matched standard” difference waves between ERPs in response to different  
 344 standard stimuli. Shaded regions denote the standard error of the mean response.

345

346 The presence of such a peak would indicate a mismatch response. An interaction with age  
 347 would indicate whether the mismatch response differs by age, for example whether a more negative  
 348 MMN response was present at eleven months but a positive MMR at seven months. The difference  
 349 waves are shown in Figure 1. ERPs to standard and oddball stimuli can be seen in Figure A1 in the  
 350 supplementary material, illustrating that standard and oddball responses both follow a typical infant  
 351 auditory ERP morphology. F tests using a Satterthwaite approximation method reveal a significant

352 contribution to the model of age,  $F(1, 3757.9) = 9.375$ ,  $p = 0.002$ , and of the interaction between  
 353 age and window,  $F(1, 9547.9) = 9.435$ ,  $p = 0.002$ , with a marginal contribution of window,  $F(1,$   
 354  $9549.1) = 3.083$ ,  $p = 0.079$ . Model estimates reveal a significant effect of window, such that the  
 355 amplitude of the response was larger in the window of interest than in the baseline window,  $\beta =$   
 356  $1.05$ ,  $SE = 0.325$ ,  $t = 3.23$ ,  $p = 0.001$ . There was an interaction between age and window, such that  
 357 the difference between difference waves in the window of interest and baseline window was smaller  
 358 at eleven months,  $\beta = -1.337$ ,  $SE = 0.435$ ,  $t = -3.0729$ ,  $p = 0.002$ . There was no main effect of age,  $\beta$   
 359  $= -0.007$ ,  $SE = 0.308$ ,  $t = -0.022$ ,  $p = 0.982$ , nor was the intercept significant,  $\beta = 0.011$ ,  $SE = 0.235$ ,  
 360  $t = 0.045$ ,  $p = 0.964$ . The model fit was significantly better than that of the random model,  $\chi^2 =$   
 361  $20.516$ ,  $p = 0.0001$ . Including electrode group as a main effect and interaction term in this model  
 362 does not affect the results (see Further Results in Supplementary Materials).

363

364 T-tests were conducted separately for seven- and eleven-month-olds, taking the difference  
 365 wave averaged across all oddballs. At seven months, there was a clear overall difference between  
 366 the window and the baseline amplitudes,  $t(73) = 2.927$ ,  $p = 0.005$ ,  $CI = [0.338, 1.781]$ ,  $BF_{10} = 6.41$   
 367 (moderate to strong evidence for  $H_1$ ). At eleven months, this effect was not present,  $t(95) = -0.2243$ ,  
 368  $p = 0.823$ ,  $CI = [-0.824, 0.657]$ ,  $BF_{10} = 0.116$  (moderate evidence for  $H_0$ ). This suggests that, at  
 369 seven months infants generally exhibited a positive MMR but at eleven months there was no  
 370 consistent MMR or MMN.

371

372 In the matched data in which the standard responses in different blocks of the experiment  
 373 were subtracted from one another, the mean amplitude in the window of interest was  $-0.018\mu V$  ( $SD$   
 374  $= 2.03$ ). This was  $-0.014\mu V$  ( $SD = 1.25$ ) at 7 months and  $-0.0223\mu V$  ( $SD = 2.475$ ) at 11 months.  
 375 The mismatch response was then compared to this “matched” response. The aim of this approach is  
 376 to investigate whether the peak previously observed in this window is specific to the mismatch  
 377 response generated by comparing the size of the difference wave to the baseline, rather than an  
 378 incidental peak that could occur when subtracting any two ERPs from one another. The model was  
 379 specified as in Equation 2, with “Response Type” referring to whether the data was the mismatch  
 380 response or the matched response. An effect of response type would suggest a difference in the  
 381 neural mismatch response when a new stimulus was played, while an interaction with age would tell  
 382 us whether the mismatch response is changing with age (e.g. a larger MMR, or a shift to a MMN).

383

384 Equation 2:  $\text{Difference Wave}_i = \beta_{0i} + \beta_1 \text{Age}_i + \beta_2 \text{Response Type}_i + \beta_3 \text{Age} * \text{Response Type}_i + u_{0i} +$   
 385  $\epsilon_i$ , where  $i =$  participant identity.

386

387 Model estimates reveal a significant effect of response type, such that the amplitude of the  
 388 mismatch response was larger than the matched response in the window of interest ( $p = 0.019$ ).  
 389 There was a marginal interaction suggesting that the mismatch response was smaller at eleven  
 390 months ( $p = 0.054$ ). Full results are given in Table A1 and under Further Results in the  
 391 supplementary materials, including when electrode group is included in the model (which does not  
 392 change the results). Taken together, the results show that there was a peak in the difference wave in  
 393 the window of interest for the mismatch response, it was specific to the occurrence of an oddball  
 394 stimulus, and it was more positive relative to the baseline at seven than eleven months.

### 395 3.2 Stimulus type

396 Stimulus type (sine tone or speech-shaped noise) was added to the model in Equation 1 to  
 397 investigate whether detection of a change in rise time would be facilitated by a more speech-like  
 398 auditory stimulus relative to a tone. This model again showed a significant contribution to the  
 399 model of age ( $F(1, 3002.8) = 9.398, p = 0.002$ ), and the window by age interaction ( $F(1, 9545.1) =$   
 400  $9.4024, p = 0.002$ ), with a marginal contribution of window ( $F(1, 9546) = 3.0631, p = 0.08$ ). None  
 401 of the effects related to stimulus type made a significant contribution. The model fit was  
 402 significantly better than that of the random model,  $\chi^2 = 21.537, p = 0.003$ . There are simple effects  
 403 of window ( $p = 0.005$ ) and window by age ( $p = 0.01$ ) but no significant effects or interactions  
 404 involving stimulus type, see Table A2 in supplementary materials for full model results. This  
 405 suggests that the mismatch response was not affected by which stimulus type the infant heard.  
 406 Inclusion of electrode group in the model does not affect these results.

407

408 Given that some infants heard the sine tone at seven months, and SSN at eleven months (or  
 409 vice versa), a random slope was included on stimulus type. This model was flagged for having  
 410 boundary issues (i.e. being overly complex for the underlying data). Nonetheless, the Satterthwaite  
 411 F tests showed the same pattern of results (window,  $p = 0.08$ ; age,  $p = 0.002$ , window by age,  $p =$   
 412  $0.002$ ). Effects are reported in Table A2. In Table A3, effects of the Equation 2 (response type)  
 413 model are reported when stimulus type is included. Satterthwaite-corrected F-tests show no effect or  
 414 interaction with stimulus type, only an effect of age ( $F(1, 9468) = 5.9449, p = 0.015$ ) and a marginal  
 415 age by response type interaction ( $F(1, 9468) = 3.6834, p = 0.055$ ). Hence the conclusion that, as a  
 416 group, infants in this study were equally responsive to sine tone rise times and SSN rise times is  
 417 supported.

418

### 419 3.3 Rise time difference and electrode group

420 Regarding the effect of age on the difference wave, older infants may be more likely to show a  
 421 nascent MMN and may be more sensitive to rise time differences that are less perceptually salient.

422 Another model was run to establish whether the difference in the rise time between an oddball and  
 423 the standard stimulus affected the overall difference wave in the window of interest. Rise time  
 424 difference was entered into the model as the difference in milliseconds between the rise times of the  
 425 oddball and standard stimuli. It was anticipated that the mismatch response would be larger when  
 426 the rise time of the oddball was longer, making it easier to discriminate against the standard. An  
 427 interaction with age might mean that easier stimuli elicited a large positive response at seven  
 428 months and a large negative response at eleven months. To examine potential topographical  
 429 differences in the neural response, electrode group was also included in this model, which is  
 430 specified in Equation 3. Given the negative results for stimulus type reported above, stimulus type  
 431 was not included in the model. The ERPs in response to the standard and oddball stimuli by  
 432 electrode group are shown in Figure 1.

433

434 Equation 3:  $\text{Difference Wave}_i = \beta_{0i} + \beta_1 \text{Rise Time difference}_i + \beta_2 \text{Age}_i + \beta_3 \text{Location}_i + \beta_4 \text{Rise Time}$   
 435  $\text{difference} * \text{Age}_i + \beta_5 \text{Rise time difference} * \text{Location}_i + \beta_6 \text{Age} * \text{Location}_i + \beta_7 \text{Rise Time}$   
 436  $\text{difference} * \text{Location} * \text{Age}_i + u_{0i} + \epsilon_i$ , where  $i$  = participant identity.

437

438 There were significant contributions to the model of the age by location interaction,  $F(2,$   
 439  $4653.4) = 6.445$ ,  $p = 0.002$ , and the age by location by rise time difference interaction,  $F(1, 4653) =$   
 440  $6.245$ ,  $p = 0.002$ . The model fit was significantly better than that of the random model,  $\chi^2 = 26.752$ ,  
 441  $p = 0.005$ .

442

443 The model estimates, given fully in Table 2, show the results when FC3 is used as the base  
 444 case for the comparison across electrodes. There is an effect of age ( $p = 0.024$ ), showing that the  
 445 MMR becomes more negative as infants get older. Overall, the MMR over FC4 is more negative  
 446 than that over FC3 ( $p = 0.002$ ), but becomes more positive as infants get older ( $p = 0.0004$ ).  
 447 Relative to FC3, the effect of the size of the difference in rise time between the oddball and standard  
 448 over FC4 is positive ( $p = 0.002$ ), suggesting a larger or more positive response for larger differences  
 449 in rise time. The three-way-interaction between age, rise time difference, and electrode location  
 450 suggests that this difference in the size of the MMR by rise time length over FC4 attenuates with  
 451 age, as depicted in Figure A2 in the supplementary materials.

452

453 The results of an additional model including the matched data and with the inclusion of  
 454 response type as a variable largely accord with these results, albeit with the model having  
 455 complexity issues. Satterthwaite-corrected F-tests show marginal effects of age by electrode group  
 456 ( $F(2, 9452) = 2.658$ ,  $p = 0.07$ ) and age by electrode group by rise time difference ( $F(2, 9452) =$

457 2.79,  $p = 0.06$ ). Mirroring the original analysis, these effects are significant in interactions with  
 458 response type (age by electrode group by response type,  $F(2, 9452) = 4.012$ ,  $p = 0.018$ ; age by  
 459 electrode group by rise time difference by response type,  $F(2, 9452) = 3.65$ ,  $p = 0.026$ ). Effects and  
 460 interactions reported in Table 2 suggest that the negative-going response over FC4 is driven by the  
 461 mismatch responses rather than the matched responses. The more positive response over FC4 as rise  
 462 time increases also interacts with mismatch response type. This suggests that the positive effect on  
 463 response amplitude over FC4 at 11 months is due to the mismatch response type and not the  
 464 matched response type. Finally, the negative three-way interaction shown in Table 2 remains  
 465 negative when it becomes a four-way interaction including response type.

466 **Table 2:** Results of model examining effects of rise time difference and electrode location, FC3  
 467 base case.

	Equation 3				Equation 3 incl. response type			
	Estimate	Standard error	t	p	Est.	Standard error	t	p
Mismatch response type (ref. matched)					3.22	4.13	0.78	0.435
Rise time difference	-0.015	0.014	-1.128	0.26	-0.006	0.014	-0.453	0.651
Mismatch * rise time difference					-0.009	0.019	-0.483	0.629
Age 11 months (ref. 7 months)	<b>-8.91</b>	<b>3.949</b>	<b>-2.256</b>	<b>0.024</b>	-1.51	3.926	-0.385	0.701
Mismatch * Age 11mo					-7.393	5.52	-1.339	0.181
FCz (ref. FC3)	-3.991	4.182	-0.954	0.34	-1.307	4.148	-0.315	0.753
Mismatch * FCz					-2.677	5.84	-0.458	0.647
FC4 (ref. FC3)	<b>-13.254</b>	<b>4.173</b>	<b>-3.176</b>	<b>0.002</b>	2.051	4.149	0.494	0.621
Mismatch * FC4					<b>-15.29</b>	<b>5.834</b>	<b>-2.621</b>	<b>0.009</b>
Rise time difference * Age 11mo	<i>0.032</i>	<i>0.018</i>	<i>1.743</i>	<i>0.081</i>	0.006	0.018	0.355	0.722
Mismatch * Rise time difference * Age 11mo					0.025	0.025	0.998	0.319
Rise time difference * FCz	0.015	0.019	0.801	0.423	0.004	0.019	0.188	0.851
Mismatch * Rise time difference * FCz					0.012	0.027	0.44	0.66
Rise time difference * FC4	<b>0.061</b>	<b>0.019</b>	<b>3.169</b>	<b>0.002</b>	-0.009	0.019	-0.467	0.64
Mismatch * Rise time difference * FC4					<b>0.07</b>	<b>0.027</b>	<b>2.6</b>	<b>0.009</b>
Age 11mo * FCz	6.743	5.594	1.205	0.228	-0.262	5.543	-0.047	0.962
Mismatch * Age 11mo * FCz					6.999	7.808	0.896	0.37
Age 11mo * FC4	<b>19.755</b>	<b>5.592</b>	<b>3.532</b>	<b>0.0004</b>	-1.943	5.547	-0.35	0.726
Mismatch * Age 11mo * FC4					<b>21.68</b>	<b>7.81</b>	<b>2.775</b>	<b>0.006</b>
Rise time difference * Age 11mo * FCz	-0.025	0.026	-0.962	0.336	0.004	0.026	0.146	0.884
Mismatch * Rise time difference * Age 11mo * FCz					-0.003	0.036	-0.794	0.427
Rise time difference * Age 11mo * FC4	<b>-0.088</b>	<b>0.026</b>	<b>-3.428</b>	<b>0.0006</b>	0.006	0.026	0.251	0.802
Mismatch * Rise time difference * Age 11mo * FC4					<b>-0.095</b>	<b>0.036</b>	<b>-2.634</b>	<b>0.008</b>

Intercept	4.655	2.946	1.58	0.114	1.409	2.95	0.479	0.632
-----------	-------	-------	------	-------	-------	------	-------	-------

468

469

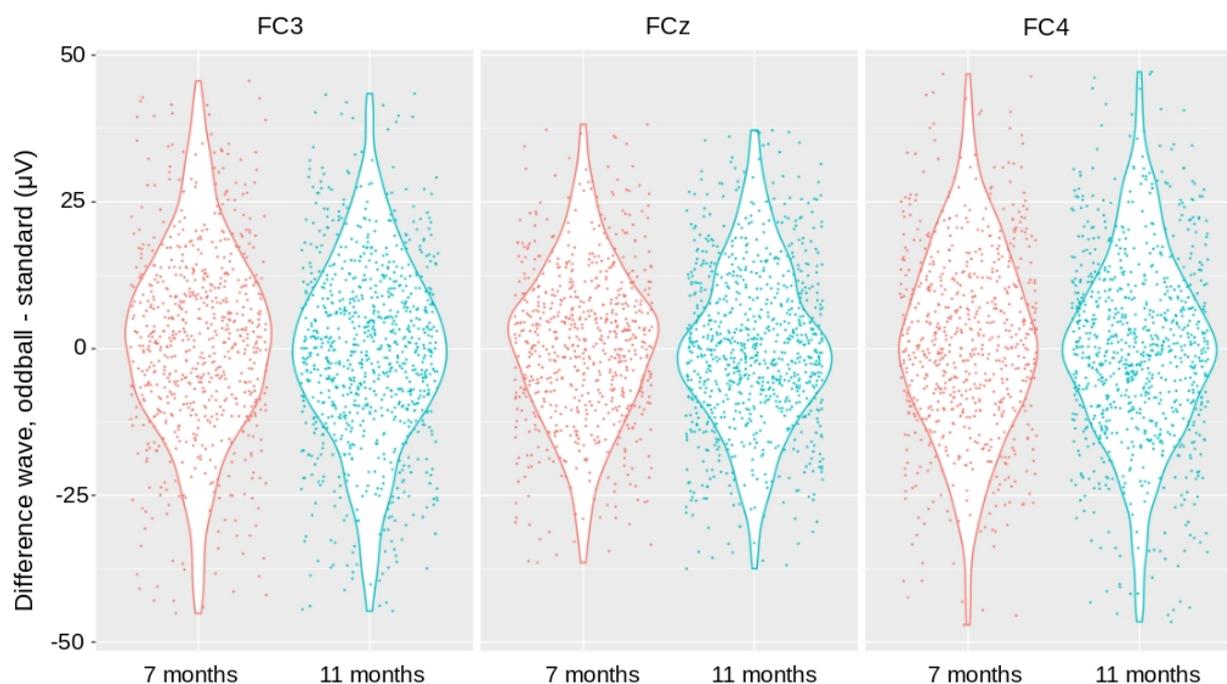
470

471

472

473

A striking aspect of Figure A2 is the similarity of the distributions of the difference waves across all the different rise time differences. Accordingly, Figure 2 illustrates the values of the difference wave by age and location, showing the large dispersal of difference wave amplitudes and valences across participants.



475

476

477

478

479

**Figure 2:** Distribution of difference waves at seven and eleven months, across three electrode groups. Each dot represents a difference wave for a particular infant; there are up to ten dots per infant (one difference wave for each oddball rise time presented).

### 3.4 Individual thresholds

480

481

482

483

484

485

486

487

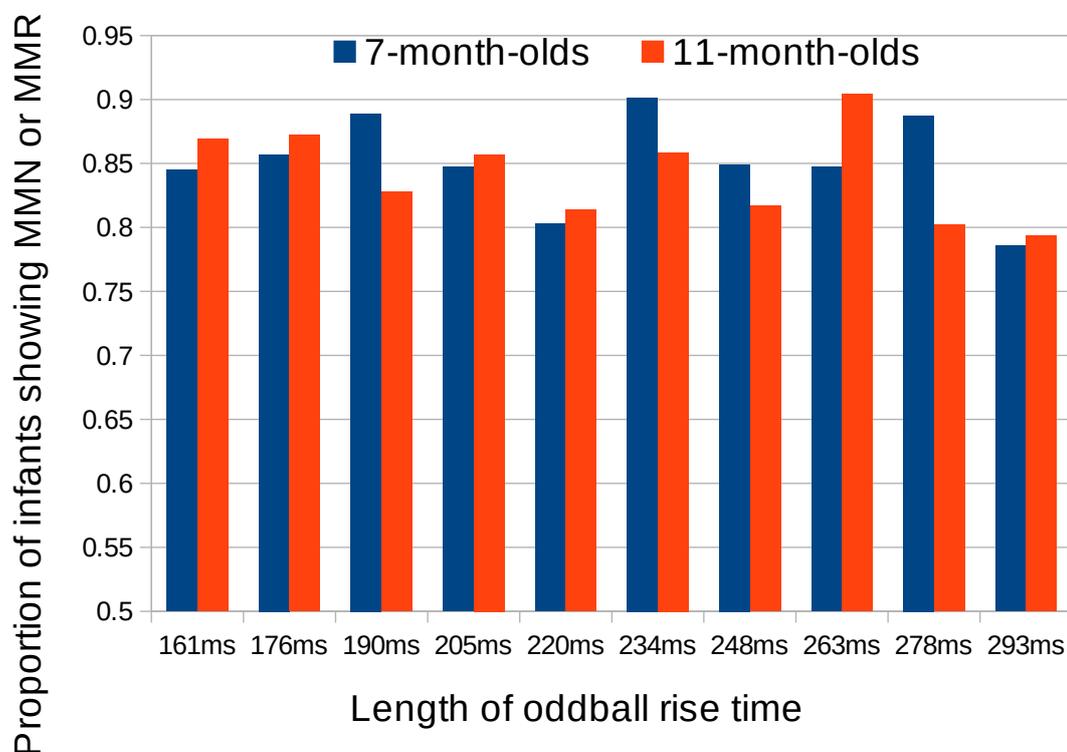
488

In this experiment, a range of ten oddball stimuli were used. Some had rise times that were very different to the standard and others were more similar. Our intention was to find at which point each individual infant ceased to display a difference wave greater than the baseline confidence interval. This point would indicate their threshold, at which they no longer perceived the oddball as different from the standard stimulus. However, the proportion of infants exhibiting a differential response to each stimulus was broadly similar across all of the oddball stimuli, as shown in Figure 3. This proportion was also similar across the two age groups, with 85.1% of responses at seven months showing a difference wave that exceeded the confidence interval, and 83.1% of responses at eleven months showing the same. However, the approximately 15% of responses without an apparent

489 mismatch response were not generated by the same 15% of infants. This indicates that the  
 490 anticipated pattern of responses “dropping off” after a certain point for each infant did not manifest.  
 491 There was no consistent pattern to the presence or absence of mismatch responses.

492

493



494

495 **Figure 3:** Proportion of infants exhibiting, in response to each oddball stimulus, a difference wave  
 496 in the time window of interest that exceeded (positively or negatively) the confidence interval of the  
 497 baseline difference wave across all stimuli. Proportions are averaged across electrode groups. From  
 498 left to right, the length of oddball rise time goes from the most similar to the standard stimulus, to  
 499 the least similar.

500

501 A consistent within-participant pattern of MMRs and MMNs did not emerge either, as  
 502 infants’ responses exhibited a mix of valences across the range of stimuli – 45.76% of responses at  
 503 seven months were positive, and 39.33% were negative. At eleven months, these figures were  
 504 39.96% and 42.96% respectively. Individual infants’ thresholds could thus not be ascertained. It  
 505 appears that by using prior behavioural data to guide our stimulus selection, we underestimated  
 506 infant sensitivity to rise time.

507

#### 508 4. Discussion

509 Here we show that the infant brain exhibits a neural response to changes in amplitude rise times, as  
 510 predicted. Further, the neural response was similar whether the stimulus was a sine tone or SSN.

511 Contrary to expectation, the infant brain showed a robust mismatch response to the full range of ten  
512 rise times utilised here. The consistent neural detection of changes in rise time, even for oddballs  
513 expected (from behavioural data) to be below perceptual threshold, indicates that rise time cues are  
514 available to infants from as young as seven months of age. This constitutes the first neural evidence  
515 for robust detection of changes in rise time in infants, and extends prior behavioural data  
516 (Kalashnikova, Goswami & Burnham., 2018). A neurophysiological approach thus suggests that  
517 perception of the different rise times that contribute to extraction of the AM hierarchy in IDS  
518 (Leong et al., 2017) is well-developed by seven months in typically-developing infants.

519

520 A negative shift in the mismatch response was observed with age. The difference wave in  
521 the window of interest relative to the baseline window was larger at seven than at eleven months of  
522 age (see Equation 1 model). Further, the difference in the mismatch difference wave was greater  
523 than the “matched standards” difference wave at seven but not eleven months (see Equation 2  
524 model). We interpret these age effects as indicating a shift towards the MMN, in line with other  
525 developmental literature showing this transition from MMR to MMN (Friedrich, Weber &  
526 Freiderici, 2004; Garcia-Sierra et al., 2011). While the ability to discriminate some auditory stimuli  
527 is lost during infancy due to perceptual narrowing, rise time discrimination remains present in  
528 childhood (e.g. Goswami et al., 2002) and individual differences in behavioural thresholds can be  
529 observed. Hence it is developmentally unlikely that infants are losing this auditory ability.  
530 Furthermore, examination of the presence of mismatch responses, regardless of valence, showed  
531 that similar proportions of difference waves (~85%) exceeded the baseline confidence interval at  
532 both seven and eleven months. Indeed, the interaction between age and electrode group (see  
533 Equation 3 model) shows that the negative shift in the mismatch response with age was smaller for  
534 right fronto-central electrodes than left fronto-central electrodes. Such data suggest that we are  
535 capturing an ongoing developmental change in the morphology of the mismatch response.

536

537 Further, the difference in rise time between the oddball and the standard affected the size of  
538 the mismatch response. This is demonstrated by the observed positive two-way interaction between  
539 electrode location and rise time difference. Over the FC4 electrode group, when the difference in  
540 rise time is larger, and thus the oddball is likely easier to discriminate, the difference wave is more  
541 positive. This suggests a sensitivity around FC4 to larger versus smaller rise time differences, with a  
542 more pronounced MMR when an oddball is easier to detect. More easily-discriminated stimuli  
543 typically elicit larger difference waves in infants (Cone, 2015; Cheour et al., 1998; Sams et al.,  
544 1985). As the current infants get older, the difference in responses to larger and smaller changes in  
545 rise time around FC4 reverses. This suggests that easy-to-detect changes in rise time elicit a MMN,

546 and more difficult-to-detect changes elicit a more positive MMR. The possibility of the same infant  
547 exhibiting an MMR to some stimuli and an MMN to other, more easily discriminated stimuli, fits  
548 with prior data from other infant MMN research (Cheng & Lee, 2018).

549

550         Regarding the difference between left (FC3) and right (FC4) fronto-central electrode groups,  
551 this should be interpreted with caution. Although the broader neural AM literature suggests that rise  
552 time processing may differ developmentally between left and right brain regions, the differential  
553 responses of the left and right frontotemporal regions reported here could be due to physiological  
554 factors affecting how electrophysiological fluctuations are transmitted from the brain to the scalp  
555 (Lew et al., 2013; Noreika et al., 2020). The prior auditory neural literature suggests that the right  
556 and left hemispheres play different roles in auditory and linguistic processing, with rapid,  
557 phonemic-rate transitions processed in the left (Boemio et al., 2005) and slower modulations  
558 processed in the right (Sammler et al., 2015). Pre-reading children show this hemispheric  
559 specialisation for “syllabic” but not “phonemic” rates of AM SSN (4 vs 80 Hz; Vanvooren et al.,  
560 2014), and both children and adults with dyslexia show atypical right hemisphere synchronization  
561 in response to 4 Hz AM noise (Lizarau et al., 2015). Our data are consistent with this literature in  
562 that frontocentral electrodes over the right side of the scalp appear more sensitive to differences in  
563 rise time than electrodes over the left, however without source localisation we cannot be assured  
564 that this is a difference in functional lateralisation.

565

566         As noted earlier, rise times play an important mechanistic role in rhythm detection.  
567 Amplitude rise times are important for the perception of rhythm because they determine the  
568 acoustic experience of “P-centres”, the perceptual moment of occurrence (“perceptual centre”) of  
569 each syllable (or musical beat) for the listener (Morton et al., 1976; Hoequist, 1983). Accurate  
570 perception of the beat structure of speech based on P-centres may be important for the temporal  
571 prediction of upcoming speech information (Kotz, Schwartz & Schmidt-Kassow, 2009), enabling  
572 infants to build a temporal framework related to extraction of the linguistic hierarchy. The current  
573 data suggest that the rise time discrimination skills required to construct such a temporal framework  
574 are already well-developed by seven months. As rise time is a dynamic measure based on changes  
575 reflecting the shape of the sound pressure wave, it cannot be compared in a simple way to other  
576 measures in the infant literature used to index temporal processing, such as duration perception or  
577 gap detection. For example, infant studies related to rapid auditory processing theory as a  
578 mechanism underpinning DLD and dyslexia (Tallal, 1980) have established that by 6 months of age,  
579 some infants can detect a gap between two tones that is as short as 70 ms (Hämäläinen et al., 2019).  
580 Data from individual tones of this nature are not comparable to the rise time measure used here.

581 Detection of a silent gap of 70 ms does not mean that the same infant brain should be able to detect  
582 an amplitude rise time of 70 ms, as the neural bases of these abilities are quite different.

583

584

#### 585 **4.1 Conclusions**

586 The results reported here are unambiguous with respect to infants' ability to detect changes in rise  
587 times. Although our stimuli did not challenge infants' detection thresholds, the data reveal greater  
588 sensitivity than anticipated from behavioural threshold research (Kalashnikova et al., 2018).  
589 Accurate detection of these rise time differences is likely to be important for phonological  
590 development, broader language development and the accuracy of neural tracking of the speech  
591 envelope (Goswami, 2019, for review). Mechanistically, rise time processing enables the infant  
592 brain to represent the amplitude envelope of the highly rhythmic stimulus that is infant-directed  
593 speech (Attaheri et al., 2021; Kalashnikova et al., 2018; Leong et al., 2017; Ortiz Barajas, Guevara  
594 & Gervain, 2021). The neural ability to discriminate these amplitude rise time cues revealed here  
595 highlights the readiness of the infant brain to process speech rhythm (Mehler et al., 1988).  
596 Accordingly, rise time discrimination is likely to support the infant brain in the acquisition of  
597 language. The neurophysiological results found here indicate robust processing by infants of this  
598 critical acoustic information during the early, pre-verbal stages of language development.

599

600 **Acknowledgments:** We are grateful to all of the families in the BabyRhythm project for their  
601 participation. This work was funded from the European Research Council (ERC) under the  
602 European Union's Horizon 2020 research and innovation programme (grant agreement No.  
603 694786).

604

605

606

607

608

609

610

611

612

613

614

615

616

617

618

619

620

621 **References**

622 Attaheri, A., Ní Choisdealbha, Á., Di Liberto, G., Rocha, S., Brusini, P., Mead, N., Olawole-Scott,  
623 H., Boutris, P., Gibbon, S., Williams, I., Grey, C., Flanagan, S., & Goswami, U. (2021). Delta-and  
624 theta-band cortical tracking and phase-amplitude coupling to sung speech by infants. *NeuroImage*,  
625 118698.

626

627 Bates, D., Sarkar, D., Bates, M. D., & Matrix, L. (2007). The lme4 package. *R package version*,  
628 2(1), 74.

629

630 Begum-Ali, J., Kolesnik-Taylor, A., Quiroz, I., Mason, L., Garg, S., Green, J., ... & Jones, E. J.  
631 (2021). Early differences in auditory processing relate to Autism Spectrum Disorder traits in infants  
632 with Neurofibromatosis Type I. *Journal of Neurodevelopmental Disorders*, 13(1), 1-19.

633

634 Bishop, D. V. M., & Hardiman, M. J. (2010). Measurement of mismatch negativity in individuals: A  
635 study using single-trial analysis. *Psychophysiology*, 47(4), 697-705.

636

637 Boemio, A., Fromm, S., Braun, A., & Poeppel, D. (2005). Hierarchical and asymmetric temporal  
638 sensitivity in human auditory cortices. *Nature Neuroscience*, 8(3), 389-395.

639

640 Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10, 433-436.

641

642 Cheour, M., Ceponiene, R., Lehtokoski, A., Luuk, A., Allik, J., Alho, K., & Näätänen, R. (1998).  
643 Development of language-specific phoneme representations in the infant brain. *Nature*  
644 *Neuroscience*, 1(5), 351-353.

645

646 Cheng, Y. Y., & Lee, C. Y. (2018). The development of mismatch responses to Mandarin lexical  
647 tone in 12-to 24-month-old infants. *Frontiers in Psychology*, 9, 448.

648

649 Cheng, Y. Y., Wu, H. C., Tzeng, Y. L., Yang, M. T., Zhao, L. L., & Lee, C. Y. (2015). Feature-  
650 specific transition from positive mismatch response to mismatch negativity in early infancy:

- 651 Mismatch responses to vowels and initial consonants. *International Journal of Psychophysiology*,  
652 96(2), 84-94.
- 653
- 654 Choudhury, N., & Benasich, A. A. (2011). Maturation of auditory evoked potentials from 6 to 48  
655 months: Prediction to 3 – and 4 – year language and cognitive abilities. *Clinical Neurophysiology*,  
656 122, 320-338. doi: 10.1016/j.clinph.2010.05.035
- 657
- 658 Cone, B. K. (2015). Infant cortical electrophysiology and perception of vowel contrasts.  
659 *International Journal of Psychophysiology*, 95(2), 65-76.
- 660
- 661 Dehaene-Lambertz, G., & Dehaene, S. (1994). Speed and cerebral correlates of syllable  
662 discrimination in infants. *Nature*, 370(6487), 292-295.
- 663
- 664 Delorme A & Makeig S (2004). EEGLAB: an open-source toolbox for analysis of single-trial EEG  
665 dynamics. *Journal of Neuroscience Methods*, 134, 9-21.
- 666
- 667 Di Liberto, G. M., Peter, V., Kalashnikova, M., Goswami, U., Burnham, D., & Lalor, E. C. (2018).  
668 Atypical cortical entrainment to speech in the right hemisphere underpins phonemic deficits in  
669 dyslexia. *Neuroimage*, 175, 70-79.
- 670
- 671 Ding, N., & Simon, J. Z. (2014). Cortical entrainment to continuous speech: functional roles and  
672 interpretations. *Frontiers in Human Neuroscience*, 8, 311.
- 673
- 674 Doelling, K. B., Arnal, L. H., Ghitza, O., & Poeppel, D. (2014). Acoustic landmarks drive delta–  
675 theta oscillations to enable speech comprehension by facilitating perceptual parsing. *Neuroimage*,  
676 85, 761-768.
- 677
- 678 Foxe, J. J., & Simpson, G. V. (2002). Flow of activation from V1 to frontal cortex in humans.  
679 *Experimental Brain Research*, 142(1), 139-150.
- 680
- 681 Friedrich, M., Weber, C., & Friederici, A. D. (2004). Electrophysiological evidence for delayed  
682 mismatch response in infants at-risk for specific language impairment. *Psychophysiology*, 41(5),  
683 772-782.
- 684

- 685 Garcia-Sierra, A., Rivera-Gaxiola, M., Percaccio, C. R., Conboy, B. T., Romo, H., Klarman, L., ...  
686 & Kuhl, P. K. (2011). Bilingual language learning: An ERP study relating early brain responses to  
687 speech, language input, and later word production. *Journal of Phonetics*, 39(4), 546-557.  
688
- 689 Giraud, A-L., & Poeppel, D. (2012). Cortical oscillations and speech processing: Emerging  
690 computational principles and operations. *Nature Neuroscience*, 15, 511–517. doi: 10.1038/nn.3063  
691
- 692 Goswami, U. (2019). Speech rhythm and language acquisition: An amplitude modulation phase  
693 hierarchy perspective. *Annals of the New York Academy of Sciences*, e14137..  
694
- 695 Goswami, U., Thomson, J., Richardson, U., Stainthorp, R., Hughes, D., Rosen, S., & Scott, S. K.  
696 (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of*  
697 *the National Academy of Sciences*, 99(16), 10911-10916.  
698
- 699 Greenberg, S. (2006). A multi-tier framework for understanding spoken language. In S. Greenberg  
700 & W. Ainsworth (Eds.), *Listening to speech: An auditory perspective*. Lawrence Erlbaum  
701 Associates.  
702
- 703 Guttorm, T. K., Leppänen, P. H. T., Hämäläinen, J. A., Eklund, K. M., & Lyytinen, H. J. (2010).  
704 Newborn event-related potentials predict poorer pre-reading skills in children at risk for dyslexia.  
705 *Journal of Learning Disabilities*, 43(5), 391–401. doi: 10.1177/0022219409345005  
706
- 707 Guttorm, T.K. , Leppänen, P.H.T. , Poikkeus, A.-M. , Eklund, K.M. , Lyytinen, P. , & Lyytinen, H.  
708 (2005). Brain event-related potentials (ERPs) measured at birth predict later language development  
709 in children with and without familial risk for dyslexia. *Cortex*, 41, 291-303.  
710
- 711 Hämäläinen, J. A., Ortiz-Mantilla, S., & Benasich, A. (2019). Change detection to tone pairs during  
712 the first year of life – Predictive longitudinal relationships for EEG-based source and time-  
713 frequency measures. *NeuroImage*, 198, 83–92. <https://doi.org/10.1016/j.neuroimage.2019.05.034>  
714
- 715 Harris, P. A., Taylor, R., Minor, B. L., Elliott, V., Fernandez, M., O'Neal, L., McLeod, L., Delacqua,  
716 G., Delacqua, F., Kirby, J., Duda, S.N., & REDCap Consortium. (2019). The REDCap consortium:  
717 Building an international community of software platform partners. *Journal of Biomedical*  
718 *Informatics*, 95, 103208. doi: 10.1016/j.jbi.2019.103208  
719

- 720 Harris, P. A., Taylor, R., Thielke, R., Payne, J., Gonzalez, N., & Conde, J. G. (2009). A metadata-  
721 driven methodology and workflow process for providing translational research informatics support.  
722 *Journal of Biomedical Informatics*, 42(2), 377-81.  
723
- 724 Hoequist, C. E. (1983). The perceptual center and rhythm categories. *Language and Speech*, 26,  
725 367-376. doi: 10.1177/002383098302600404  
726
- 727 Jessen, S., Fiedler, L., Münte, T. F., & Obleser, J. (2019). Quantifying the individual auditory and  
728 visual brain response in 7-month-old infants watching a brief cartoon movie. *NeuroImage*, 202,  
729 116060.  
730
- 731 Kalashnikova, M., Goswami, U., & Burnham, D. (2018). Mothers speak differently to infants at risk  
732 for dyslexia. *Developmental Science*, 21(1), e12487.  
733
- 734 Kalashnikova, M., Goswami, U., & Burnham, D. (2019). Sensitivity to amplitude envelope rise  
735 time in infancy and vocabulary development at 3 years: A significant relationship. *Developmental*  
736 *Science*, 22(6), e12836.  
737
- 738 Kalashnikova, M., Peter, V., Di Liberto, G. M., Lalor, E. C., & Burnham, D. (2018). Infant-directed  
739 speech facilitates seven-month-old infants' cortical tracking of speech. *Scientific Reports*, 8(1),  
740 13745. doi: 10.1038/s41598-018-32150-6  
741
- 742 Kleiner, M., Brainard, D., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception*, 36,  
743 ECVF Abstract Supplement.  
744
- 745 Kotz, S. A., Schwartze, M., & Schmidt-Kassow, M. (2009). Non-motor basal ganglia functions: A  
746 review and proposal for a model of sensory predictability in auditory language perception. *Cortex*,  
747 45, 982-990. doi: 10.1016/j.cortex.2009.02.010  
748
- 749 Kushnerenko, E., Ceponiene, R., Balan, P., Fellman, V., & Näätänen, R. (2002a). Maturation of the  
750 auditory change detection response in infants: a longitudinal ERP study. *Neuroreport*, 13, 1843–  
751 1848.  
752

- 753 Kushnerenko, E., Ceponiene, R., Balan, P., Fellman, V., Huotilainen, M., & Näätänen, R. (2002b).  
754 Maturation of the auditory event-related potentials during the first year of life. *Neuroreport*, *13*, 47–  
755 51. doi: 10.1097/00001756-200201210-00014  
756
- 757 Jessen, S., Fiedler, L., Münte, T., & Obleser, J. (2019). Quantifying the individual auditory and  
758 visual brain response in 7-month-old infants watching a brief cartoon movie. *NeuroImage*, *202*,  
759 116060. doi: 10.1016/j.neuroimage.2019.116060  
760
- 761 Law, M. J., Vandermosten, M., Ghesquiere, P., & Wouters, J. (2017). Predicting future reading  
762 problems based on pre-reading auditory measures: A longitudinal study of children with familial  
763 risk of dyslexia. *Frontiers in Psychology*, *8*, 124. doi: 10.3389/fpsyg.2017.00124  
764
- 765 Leong, V., & Goswami, U. (2015). Acoustic-emergent phonology in the amplitude envelope of  
766 child-directed speech. *PloS one*, *10*(12), e0144411.  
767
- 768 Leong, V., Kalashnikova, M., Burnham, D., & Goswami, U. (2017). The temporal modulation  
769 structure of infant-directed speech. *Open Mind*, *1*(2), 78-90.  
770
- 771 Lew, S., Sliva, D. D., Choe, M. S., Grant, P. E., Okada, Y., Wolters, C. H., & Hämäläinen, M. S.  
772 (2013). Effects of sutures and fontanels on MEG and EEG source analysis in a realistic infant head  
773 model. *NeuroImage*, *76*, 282-293.  
774
- 775 Leppänen, P. H. T., Hämäläinen, J. A., Salminen, H. K., Eklund, K. M., Guttorm, T. K., Lohvansuu,  
776 K., Puolakanaho, A., & Lyytinen, H. J. (2010). Newborn brain event-related potentials revealing  
777 atypical processing of sound frequency and the subsequent association with later literacy skills in  
778 children with familial dyslexia. *Cortex*, *46*(10), 1362–1376. doi: 10.1016/j.cortex.2010.06.003  
779
- 780 Liberman, M., & Prince, A. (1977). On stress and linguistic rhythm. *Linguistic Inquiry*, *8*(2), 249–  
781 336.  
782
- 783 Lippé, S., Kovacevic, N., & McIntosh, A. R. (2009). Differential maturation of brain signal  
784 complexity in the human auditory and visual system. *Frontiers in Human Neuroscience*, *3*, 48. doi:  
785 10.3389/neuro.09.048.2009  
786

- 787 Lizarau, M., Lallier, M., Molinaro, N., Bourguignon, M., Paz-Alonso, P. M., Lerma-Usabiaga, G.,  
788 & Carreiras, M. (2015). Developmental evaluation of atypical auditory sampling in dyslexia:  
789 Functional and structural evidence. *Human Brain Mapping, 36*(12), 4986-5002.  
790
- 791 Lopez-Calderon, J., & Luck, S.J. (2014). ERPLAB: an open-source toolbox for the analysis of  
792 event-related potentials. *Frontiers in Human Neuroscience, 8*, 213. doi:  
793 10.3389/fnhum.2014.00213.  
794
- 795 Mehler, J., Jusczyk, P., Lambertz, G., Halsted, N., Bertoncini, J., & Amiel-Tison, C. (1988). A  
796 precursor of language acquisition in young infants. *Cognition, 29*(2), 143-178.  
797
- 798 Morton, J., Marcus, S., & Frankish, C. (1976). Perceptual centers (P-centers). *Psychological*  
799 *Review, 83*, 405-408. doi: 10.1037//0033-295X.83.5.405  
800
- 801 Nazzi, T., Bertoncini, J., & Mehler, J. (1998). Language discrimination by newborns: Toward an  
802 understanding of the role of rhythm. *Journal of Experimental Psychology: Human Perception and*  
803 *Performance, 24*, 756-766. doi: 10.1037/0096-1523.24.3.756  
804
- 805 Noreika, V., Georgieva, S., Wass, S., & Leong, V. (2020). 14 challenges and their solutions for  
806 conducting social neuroscience and longitudinal EEG research with infants. *Infant Behavior and*  
807 *Development, 58*, 101393.  
808
- 809 Ortiz-Mantilla, S., Hämäläinen, J. A., Realpe-Bonilla, T., & Benasich, A. A. (2016). Oscillatory  
810 Dynamics Underlying Perceptual Narrowing of Native Phoneme Mapping from 6 to 12 Months of  
811 Age. *Journal of Neuroscience, 36* (48), 12095-12105. doi: 10.1523/JNEUROSCI.1162-16.2016  
812
- 813 Ortiz Barajas, M. C., Guevara, R., & Gervain, J. (2021). The origins and development of speech  
814 envelope tracking during the first months of life. *Developmental Cognitive Neuroscience, 100915*.  
815
- 816 Pasquini, E. S., Corriveau, K. H., & Goswami, U. (2007). Auditory processing of amplitude  
817 envelope rise time in adults diagnosed with developmental dyslexia. *Scientific Studies of Reading,*  
818 *11*(3), 259-286.  
819
- 820 Peter, V., Kalashnikova, M., & Burnham, D. (2016). Neural processing of amplitude and formant  
821 rise time in dyslexia. *Developmental Cognitive Neuroscience, 19*, 152-163.

822

823 Plakas, A., van Zuijen, T., van Leeuwen, T., Thomson, J. M., & van der Leij, A. (2013). Impaired  
824 non-speech auditory processing at a pre-reading age is a risk-factor for dyslexia but not a predictor:  
825 an ERP study. *Cortex*, 49(4), 1034-1045.

826

827 Richardson, U., Leppänen, P. H. T., Leiwo, M., & Lyytinen, H. (2003). Speech perception of infants  
828 with high familial risk for dyslexia differ at the age of 6 months. *Developmental Neuropsychology*,  
829 23, 385-397. doi: 10.1207/S15326942DN2303\_5

830

831 Richardson, U., Thomson, J. M., Scott, S. K., & Goswami, U. (2004). Auditory processing skills  
832 and phonological representation in dyslexic children. *Dyslexia*, 10(3), 215-233.

833

834 Sammler, D., Grosbras, M. H., Anwander, A., Bestelmeyer, P. E., & Belin, P. (2015). Dorsal and  
835 ventral pathways for prosody. *Current Biology*, 25(23), 3079-3085.

836

837 Sams, M., Paavilainen, P., Alho, K., & Näätänen, R. (1985). Auditory frequency discrimination and  
838 event-related potentials. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials*  
839 *Section*, 62(6), 437-448.

840

841 Spence, M. J., & DeCasper, A. J. (1987). Prenatal experience with low-frequency maternal-voice  
842 sounds influence neonatal perception of maternal voice samples. *Infant Behavior and Development*,  
843 10, 2, 133-142.

844

845 Stahl, D., Parise, E., Hoehl, S., & Striano, T. (2010). Eye contact and emotional face processing in  
846 6-month-old infants: Advanced statistical methods applied to event-related potentials. *Brain and*  
847 *Development*, 32(4), 305-317.

848

849 Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain*  
850 *and Language*, 9, 182-198. doi: 10.1016/0093-934X(80)90139-X

851

852 Vanvooren, S., Poelmans, H., Hofmann, M., Ghesquière, P., & Wouters, J. (2014). Hemispheric  
853 asymmetry in auditory processing of speech envelope modulations in prereading children. *Journal*  
854 *of Neuroscience*, 34(4), 1523-1529.

855

- 856 van Zuijen, T. L., Plakas, A., Maassen, B. A. M., Maurits, N. M., & van der Leij, A. (2013). Infant  
857 ERPs separate children at risk of dyslexia who become good readers from those who become poor  
858 readers. *Developmental Science*, *16*(4), 554–563. doi: 10.1111/desc.12049  
859
- 860 Vouloumanos, A., & Werker, J. F. (2004). Tuned to the signal: the privileged status of speech for  
861 young infants. *Developmental Science*, *7*(3), 270-276. doi: 10.1111/j.1467-7687.2004.00345.x.  
862
- 863 Zhao, T. C., & Kuhl, P. K. (preprint). Development of infants' neural speech processing and its  
864 relation to later language skills: an MEG study. *BioRxiv*. doi: 10.1101/2021.09.16.460534v1

865 **APPENDIX A: SUPPLEMENTARY INFORMATION FOR “NEURAL DETECTION OF CHANGES IN**  
866 **AMPLITUDE RISE TIME IN INFANCY.”**

867

868 **Further methodological information**

869 **Missing participants**

870 Reasons for the 49 missing recordings included missed appointments (n=8), fussiness (n=5),  
871 technical issues (n=2), dropping out of the study before reaching eleven months (n=1), and no  
872 reason recorded (n=13). The remaining twenty missing cases participated in either a habituation-  
873 based or a preferential looking-based rise time change detection paradigm. The behavioural  
874 paradigms did not provide sufficient data for analysis because infants became fussy before their  
875 detection thresholds could be determined.

876

877 **Block length variation**

878 For a small number of participants there were four blocks of 72 stimuli (7 seven-month-olds, 14  
879 eleven-month-olds), or six blocks of 48 stimuli (5 seven-month-olds, 2 eleven-month-olds). In these  
880 latter two cases, the extra stimuli included the 131.9 and 146.5ms rise time oddballs. The  
881 probability of an oddball was slightly lower in the blocks with 72 stimuli, at 14.3%.

882

883 **Data cleaning**

884 Filtered continuous data were epoched to 160ms before the onset of stimuli (both standards and  
885 oddballs) and 800ms after. A baseline correction was applied based on the 160ms pre-stimulus  
886 period. Transiently bad channels were identified epoch-by-epoch using the EEGLab `pop_eegthresh`  
887 function to detect epochs in which the absolute amplitude of any channel exceeded  $\pm 500\mu\text{V}$ , and  
888 the specific channels exceeding this threshold were identified. For epochs in which the sum of the  
889 persistently bad channels and transiently threshold-exceeding channels did not exceed 20% of all  
890 channels (12 out of 60 channels), bad channels were interpolated. Otherwise, only the persistently  
891 bad channels were interpolated in each epoch, under the assumption that the artefact-detection  
892 process would reject the noisiest epochs with over 20% of channels marked for rejection.

893

894 Detection of bad epochs was performed via two procedures. ERPlab's (Lopez-Calderon &  
895 Luck, 2015) automated peak-to-peak artefact detection procedure was used to identify epochs in  
896 which there were fluctuations of over  $200\mu\text{V}$  occurring within a 200ms window moving in  
897 increments of 100ms, with additional code written to flag only those epochs with 5 or more  
898 channels showing these fluctuations. A human coder also visually inspected all epochs and noted  
899 those with artefacts. On average, participants' data contained 242.6 epochs (SD = 23.6). The

900 automated rejection protocol and the experimenter agreed to keep, on average, 181.6 epochs (SD =  
901 41.1) per participant and to reject 26.4 (33.6). On average, there were 3 epochs (6.17) per  
902 participant that only the automated protocol rejected and 28 (17.3) that only the coder opted to  
903 reject. All epochs detected by the ERPlab protocol were rejected. Those identified for rejection by  
904 the human coder alone were reviewed, and rejected if there was an artefact that could not have been  
905 identified by the peak-to-peak automated procedure because it did not contain high amplitude  
906 fluctuations. One example might be the high frequency noise characteristic of the cap resettling on  
907 the infant's head if they had recently touched it, another would be an artefact causing a large  
908 variation in amplitude but affecting fewer than five channels. This amounted to 17.23 (12.78)  
909 epochs on average.

910

### 911 **Cluster-based approach to time window selection**

912 An electrode-level cluster-based analysis was implemented in EEGlab to ascertain whether the  
913 electrode groupings and time window selected a priori did indeed line up with scalp regions where  
914 significant differences could be found. Due to the fully factorial implementation of cluster-based  
915 permutation testing in EEGlab, we could use only the 64 infants who attended both the seven and  
916 eleven month sessions in this analysis. As we would not expect activation across the scalp to vary  
917 on the basis of differences in rise time length, we entered all oddball trials into the analysis, and  
918 compared to the relevant standard trials. We also conducted a comparison by age. Figure A3 shows  
919 changes in neural response across the scalp over different time windows. Figure A4 highlights  
920 where and when significant clusters were found. Omitted cells show no significant clusters. The  
921 cluster-based permutation tests were corrected using the false discovery rate (FDR) correction in  
922 EEGlab. Results suggest that the time window selected for analysis (highlighted in red) did contain  
923 differences in activation by age and by stimulus type over the frontocentral electrodes selected for  
924 analysis. The greater amplitude over right than left frontocentral electrodes accords with the  
925 reported results. It is notable that there is a significant cluster over parieto-occipital electrodes with  
926 a later time course, which appears to emerge at 11 months. Though not part of our planned analysis,  
927 this more posterior response could be investigated in future.

928

### 929 **Further results: Inclusion of electrode group as factor**

930 Equation 1 model: Including electrode group as a factor, Satterthwaite-approximation F tests still  
931 show only effects of age ( $F(1, 3756.8) = 9.37, p = 0.002$ ) and the window by age interaction ( $F(1,$   
932  $9539.9) = 9.43, p = 0.002$ ) with a marginal effect of window ( $F(1, 9541.1) = 3.077, p = 0.079$ ). In  
933 terms of simple effects, we still see a significant effect of window,  $\beta = 1.376, SE = 0.563, t = 2.444,$

934  $p = 0.015$ , and an interaction between age and window,  $\beta = -2.138$ ,  $SE = 0.754$ ,  $t = -2.837$ ,  $p =$   
 935  $0.005$ .

936

937 Equation 2 model: F tests using a Satterthwaite approximation method reveal a significant  
 938 contribution to the model of age,  $F(1, 9472) = 5.927$ ,  $p = 0.015$  and a marginal contribution of the  
 939 age by response type interaction,  $F(1, 9472) = 3.72$ ,  $p = 0.054$ . The model fit was significantly  
 940 better than that of the random model,  $\chi^2 = 11.582$ ,  $p = 0.009$ . Comparing the mismatch response to  
 941 the “matched” response using separate t-tests for each age group, differences are seen at seven but  
 942 not eleven months (7 months:  $t(73) = 2.962$ ,  $p = 0.004$ ,  $CI = [0.35, 1.797]$ ,  $BF_{10} = 7.007$ ; 11 months:  
 943  $t(95) = -0.132$ ,  $p = 0.868$ ,  $CI = [-0.99, 0.866]$ ,  $BF_{10} = 0.114$ ). When electrode group is included in  
 944 the model, the contribution of age ( $F(1, 9464) = 5.937$ ,  $p = 0.015$ ) and marginal contribution of age  
 945 by response type ( $F(1, 9464) = 3.709$ ,  $p = 0.054$ ) remain, with no further significant results.

946

947 **Table A1:** Equation 2 “matched standards” model results

	Estimate	Standard error	t	p
Age 11 months (ref. 7 months)	-0.155	0.435	-0.357	0.721
<b>Mismatch response type (ref. matched)</b>	<b>1.08</b>	<b>0.459</b>	<b>2.356</b>	<b>0.019</b>
<b>Age 11mo * Mismatch response type</b>	<b>-1.183</b>	<b>0.613</b>	<b>-1.929</b>	<b>0.054</b>
Intercept	-0.03	0.325	-0.092	0.927

948

949 Stimulus type model: Including electrode group alongside stimulus type does not alter the model’s  
 950 overall results. Satterthwaite approximated F-tests show an effect of age ( $F(1, 3370.9) = 9.3775$ ,  $p =$   
 951  $0.002$ ), an interaction between window and age ( $F(1, 9529.8) = 9.431$ ,  $p = 0.002$ ), and a marginal  
 952 effect of window ( $F(1, 9530.6) = 3.069$ ,  $p = 0.08$ ). There is a simple effect of window,  $\beta = 1.875$ ,  
 953  $SE = 0.798$ ,  $t = 2.349$ ,  $p = 0.019$ , and a simple interaction between window and age  $\beta = -2.301$ ,  $SE$   
 954  $= 1.085$ ,  $t = -2.122$ ,  $p = 0.034$ .

955

956 **Table A2:** Results of model on effects of stimulus type by window. Results from the second model  
 957 including stimulus type as a random slope are included in brackets

	Estimate	Standard error	t	p
Age 11 months (ref. 7 months)	-0.011 (-0.009)	0.433 (0.436)	-0.025 (-0.02)	0.98 (0.984)
<b>Window (ref. baseline)</b>	<b>1.282 (1.283)</b>	<b>0.46 (0.46)</b>	<b>2.791 (2.791)</b>	<b>0.005 (0.005)</b>
Sine tone stimulus (ref. SSN)	-0.015 (-0.021)	0.471 (0.471)	-0.033 (-0.046)	0.974 (0.964)
<b>Age 11mo * Window</b>	<b>-1.564 (-1.563)</b>	<b>0.606 (0.606)</b>	<b>-2.579 (-2.579)</b>	<b>0.01 (0.01)</b>
Age 11mo * Sine tone	0.005 (0.008)	0.627 (0.625)	0.009 (0.012)	0.993 (0.99)
Window * Sine tone	-0.466 (-0.467)	0.651 (0.65)	-0.717 (-0.717)	0.474 (0.473)
Age 11mo * Window * Sine tone	0.456 (0.455)	0.871 (0.871)	0.523 (0.522)	0.601 (0.602)

Intercept	0.019 (0.02)	0.333 (0.34)	0.057 (0.06)	0.955 (0.952)
-----------	--------------	--------------	--------------	---------------

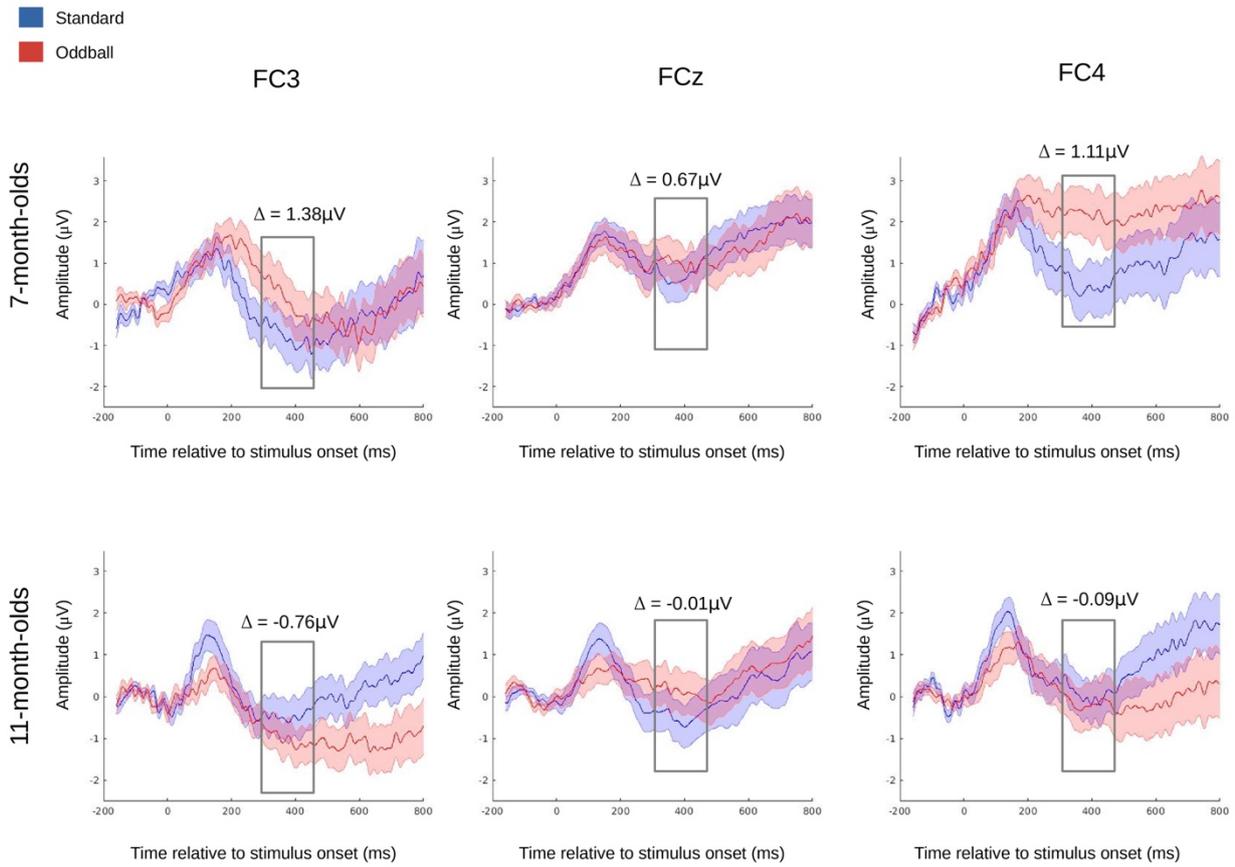
958

959 **Table A3:** Results of model on effects of stimulus type by response type (matched vs mismatch  
960 responses<sup>1</sup>.

	Estimate	Standard error	t	p
Age 11 months (ref. 7 months)	-0.089	-0.603	-0.148	0.882
<b>Response type</b>	<b>1.336</b>	<b>0.645</b>	<b>2.07</b>	<b>0.039</b>
Sine tone stimulus (ref. SSN)	0.048	0.65	0.073	0.942
<b>Age 11mo * Mismatch response</b>	<b>-1.476</b>	<b>0.852</b>	<b>-1.733</b>	<b>0.083</b>
Age 11mo * Sine tone	-0.139	0.871	-0.159	0.874
Mismatch response * Sine tone	-0.514	0.917	-0.561	0.575
Age 11mo * mismatch response * Sine tone	0.596	1.228	0.485	0.874
Intercept	-0.053	0.456	-0.117	0.9072

961

963 <sup>1</sup> “Rise time difference” refers to the difference in rise time length between a given oddball and the standard stimulus.  
964 For the mismatch response types, this refers to the actual difference in rise time; for the “matched” response type –  
965 which involves subtracting one standard stimulus from another – this refers to the difference between the standard  
966 stimulus rise time and the rise time of the oddball from the same block.



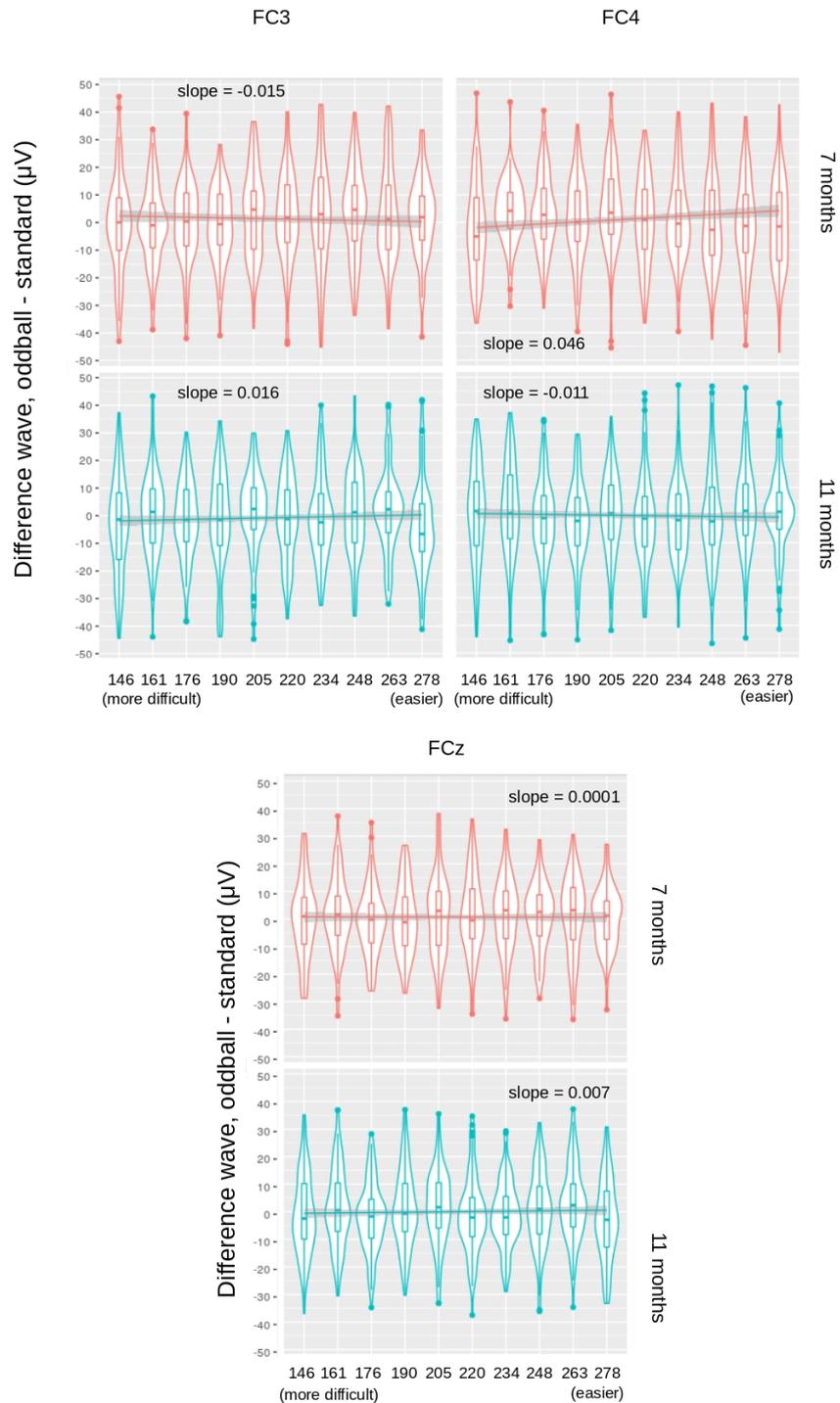
967

968 **Figure A1:** Average ERPs in response to the standard (blue) and oddball (red) stimuli at seven (top) and  
 969 eleven (bottom) months of age, over electrode groups. Shaded regions denote the standard error of the mean  
 970 response.  $\Delta$  denotes the mean amplitude across each difference wave per infant for the window of interest,  
 971 contained within each grey box.

972

973

974

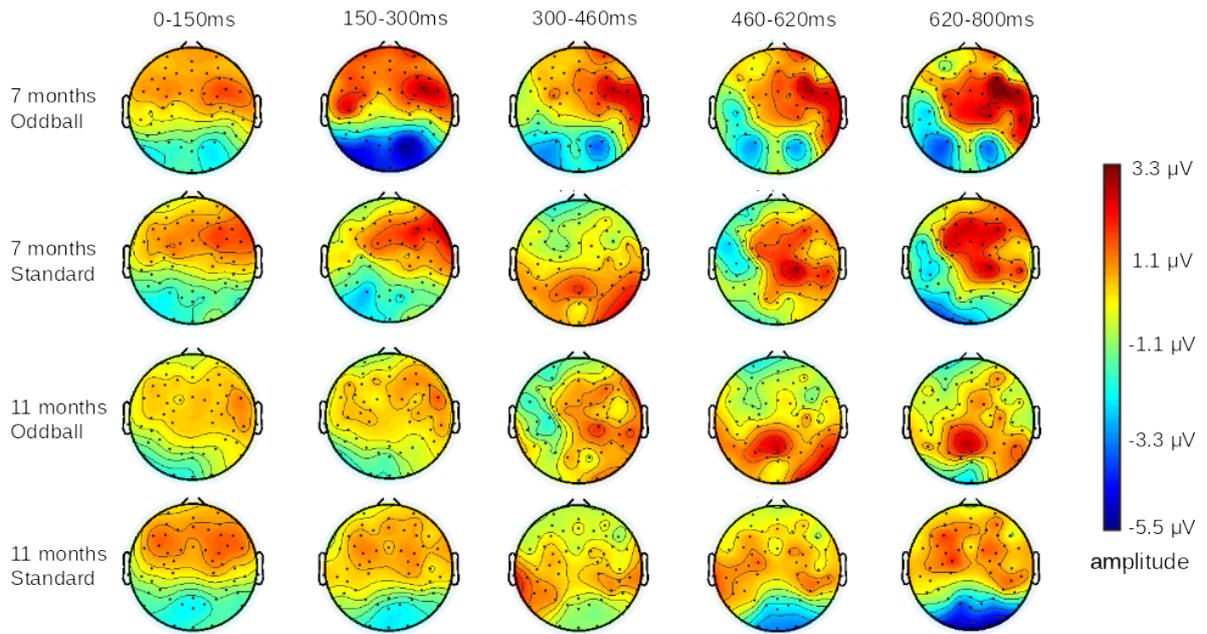


Rise Time Difference (Oddball – Standard) – from smallest to largest difference in ms

976

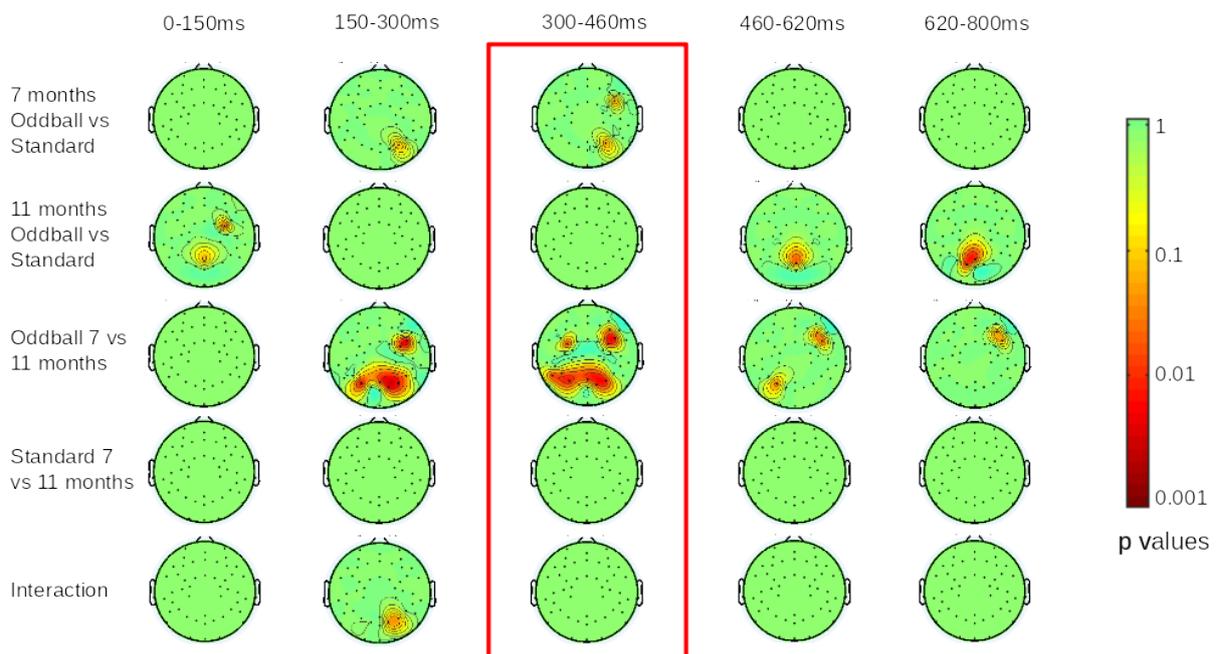
977 **Figure A2:** Distribution of difference waves by age, scalp location, and rise time difference, with plotted  
 978 linear slope of difference wave by rise time difference. Differences in stimulus rise time length are plotted  
 979 from shortest (more difficult to discriminate oddball from standard) to longest (easier to discriminate).  
 980

980



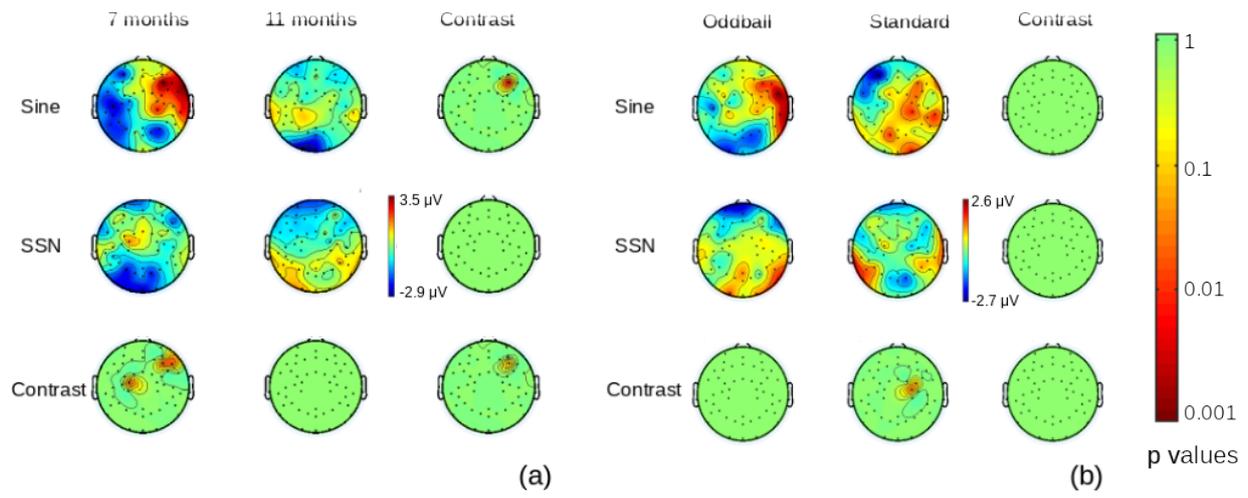
981

982 **Figure A3:** Time course of activation over the scalp by age and in response to oddball versus  
 983 standard stimulus



984

985 **Figure A4:** Condition and age comparisons (and their interaction) by time window, with significant  
 986 FDR-corrected clusters.



987 **Figure A5:** Age (a) and condition (b) comparisons by stimulus type, with significant FDR-corrected  
 988 clusters for each variable and their interaction under “Contrast”.