Journal Pre-proof

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Please cite this article as: Leminen, M., Leminen, A., Smolander, S., Arkkila, E., Shtyrov, Y., Laasonen, M., Kujala, T., Quick reorganization of memory traces for morphologically complex words in young children, *Neuropsychologia* (2020), doi: https://doi.org/10.1016/j.neuropsychologia.2019.107309.

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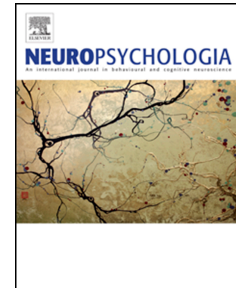
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Yury Shtyrov: Conceptualization, Writing – review & editing, Funding Acquisition

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Quick reorganization of memory traces for morphologically complex words in young children

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28 **Abstract**

29 Formation of neural mechanisms for morphosyntactic processing in young children is still poorly

30 understood. Here, we addressed neural processing and rapid online acquisition of familiar and unfamiliar

31 combinations of morphemes. Three different types of morphologically complex words – derived, inflected,

32 and novel (pseudostem + real suffix) – were presented in a passive listening setting to 16 typically

33 developing 3-4-year old children. The mismatch negativity (MMN) component of event-related potentials

34 (ERP), an established index of long-term linguistic memory traces in the brain, was analysed separately for

35 the initial and final periods of the exposure to these items. We found MMN response enhancement for the

36 inflected words towards the end of the recording session, whereas no response change was observed for

37 the derived or novel complex forms. This enhancement indicates rapid build-up of a new memory trace for

38 the combination of real morphemes, suggesting a capacity for online formation of whole-form lexicalized

39 representations as one of the morphological mechanisms in the developing brain. Furthermore, this

40 enhancement increased with age, suggesting the development of automatic morphological processing

41 circuits in the age range of 3-4 years.

42

43 **Highlights**

44 • We studied the acquisition of morphologically complex words in passive listening

45 • 3-4-year-old children showed evidence of rapid learning of complex words

46 • The results demonstrate children's greater flexibility to rearrange lexical storage

47 • The effect was specific to inflected words and gradually increased with age

48

49

50 **Graphical abstract**

51

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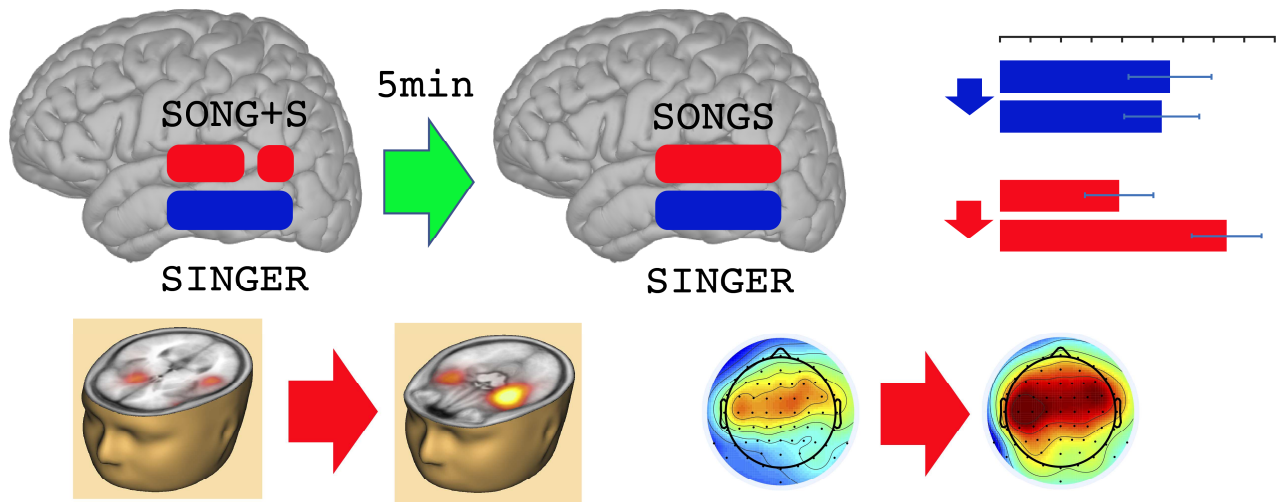
1 Introduction

54 Morphemes (such as stems and affixes) are the smallest linguistic items carrying their own meaning. In

55 morphologically rich languages, such as Finnish, speech comprehension relies heavily on using

56 morphological rules and on parsing of a morphologically complex word to its morpheme constituents, such

57 as word stems (e.g., 'light'), as well as inflectional (e.g., plural '-s', lights) and derivational (e.g., '-ness',

58 lightness) suffixes (Niemi et al., 1994). Thus, a complex word (such as 'light+s') has its inner combinatorial

59 structure, and the meaning of the complex word might be computed by analyzing and integrating its

60 morpheme constituents. Such morphological analysis seems to take place automatically even if one has not

61 heard/seen the full complex word before (e.g., Leminen et al., 2016, 2010; McKinnon et al., 2003). Different

62 neurocognitive models have been suggested to explain the details of cognitive mechanisms behind this

63 analysis. For instance, some models propose that all morphologically complex words (i.e. derived and

64 inflected) are processed through obligatory morphological decomposition into their constituent

65 morphemes (e.g., Rastle and Davis, 2008), while others postulate at least partially distinct neural processing

66 and representation for inflections and derivations (Bozic and Marslen-Wilson, 2010; Clahsen et al., 2003;

67 Niemi et al., 1994); still others claim that all morphological effects arise from the correlation between form

68 and meaning (Gonnerman et al., 2007; Seidenberg and Gonnerman, 2000). There are also different

69 accounts regarding the presence of a single or two routes of morphological processing, as well as the role

70 of semantic information at the very early stages of processing (for a review on studies employing visually

71 presented morphologically complex words, see Amenta and Crepaldi, 2012). Notably, the current

72 knowledge on neural underpinnings of these cognitive processes is mainly based on reading experiments

73 and on studies performed in adults or adolescents. Very little is known about the neural basis of

74 morphological processing and learning in young children (before school age) when the language system is

75 most amenable. Furthermore, there is particularly little evidence available in the auditory domain, which is

76 the primary pathway of language acquisition in childhood. To fill these gaps, the present study aims to

77 elucidate the neural mechanisms of processing and acquisition of different types of morphologically

78 complex spoken words in young children.

1.1   Structure of neural lexicon in adults

80 Several neuroimaging studies in various languages suggest that, in adults, inflected and derived words

81 might be processed and represented differently in the brain, at least to a degree (for a review, see Bozic

82 and Marslen-Wilson, 2010; see also A Leminen et al., 2013a). More specifically, it has been suggested that

83 due to their idiosyncratic nature, existing derived words (develop-ment, jump-er, dark-ness) are likely to be

84 represented by a whole-form lexical memory trace, whereas morphemes of more transparent and

85 predictable inflected words (book-s, walk-ed, bring-s) are more likely parsed on the fly to re-create their

86 combined meaning by combining their constituents (e.g., Bozic & Marslen-Wilson, 2010; Carota, Bozic, &

87 Marslen-Wilson, 2016; Clahsen, Sonnenstuhl, & Blevins, 2003; Leminen et al., 2011; Leminen, Leminen,

88 Kujala, & Shtyrov, 2013). This parsing route appears a particularly efficient strategy in languages with a very

89 rich inflectional system where whole-form storage of multiple inflections and declinations is not

90 economical (Laine et al., 1994; Niemi et al., 1994). In line with this proposal, derivations, similar to

91 monomorphemic words, seem to be processed in bilateral temporal brain areas, whereas inflections

92 engage predominantly the left frontotemporal neural network linked to combinatorial syntactic processes

93 in general (Bozic, Tyler, Ives, Randall, & Marslen-Wilson, 2010; Bozic & Marslen-Wilson, 2010). This

94   combinatorial activity has a processing cost (the cognitive load), manifest behaviorally in longer reaction

95   times in lexical decision tasks (e.g., Bertram, Laine, & Karvinen, 1999; Lehtonen & Laine, 2003; Niemi et al.,

96   1994) and longer fixations in reading (Hyönä et al., 1995) in comparison to otherwise matched

97   monomorphemic words (see the model in Figure 1A).

98   On the other hand, some authors have suggested that derivation and inflection are not the most optimal

99   morphological categories to dissociate between the use of parsing vs. storage route, but a better way to

100 describe them could be the continuum between meaning-changing (e.g. change from verb to noun: sing-

101 singer) and meaning-invariant morphology (Bertram, Schreuder, & Baayen, 2000). However, in many cases

102 derivations and inflections can be contrasted even with this measure. It has also been suggested that all

103 morphologically complex words trigger very automatic decompositional processing, even when the whole

104 form of the word would be already stored in the neural lexicon (e.g., corner, apartment; Marslen-Wilson

105 and Tyler, 2007; Rastle and Davis, 2008). This parsing route may be the only option if a pseudo morpheme

106 is embedded in complex word (e.g. existing stem with novel suffix; Leminen et al., 2016). Importantly,

107 unlike brain responses to monomorphemic items, neurocognitive activity reflecting inflectional

108 decomposition do not vary with word frequency, which indicates that the vast majority of them were going

109 through the parsing route with similar intensity (Vartiainen et al., 2009), whereas only exceptionally high

110 frequency inflections may have the full-form representation (Soveri et al., 2007).

111 Language processing is a complex cognitive task with several subprocesses. Thus, one experimental

112 strategy that enables focusing on the core properties of linguistic processing is to use passive listening

113 paradigms, in which different cognitive strategies and the effect of modulated attentional load and working

114 memory processes can be reduced (Shtyrov, 2010). Passive listening experiments have indeed been

115 successful in contrasting lexical properties of language (for a review, see Pulvermüller & Shtyrov, 2006;

116 Shtyrov & Pulvermüller, 2007). For example, existing (lexical) monomorphemic words show enhanced

117 responses in comparison to non-existing (novel) monomorphemic words reflecting stronger automatically

118 activated neural memory traces for familiar words (so-called lexical MMN; e.g., Bakker et al., 2013;

119   Garagnani et al., 2009). Following the same logic, the lexical MMN is larger to high frequency

120   monomorphemic words than to existing low frequency words, suggesting that this ERP reflects the strength

121   of connections in memory circuits stemming from the intensity of its use (Alexandrov, Boricheva,

122   Pulvermüller, & Shtyrov, 2011; Shtyrov, Kimppa, Pulvermuller, & Kujala, 2011). Using the same procedure,

123   responses to morphologically complex words have also been recorded in a few studies. They found that

124   MMN responses for derived complex words were enhanced in comparison to inflected words (A Leminen et

125   al., 2013b; Whiting et al., 2013) and responses for congruent (existing) derived words were larger than

126   those for incongruent (but meaningful) derived words (Hanna and Pulvermuller, 2014). This pattern of

127   responses is highly similar to the lexical MMN for monomorphemic words, and is thus hypothesized to

128   reflect the strength of the existing neural memory trace for the whole form of the complex word.

129   Equivalently, lexical MMN for compound words has been found to reflect the strength of the lexical

130   representation for the stem combination (MacGregor and Shtyrov, 2013) and even particle verbs (Cappelle

131   et al., 2010), reinforcing the notion of whole-form lexicalized (even supra-lexical) representations for this

132   type of morphology. Lower response amplitudes for complex inflected forms, in turn, suggest the

133   absence/weakness of a whole-form representation implying a step-wise parsing route for such items.

134   **1.2   Structure of neural lexicon and its development in children**

135   Children use inflectional rules already during their first years of life (Stolt et al., 2009; Toivainen, 1980),

136   although they tend to over-extend regular inflections and incorrectly apply those to irregular words (e.g.

137   '*goed') (Clahsen, Aveledo, & Roca, 2002). Sometimes suffixes can even help language comprehension. For

138   instance, children can guess the word meaning based on a highly productive derivative suffix (Bertram,

139   Laine, & Virkkala, 2000). However, children's explicit knowledge about morphological elements of complex

140   words continues to develop during school years even after 8 years of school (Tyler and Nagy, 1989). It is,

141   however, unclear whether it is due to the development of neurocognitive resources needed in

142   morphological parsing during online comprehension, or to explicit cognitive skills in linguistic reasoning.

143   Neuroimaging evidence has shown that fronto-temporal brain networks are maturing slowly (Gogtay et al.,

144   2004). For instance, an fMRI study showed that while semantic and syntactic networks were distinct in the

145 adult brain, five-year-old children showed more similar activation patterns for both types of experimental

146 manipulations (Wu et al., 2016). This indicates that while first signs of adult-like lexical-semantic processing

147 develop already during the first 2 years of life (Stolt et al., 2009; Toivainen, 1980), combinatorial

148 mechanisms needed in syntactic and morphological processes are dependent on neural resources that

149 begin to be available slightly later (Friederici, 2005). These combinatorial skills modulate morphosyntactic

150 processing in a continuous manner over the years of development (Clahsen et al., 2002; Friederici, 2005).

151 Only few studies have investigated differences in the processing of different types of complex words in

152 children. Using morphological priming with both derived and inflected words, Rabin & Deacon (2008) found

153 no differences in visual priming effects (response accuracy) when children in first and fifth grades were

154 compared. In another study, 5- to 8-year-old children were asked to spell word endings (Deacon and

155 Bryant, 2005). Spellings were more correct for inflected than derived words, and interestingly, again the

156 effect was similar in both age groups. This suggests that children were more aware of inflectional rules than

157 derivational rules, and this distinction remained similar during the development in these age groups.

158 However, there are no studies on younger children (<5 years when the semantic and combinatorial systems

159 begin to diverge). With most studies focused on reading, an acquired "add-on" for the language system,

160 more evidence is required in the auditory modality, the "native" modality of language in which most of the

161 acquisition takes place during the early childhood.

162 **1.3   Memory trace formation and learning of word forms**

163 Word learning in adults includes components some of which are hippocampus-dependent (e.g. so-called

164 explicit encoding), whereas some rely on cortical mechanisms (Davis and Gaskell, 2009; Warren and Duff,

165 2014). Focused attention has also been found to be important in learning the contextual meaning of a word

166 (see de Diego-Balaguer et al., 2016 for a proposed developmental link between attention and linguistic

167 skills) and integrating it into a semantic network (for a review, see Smith et al., 2010), although the effect is

168 modulated by individual differences, such as experience related to music expertise (Dittinger et al., 2017,

169 2016). Explicit encoding (with focused attention) tasks have been used to study learning of word forms with

170 or without meaning, the latter sometimes being called form-only words (for a recent fMRI study, see e.g.,

171 Takashima et al., 2017). In contrast, implicit learning of word forms may give important details on the core

172 neural mechanisms behind initial stages of word learning. For example, Szmalec et al. (2012) found that

173 implicit statistical learning of novel word forms through reading led to interference with existing

174 phonological neighbor words in an auditory task, making the reaction times slower due to larger lexical

175 competition. This suggests that implicitly acquired word forms (without learned meaning) are not

176 independent of the neural lexicon, but instead interact with modality independent lexical processing. In a

177 recent study, Sandoval et al. (2017) showed that implicit statistical learning paradigm can also be applied to

178 acquisition of morphological rules of an unfamiliar language. To sum up these views, word learning is

179 typically assessed via explicit learning, where attention is directed to the to-be-learned material. The

180 learning process involves hippocampus-dependent distributed networks to store the meaning of a word as

181 well as the word form, which gradually become consolidated in neocortical circuits. Implicit learning

182 paradigms in which the new word forms are to be inferred from context rather than introduced via a direct

183 instruction, are thought to induce a learning effect in cortical networks, independently of the hippocampus

184 (Shtyrov et al., 2019).

185 The first study showing neurophysiological evidence of fast memory-trace buildup of monomorphemic

186 words found that, only after 14 minutes of passive exposure, novel words had created their real-word-like

187 memory-traces in perisylvian language cortices (Shtyrov, Nikulin, & Pulvermuller, 2010). After these initial

188 findings, similar results have been found by several other studies using different languages, stimuli, and

189 exposure sequences. These studies have shown that this rapid memory trace formation is specific to speech

190 sounds (Shtyrov, 2011) and native phonology (Kimppa et al., 2015), is modulated by the previous

191 experience in language acquisition (Kimppa et al., 2016), and is independent of locus of attention (Kimppa

192 et al., 2015). The first and only study conducted in children (6- to 13-year-olds) showed that the response

193 increase indicating memory trace build-up was evident much faster that previously shown in adults, already

194 after 4 minutes of exposure (Partanen et al., 2017). Additionally, this study also found that, unlike in adults,

195 the memory trace was strengthened even for phonologically non-native words and non-speech sounds. In

196   these cases, the response growth was bilateral indicating contribution of a wider neural network than the

197   typical left-lateralized circuits in native language processing and acquisition. However, these previous

198   studies used only monomorphemic words and not morphologically complex stimuli. A previous study

199   investigating acquisition of new morphologically complex words in adults showed that new memory traces

200   for novel combinations of two morphemes (novel suffix combined with an existing/non-existing stem) can

201   be formed also during passive listening (Leminen et al, 2016). However, the developmental perspective of

202   new morpheme acquisition remains unexplored.

203   **1.4   The current study**

204   Here, we aimed at elucidating neural underpinnings of morphological processing in young children at pre-

205   reading stage, at the ages of 3 to 4 years. This age group was chosen because only few studies have

206   approached this topic with pre-school-aged children during the most active stages of language

207   development, and even fewer studies have addressed groups at pre-reading age. More specifically, we

208   wanted to focus on the dynamics of memory trace formation and its development in this age range. Such

209   young children are a challenging participant group for active tasks and, hence, potential unwanted variance

210   can be minimized with a passive listening paradigm. We therefore employed the passive paradigm and

211   stimuli previously successfully used with adult participants (Alina Leminen et al., 2013). The change in

212   neural responses over the course of an 11-minute-long block was analysed in three experimental conditions

213   including an existing derived word, an existing inflected word, and a novel complex word combining a novel

214   stem with an existing suffix (see Methods section for more details). The chosen technique of passive

215   listening paradigm with repeating stimuli is a particularly suitable and reliable method for revealing

216   automatic activation of word-specific memory traces.

217   In line with previous studies using similar methodology, the enhanced responses would suggest

218   reorganization of neural activity and thus formation of new memory traces (Kimppa et al., 2015, 2016;

219   Partanen et al., 2017; Shtyrov, 2011; Shtyrov, Nikulin, & Pulvermuller, 2010). As the stimuli consist of

220   morphologically complex words, the response strength in this study will reflect the memory trace of the

221 whole form, i.e., the stem and suffix combination. If the responses change during experiment differently to

222 derived, inflected, and novel words, it would indicate that the original representations of these words

223 differ, and thus, shape the ability to strengthen neural memory traces. Presumably the initial strength of

224 the memory trace is weaker for the whole-form of the inflected word than that of derived complex word

225 (based on previous findings with passive listening). According to this hypothesis, the inflected word is

226 mainly processed via the parsing route. If repetitive exposure to existing morphemes in an inflectional

227 combination increases the response amplitude, it would indicate that the neural link between these two

228 morphemes has been created, connecting them into a whole-form representation with a unified memory

229 trace. Further, it would indicate that the brain is capable of lexicalizing even familiar inflections if massively

230 exposed to them, to facilitate their processing. The complex pseudo-word with pseudo stem and existing

231 suffix will show whether similar whole-form acquisition is possible in parallel with the acquisition of the

232 stem.

233 To track the developmental change during the 3rd and 4th years of life, the correlation with age and event-

234 related potential amplitudes was calculated. It is unclear whether general statistical learning abilities

235 improve, deteriorate, or remain stable during childhood (Arciuli, 2017). Studies contrasting morphologically

236 complex words with somewhat older children (age range of 5 to 10 years), suggest no fundamental

237 developmental change in the neural learning dynamics (Deacon and Bryant, 2005; Rabin and Deacon,

238 2008). However, as discussed above, in the present age group the neurolinguistics system is at its most

239 plastic, undergoing rapid development. Therefore, we can hypothesize that if our results in 3-to-4-year-old

240 children show age-related decrease in the ability to form memory traces, it will suggest that memory trace

241 formation for morpheme combinations declines with overall decrease of brain plasticity in children. If we

242 instead find response dynamics enhancement with age, it will suggest that the memory system supporting

243 storage of morpheme combinations relies on more complex linguistic brain mechanisms that are still

244 maturing in 3-to-4-year-old children (Skeide and Friederici, 2016).

245

246 **2   Material and methods**

247 **2.1   Participants**

248 16 young 3-to-4-year-old monolingual Finnish speaking children (mean age of 52.7±5.1 Months, range 45.2-

249 59.7 Months, 14 boys[1]) participated in the study. None of the participants had any diagnosed neurological

250 or developmental disorders, including language development disabilities, or hearing impairments. Two

251 additional children were also recruited, but their data had to be rejected from the analyses due to massive

252 movement artefacts and low data quality.

253 The experiment was conducted in accordance with the Declaration of Helsinki with the permission from the

254 Ethical Board of Helsinki University Hospital (approval reference number: § 248/2012). Written informed

255 consents were obtained from all adult participants and child participants' parents.

256 **2.2   Experimental design and procedures**

257 EEG recording was conducted using an active electrode system (Biosemi Active Two, Biosemi B.V.,

258 Netherlands) in an acoustically and electrically shielded chamber. The EEG was recorded with 66 channels

259 (64 standard 10-20 system and two electrodes at mastoids), mounted in a cap. Participants chose a film

260 which they watched without sound during the experiment. To make the recording session more

261 comfortable for the children, the stimuli were presented through 2 loudspeakers (and not headphones),

262 which were located on both sides of the display in approximately 45 degrees angle, at the distance of about

263 150 cm from the participants' head. The sound level at the head position was fixed to be comfortable

264 (about 65 dB(A) SPL). Most of the children sat alone in a comfortable chair during the experiment (2

265 participants sat on the lap of their caretaker). The children's caretaker was present in the same chamber.

266 All the participants were given a possibility to have small breaks between the experiment blocks (every 12

267 minutes) when needed and were served with refreshments.

268 The paradigm was a traditional oddball sequence (with a 1000 ms stimulus onset asynchrony (SOA)),

269 including a frequently presented (79%) monomorphemic word and an occasionally occurring rare (21%)

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[1] Note that gender was unbalanced and thus, the results may not be generalized to girls.

270 complex form of the same word, which was created by adding a '-ja' suffix to the word stem. This suffix was

271 chosen because, rather uniquely, in Finnish it represents the same surface form for an inflection (plural

272 partitive) and derivation (profession, occupation) allowing for a strict matching of phonology and acoustics

273 between different morphological conditions. Three different Finnish word stems were used in the current

274 study; 'laula' (sing), 'laulu' (song), and 'raulu' (pseudo word). To control the acoustics of the word-final affix

275 and avoid co-articulatory bias, stems and suffixes were obtained separately and cross-spliced together. The

276 stems were used as such as the frequent ("standard") monomorphemic stimuli. The '-ja' suffix was taken

277 from a separate word, in which the final phoneme was neither 'a' nor 'u', but 'i' ('tutki+ja'). To create the

278 deviant stimuli, the same '-ja' suffix was cross-spliced to each stem with a natural 12 ms silent gap between

279 the offset of stem and onset of a suffix. The stem length was 409 ms and, thus, a suffix onset was at 421 ms

280 in all the conditions. The complex words constructed by combining stems with '-ja' suffix, resulted in three

281 different morphological conditions; 'laulaja' ('singer', a real derived word), 'lauluja' ('songs', a real inflected

282 word, the partitive plural form), and 'rauluja' (unfamiliar complex word, consisting of a pseudostem and a

283 real suffix; see Figures 1A and 1B). The surface frequencies were 24.93 and 26.46 per million for derived

284 and inflected words respectively (frequencies were obtained from the Finnish corpus composed by the

285 Research Institute for the Languages of Finland, the Finnish IT Centre for Science and the Department of

286 General Linguistics, University of Helsinki). However, surface frequencies are based on written language

287 sources and more suitable for adult language processing measures, but most probably both stems and

288 morphologically complex forms are familiar to all 3-to-4-year-old Finnish children. Due to carefully

289 preserved phonotactics, the unfamiliar complex word sounds like a plural inflection to the native ear.

290 Originally there were also a 'raulaja' condition (to act as a "derived" pseudo stem) in the paradigm

291 (Leminen et al., 2013), but it was deemed necessary to leave it out from the current study to shorten the

292 already one hour long recording session. The stimuli were uttered by a female native speaker of Finnish.

293 The recordings were stored with a 44.1 kHz sampling frequency and 16-bit quantization. All stimulus items

294 had matching fundamental frequency (F0) and duration. They were normalized to have the same peak

295 sound energy (for more details, see Leminen et al., 2013). The stimuli were presented by NBS Presentation

296 software (Neurobehavioral Systems, Inc., USA). A pseudo-randomized stimulus sequence was used so that

297 there were always at least two standard stimuli after any deviant. The stimuli were presented in 3 blocks

298 (one condition per block), and the order of the blocks was counter-balanced across the participants using a

299 Latin square design.

300 EEG data were recorded with a sampling rate of 512 Hz, signal bandwidth of DC-104 Hz, and a resolution of

301 31 nV. The PO1 electrode site was used as the reference electrode during the recording (CMS electrode of

302 Biosemi's standard 64 channel layout). The EEG data were offline processed in BESA (Besa Research 6.1,

303 Besa GmbH, Germany) and Matlab (R2016a, Mathworks Inc., USA). First, the eye movements and eye blinks

304 were cleaned with automated PCA algorithm (Berg and Scherg, 1994) and the result was visually

305 monitored. After interpolating bad channels, offline filtering (0.5-45 Hz, 48dB/oct), and epoching (from -

306 100 ms to 1000 ms, based on word onsets), the single trial data were exported to Matlab (540 standards

307 and 119 deviants per condition). Thereafter the data were re-referenced to the average of all channels,

308 baseline corrected (with 100 ms pre-word baseline), and trials exceeding ±100 µV amplitude criteria were

309 rejected. After rejection, 450/98 epochs (for standards and deviants, respectively; minimum of 308/65)

310 were re-referenced to the average of mastoids and forwarded to analysis. These remaining trials were

311 divided to two averages separately for each condition and stimulus type to first half and second half of the

312 block, with equal number of trials (i.e. median split, see Figure 1C). Split half method was chosen as a

313 compromise between signal to noise ratio of averages (with less epochs than usually acceptable in ERPs)

314 and sensitivity to neural dynamics.

315

316   Figure 1 about here [width: 2 columns]
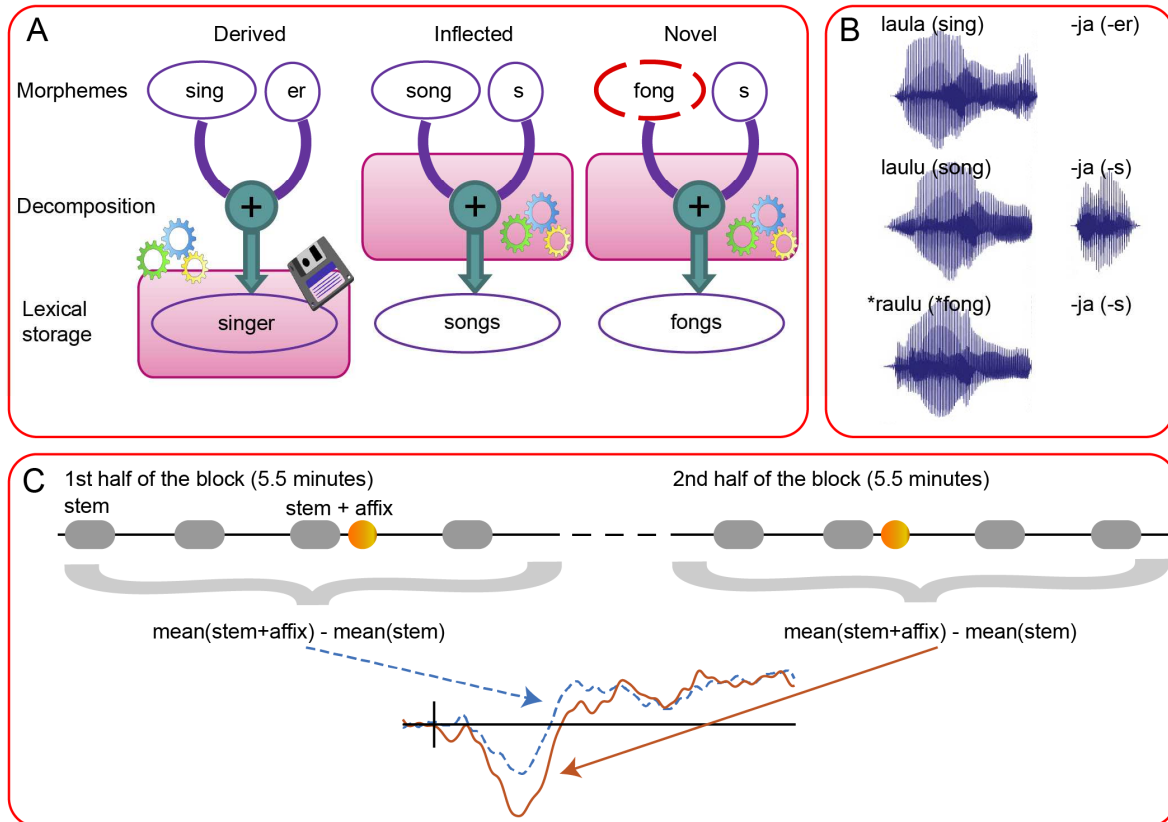
317

Figure 1. Details of the stimuli, paradigm, and the experimental design. A) Stimulus categories and the visualization of the storage vs. decomposition model of morphologically complex words. B) Stimulus waveforms. C) Visualization of the stimulus paradigm and how the response change during the experiment was measured.

2.3 ERP analyses

ERP analyses of difference waves (the response to deviant stimuli minus the response to standard stimuli) for each condition (Derived, Inflected, and Novel complex word conditions) and each state of exposure (Initial and Final, first half and second half of epochs, respectively) were conducted in the time window of interest. The time window was chosen to cover the typical MMN/MMR peak interval of 120-160 ms from the suffix onset.

329   The areal means were used to improve the signal to noise ratio (which was lower than usual due to the

330   overall lower quality of the child data and the smaller number of trials because of splitting into sub-

331   averages to trace their dynamics during the exposure). These regions of interest (ROIs) were left (FC3, FC5,

332   C3, and C5) and right (F4, F6, FC4, and FC6) fronto-temporal clusters in children (see Figure 2). ROIs were

333   placed based on the topographic maps indicating activity maxima.

334   Statistical analyses were conducted for difference waveforms in IBM SPSS Statistics for Macintosh (version

335   23, IBM Corp., NY). The repeated measures ANOVA was calculated with within-subject factors of Condition

336   (3 levels; Derived, Inflected, and Novel complex word), Exposure (2 levels; Initial and Final), and Laterality

337   (two levels; Left and Right ROI). Mauchly's Test for Sphericity did not show any violations of sphericity

338   assumptions. Effect sizes for statistical comparisons are reported as the means of partial eta-squared (η_P^2).

339   Significant effects were followed with Bonferroni corrected simple pair-wise t-tests. The alpha level of 0.05

340   was used in all the statistical tests and accurate p values are reported.

341   To test the developmental aspect of changes in the responses, an additional repeated measures ANOVA

342   was calculated by adding a continuous covariate of age in months. Significant effects were followed with

343   condition-specific correlation analyses (two-tailed Pearson's correlation).

344

345   **3   Results**

346   In the time window of 120-160 ms after the suffix onset, repeated measures ANOVA showed a significant

347   interaction of Condition × Exposure for the MMR responses (F(2,30) = 5.30, p = .011, η_P^2 = 0.261). Post-hoc

348   analyses (tests of simple effects) showed that the response enhancement during the experiment was

349   significant only in the Inflected condition (from 3.9±1.1 µV to 6.8±1.0 µV, p=.013). Furthermore, Inflected

350   and Novel conditions differed from each other only in the second half of the experiment (p=.020), showing

351   larger amplitudes for the Inflected condition than for the Novel condition (6.8±1.0 and 4.2±1.1 µV

352   respectively) whereas other simple contrasts between the conditions were insignificant (see Figure 2). Note

353 that MMN responses were positive in polarity, which is typical with for young children (Kujala and Leminen,

354 2017).

355

356 Figure 2 about here [width: 2 columns]
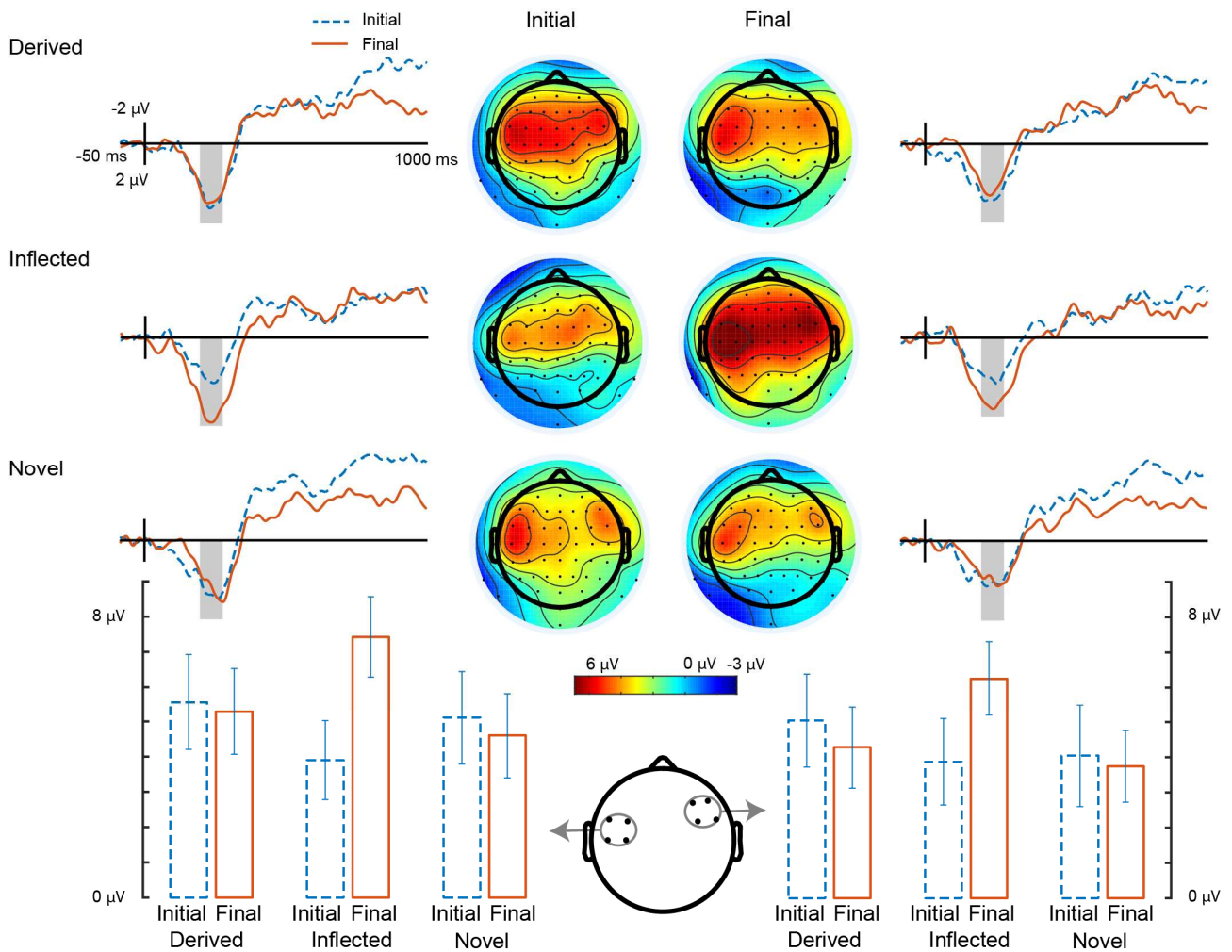
358 Figure 2. Scalp maps and difference wave ERPs (response for deviants minus response for standards). ERPs

359 and scalp maps are shown separately for the first half (Initial) and the second half (Final) of the exposure.

360 Bar diagrams show mean amplitudes (and their standard errors) of regions of interest (shown in a ROI

361 scalp) within the time window of interest (shown as grey box on ERPs). Blue dashed line: Initial. Red solid

362 line: Final.

363

364 When Age was added to the model as a covariate, the results showed significant interaction of Condition $\times$

365 Exposure $\times$ Age (F(2,28) = 4.20, p = .025, η_P^2 = 0.231). The post-hoc correlation tests showed that the

366 Exposure-related change in the response amplitude was linearly increasing with the age in Inflected

367 condition (r = 0.49, p = .055) whereas in the other two conditions the relationship was less clear (Derived: r

368 = -2.2, p = .417; Novel: r = -0.14, p = .614; see Figure 3).

369

370 Figure 3 about here [width: 2 columns]

371
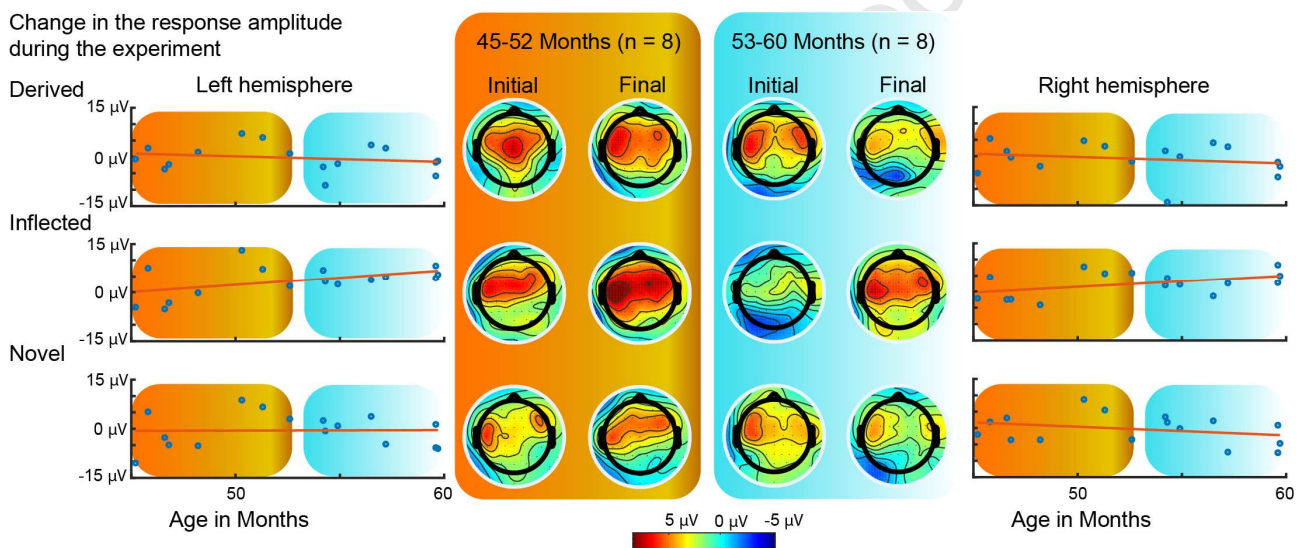
372

373 Figure 3. The effect of age on ERP dynamics. Scalp maps separately for younger and older children along

374 with the ERP change during the experiment as a function of age. The zero line represents the case with no

375 change during the experiment, while positive values represent response enhancement. Red line is a linear

376 fit for all the data.

377

378 **4   Discussion**

379 In the current study, we aimed at elucidating the neural mechanisms involved in the early, most automatic

380 stages of online processing and acquisition of morphologically complex words in young children.

381 Furthermore, we investigated whether development during the age range of 3-4 years affects these

382 abilities. Our participants passively listened to derived, inflected, and novel complex words, which allowed

383 tracking the different aspects of linguistic representations in the neural lexicon, and their dynamics during

384 the passive stimulus exposure. Our results showed differential response dynamics depending on the

385 experimental conditions and on the age of the children.

386 **4.1   Derivation vs. Inflection in children**

387 Typically developing native Finnish-speaking children are known to use inflections before they reach the

388 age of 2 years (Stolt et al., 2009; Toivainen, 1980). There is also some evidence of distinct developmental

389 trajectories for processing of inflected and derived complex words in English, as 5- and 8-year-old children

390 showed an awareness of inflectional mechanisms in spelling, but not of derivations (Deacon and Bryant,

391 2005). Similarly, German-speaking children showed an adult-like behavioral cross-modal morphological

392 priming effect for irregular inflections, evident in 10-year-olds, but still missing in 8-year-olds (Clahsen &

393 Fleischhauer, 2013). In that study, regular inflections were similarly primed in all age groups. These findings

394 were interpreted such that neural mechanisms for combinatorial inflections are developing earlier in life,

395 while irregular inflections may be at least initially stored as full-forms in the neural lexicon and their parallel

396 parsing route develops later. However, while the relationship between derivations vs. inflections and

397 regular vs. irregular inflections in some languages is not straightforward, similar distinctions have been

398 found in both contrasts.

399 Our results in 3-to-4-year-old children clearly show distinct processing of derived and inflected complex

400 words. The response for the derived word did not change during the course of the experiment. This

401 suggests that the neural representation of the derived word does not change due to passive exposure. The

402 effect is similar that has been found earlier in adults with existing monomorphemic words (e.g., Shtyrov,

403 Nikulin, & Pulvermuller, 2010) and indicates that the word most probably already has an existing memory

404 trace for the whole form. However, the response for the inflected word condition was enhanced during the

405 experiment. It suggests an enhancement of the neural memory trace for this type of complex word,

406 similarly to what has been found for novel monomorphemic words in adults (Shtyrov, 2011) and in older

407 children (Partanen et al., 2017). The effect can be explained if we assume that children initially had lacking

408 (or weaker) whole-form representation for the plural inflected form of the word, with its processing chiefly

409 relying on decomposition, in line with the main findings for regular inflection processing. The magnitude of

410 the lexical MMN response for monomorphemic words, occurring about 120-200 ms after the recognition

411 point, has been shown to reflect lexicality and lexical frequency, so that existing high frequency words show

412 larger amplitudes than low frequency words, and existing words show larger amplitudes than pseudowords

413 (Bakker et al., 2013; Garagnani et al., 2009; Shtyrov et al., 2011). One could thus also hypothesize that

414 repeating the same auditorily presented complex word for about 100 times during the experiment

415 artificially increases word's surface frequency and leads to the build-up of a new or enhanced whole-form

416 representation by linking two existing morphemes into a single memory circuit. Importantly, in the current

417 study this effect was prominent only for the inflectional condition, which suggests that in the derived

418 condition the existing memory trace was most likely already saturated and any further development of the

419 response to it suppressed. Similar findings have been found in adults, for which processing of newly

420 (explicitly) learned high frequency inflectional affixes showed less activation in brain structures underlying

421 decomposition, in comparison to low frequency affixes or applying newly learned affixes into new stems

422 (Nevat et al., 2017).

423 **4.2   Development of language acquisition skills**

424 We found that the ERP response enhancement for inflectional word ending increased from 3 to 4-year-olds.

425 This could indicate that the maturation of neural networks involved in this response enhancement is in

426 active phase during this age range[2]. It has been hypothesized that while the bottom-up language processing

427 skills develop rapidly during the first 3 years of life, the neural capacity for top-down processing, needed for

428 processing of syntactical hierarchies, develops later (Skeide and Friederici, 2016). It is possible that partly

429 the same networks are also involved in morphological processes. Despite the fact that large scale linguistic

430 networks are somewhat differently organized in 5-year-olds compared to adults, the resting state

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[2] However, we cannot definitely exclude other possible factors in which 3- and 4-year-olds differed from each other, such as, exposure to musical and linguistic activities in kindergartens and more formal lessons.

431 connectivity between temporal and frontal areas in the left hemisphere correlate with skills to comprehend

432 complex sentences (Xiao et al., 2016). The same inferior frontal gyrus area has also been shown to be

433 specifically activated during an auditory morphological awareness task in 7-13-year-old children (Arredondo

434 et al., 2015).

435 Furthermore, functional connectivity between the left posterior superior temporal gyrus (pSTG) and the left

436 inferior frontal cortex (IFC) has been found already in 3- and 6-year-olds for syntactic processing

437 (Vissiennon et al., 2017). Interestingly, however, these age groups were different: 3-year-olds had stronger

438 functional connectivity with Brodmann area (BA) 45 whereas 6-year-olds had a stronger functional

439 connectivity with BA 44. Authors linked this group difference to maturation of ventral and dorsal pathways.

440 The ventral pathway linking pSTG to BA 45 is present already at birth while the dorsal pathway (also called

441 the arcuate fasciculus, AF) linking pSTG to BA 44 matures later during childhood (Brauer et al., 2013, 2011).

442 Especially the AF has been shown to be crucial for syntactic processing (Wilson et al., 2011). Moreover, the

443 dynamic changes during the repetition of syntactic structures have been found in these same cortical areas.

444 More specifically, the repetition of novel syntactic structures led to activation increase at both ends of the

445 dorsal pathway, namely in posterior temporal and inferior frontal cortices while the repetition of initially

446 known syntactic structures led to repetition suppression in the same cortical areas (Weber et al., 2016).

447 However, it is debatable whether the same neural mechanisms are involved in the combinatorial

448 processing of single-word-level morphology and multiple-word-level syntax (Marantz, 2013). One could still

449 speculate whether memory traces for morpheme combinations are also partly dependent on the

450 maturation of the dorsal pathway.

451 The findings of the current study suggest that young children have the ability to store new memory traces

452 for streams of existing morphemes in passive listening. This is in line with a recent study on

453 monomorphemic novel words with native and non-native phonology (Partanen et al., 2017). In that study,

454 in contrast to previous findings in adults, Danish children showed response enhancement even when non-

455 native phonology or non-speech sounds were used. Overall, these two studies demonstrate the increased

456 versatile flexibility of children's brain to form neural memory traces in passive listening for different types

457 of auditory input, including both monomorphemic and bimorphemic words.

458 **4.3   Morphological processing of non-words**

459 In the current study, the third experimental condition included a novel complex word made of a pseudo

460 word stem and an existing suffix (acoustically/phonologically identical suffix to that used in the other two

461 conditions). Contrary to our expectations, the results did not show response enhancement during the

462 exposure to this stimulus. This does not follow the findings with monomorphemic words in adults (Kimppa,

463 Kujala, Leminen, Vainio, & Shtyrov, 2015; Kimppa, Kujala, & Shtyrov, 2016; Partanen et al., 2017; Shtyrov,

464 2011; Shtyrov, Nikulin, & Pulvermuller, 2010). The discrepancy between the previous and current findings

465 might result from differences in morphological structure of the stimulus words. It has been found that

466 morphologically complex words that contain either a real stem with pseudo-suffix or a pseudo stem with a

467 real suffix, are more difficult to reject in lexical decision task than pseudowords without embedded real

468 morphemes (Caramazza et al., 1988; see also Post et al., 2008). This indicates that the parsing route is at

469 least partly activated even if one of the morphemes is non-existing. The ignited decomposition might

470 indeed be a potential explanation, why in the current study pseudo words were not processed and

471 lexicalized like monomorphemic words. On the other hand, and critically, they were neither lexicalized as a

472 pair of existing morphemes. So, for existing inflections, it might be easier to boot-strap the two existing

473 representations into a single one within the short exposure time employed here. For the pseudo stem +

474 real affix combination this process may be more difficult, as the process requires both the construction of a

475 new trace for the stem and its linkage with the affix, for which 11 minutes may be too short as a learning

476 period. The order of pseudo and real morphemes may play a critical role especially in the auditory domain,

477 i.e. the first morpheme (the pseudo stem in the current study) modulates the way how forthcoming

478 morphemes are processed (see also Leinonen et al., 2009).

479

5   Conclusions

480

481   We examined the online neural processing and acquisition of combinations of morphemes in young

482   children. Neural responses showed bilateral increase for the inflected complex words towards the end of

483   the experiment. This enhancement increased with age, indicating development of automatic morphological

484   processing circuits in age range of 3 to 4 years. No response change was observed for the derived words.

485   Hence, it is possible that young children have an automatic ability to quickly and flexibly form memory

486   traces for the combination of existing morphemes even without focusing their attention on the stimuli.

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694   **Figure colors:** for online only.

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696   **Figure legends**

697   Figure 1. Details of the stimuli, paradigm, and the experimental design. A) Stimulus categories and the

698   visualization of the storage vs. decomposition model of morphologically complex words. B) Stimulus

699 waveforms. C) Visualization of the stimulus paradigm and how the response change during the experiment

700 was measured.

701 Figure 2. Scalp maps and difference wave ERPs (response for deviants minus response for standards). ERPs

702 and scalp maps are shown separately for the first half (Initial) and the second half (Final) of the exposure.

703 Bar diagrams show mean amplitudes (and their standard errors) of regions of interest (shown in a ROI

704 scalp) within the time window of interest (shown as grey box on ERPs). Blue dashed line: Initial. Red solid

705 line: Final.

706 Figure 3. The effect of age in ERP dynamics. Scalp maps separately for younger and older children along

707 with the ERP change during the experiment as function of age. The zero line represents the case with no

708 change during the experiment, while positive values represent response enhancement. Red line is a linear

709 fit for all the data.

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