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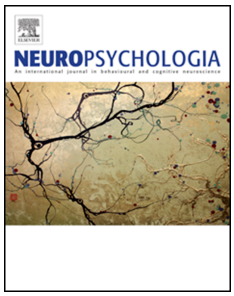

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Quick reorganization of memory traces for morphologically complex words in young children

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Key words: lexical memory traces, morphologically complex words, lexical MMN, neurocognitive development

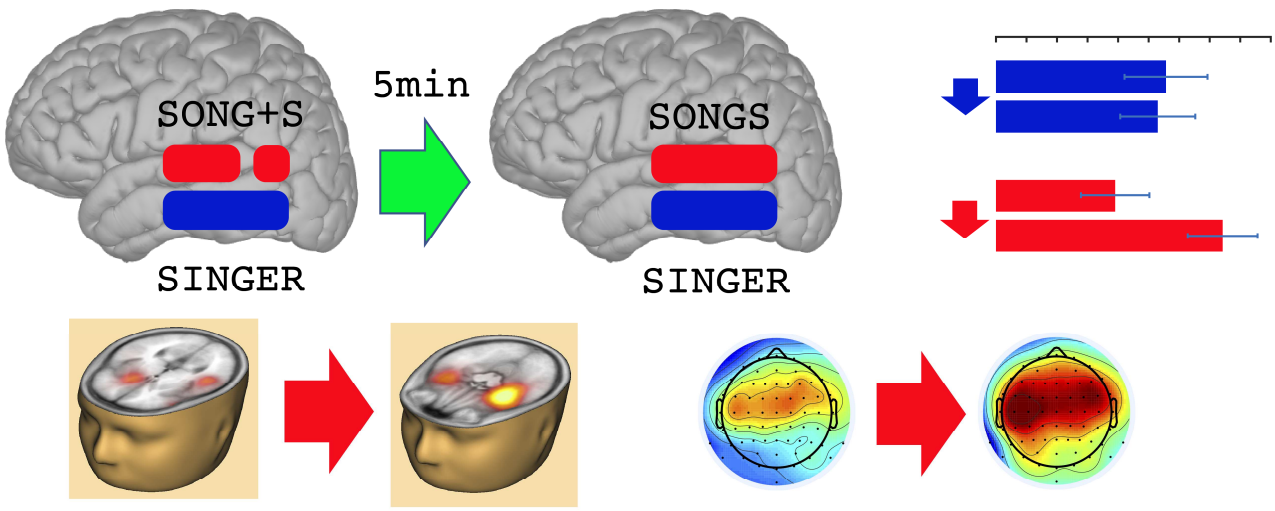
Abstract

Formation of neural mechanisms for morphosyntactic processing in young children is still poorly understood. Here, we addressed neural processing and rapid online acquisition of familiar and unfamiliar combinations of morphemes. Three different types of morphologically complex words – derived, inflected, and novel (pseudostem + real suffix) – were presented in a passive listening setting to 16 typically developing 3-4-year old children. The mismatch negativity (MMN) component of event-related potentials (ERP), an established index of long-term linguistic memory traces in the brain, was analysed separately for the initial and final periods of the exposure to these items. We found MMN response enhancement for the inflected words towards the end of the recording session, whereas no response change was observed for the derived or novel complex forms. This enhancement indicates rapid build-up of a new memory trace for the combination of real morphemes, suggesting a capacity for online formation of whole-form lexicalized representations as one of the morphological mechanisms in the developing brain. Furthermore, this enhancement increased with age, suggesting the development of automatic morphological processing circuits in the age range of 3-4 years.

Highlights

- We studied the acquisition of morphologically complex words in passive listening
- 3-4-year-old children showed evidence of rapid learning of complex words
- The results demonstrate children's greater flexibility to rearrange lexical storage
- The effect was specific to inflected words and gradually increased with age

Graphical abstract



1 Introduction

Morphemes (such as stems and affixes) are the smallest linguistic items carrying their own meaning. In morphologically rich languages, such as Finnish, speech comprehension relies heavily on using morphological rules and on parsing of a morphologically complex word to its morpheme constituents, such as word stems (e.g., 'light'), as well as inflectional (e.g., plural '-s', lights) and derivational (e.g., '-ness', lightness) suffixes (Niemi et al., 1994). Thus, a complex word (such as 'light+s') has its inner combinatorial structure, and the meaning of the complex word might be computed by analyzing and integrating its morpheme constituents. Such morphological analysis seems to take place automatically even if one has not heard/seen the full complex word before (e.g., Leminen et al., 2016, 2010; McKinnon et al., 2003). Different neurocognitive models have been suggested to explain the details of cognitive mechanisms behind this analysis. For instance, some models propose that all morphologically complex words (i.e. derived and inflected) are processed through obligatory morphological decomposition into their constituent morphemes (e.g., Rastle and Davis, 2008), while others postulate at least partially distinct neural processing and representation for inflections and derivations (Bozic and Marslen-Wilson, 2010; Clahsen et al., 2003; Niemi et al., 1994); still others claim that all morphological effects arise from the correlation between form

and meaning (Gonnerman et al., 2007; Seidenberg and Gonnerman, 2000). There are also different accounts regarding the presence of a single or two routes of morphological processing, as well as the role of semantic information at the very early stages of processing (for a review on studies employing visually presented morphologically complex words, see Amenta and Crepaldi, 2012). Notably, the current knowledge on neural underpinnings of these cognitive processes is mainly based on reading experiments and on studies performed in adults or adolescents. Very little is known about the neural basis of morphological processing and learning in young children (before school age) when the language system is most amenable. Furthermore, there is particularly little evidence available in the auditory domain, which is the primary pathway of language acquisition in childhood. To fill these gaps, the present study aims to elucidate the neural mechanisms of processing and acquisition of different types of morphologically complex spoken words in young children.

1.1 Structure of neural lexicon in adults

Several neuroimaging studies in various languages suggest that, in adults, inflected and derived words might be processed and represented differently in the brain, at least to a degree (for a review, see Bozic and Marslen-Wilson, 2010; see also A Leminen et al., 2013a). More specifically, it has been suggested that due to their idiosyncratic nature, existing derived words (develop-ment, jump-er, dark-ness) are likely to be represented by a whole-form lexical memory trace, whereas morphemes of more transparent and predictable inflected words (book-s, walk-ed, bring-s) are more likely parsed on the fly to re-create their combined meaning by combining their constituents (e.g., Bozic & Marslen-Wilson, 2010; Carota, Bozic, & Marslen-Wilson, 2016; Clahsen, Sonnenstuhl, & Blevins, 2003; Leminen et al., 2011; Leminen, Leminen, Kujala, & Shtyrov, 2013). This parsing route appears a particularly efficient strategy in languages with a very rich inflectional system where whole-form storage of multiple inflections and declinations is not economical (Laine et al., 1994; Niemi et al., 1994). In line with this proposal, derivations, similar to monomorphemic words, seem to be processed in bilateral temporal brain areas, whereas inflections engage predominantly the left frontotemporal neural network linked to combinatorial syntactic processes in general (Bozic, Tyler, Ives, Randall, & Marslen-Wilson, 2010; Bozic & Marslen-Wilson, 2010). This

combinatorial activity has a processing cost (the cognitive load), manifest behaviorally in longer reaction times in lexical decision tasks (e.g., Bertram, Laine, & Karvinen, 1999; Lehtonen & Laine, 2003; Niemi et al., 1994) and longer fixations in reading (Hyönä et al., 1995) in comparison to otherwise matched monomorphemic words (see the model in Figure 1A).

On the other hand, some authors have suggested that derivation and inflection are not the most optimal morphological categories to dissociate between the use of parsing vs. storage route, but a better way to describe them could be the continuum between meaning-changing (e.g. change from verb to noun: sing-singer) and meaning-invariant morphology (Bertram, Schreuder, & Baayen, 2000). However, in many cases derivations and inflections can be contrasted even with this measure. It has also been suggested that all morphologically complex words trigger very automatic decompositional processing, even when the whole form of the word would be already stored in the neural lexicon (e.g., corner, apartment; Marslen-Wilson and Tyler, 2007; Rastle and Davis, 2008). This parsing route may be the only option if a pseudo morpheme is embedded in complex word (e.g. existing stem with novel suffix; Leminen et al., 2016). Importantly, unlike brain responses to monomorphemic items, neurocognitive activity reflecting inflectional decomposition do not vary with word frequency, which indicates that the vast majority of them were going through the parsing route with similar intensity (Vartiainen et al., 2009), whereas only exceptionally high frequency inflections may have the full-form representation (Soveri et al., 2007).

Language processing is a complex cognitive task with several subprocesses. Thus, one experimental strategy that enables focusing on the core properties of linguistic processing is to use passive listening paradigms, in which different cognitive strategies and the effect of modulated attentional load and working memory processes can be reduced (Shtyrov, 2010). Passive listening experiments have indeed been successful in contrasting lexical properties of language (for a review, see Pulvermüller & Shtyrov, 2006; Shtyrov & Pulvermüller, 2007). For example, existing (lexical) monomorphemic words show enhanced responses in comparison to non-existing (novel) monomorphemic words reflecting stronger automatically activated neural memory traces for familiar words (so-called lexical MMN; e.g., Bakker et al., 2013;

Garagnani et al., 2009). Following the same logic, the lexical MMN is larger to high frequency monomorphemic words than to existing low frequency words, suggesting that this ERP reflects the strength of connections in memory circuits stemming from the intensity of its use (Alexandrov, Boricheva, Pulvermüller, & Shtyrov, 2011; Shtyrov, Kimppa, Pulvermuller, & Kujala, 2011). Using the same procedure, responses to morphologically complex words have also been recorded in a few studies. They found that MMN responses for derived complex words were enhanced in comparison to inflected words (A Leminen et al., 2013b; Whiting et al., 2013) and responses for congruent (existing) derived words were larger than those for incongruent (but meaningful) derived words (Hanna and Pulvermuller, 2014). This pattern of responses is highly similar to the lexical MMN for monomorphemic words, and is thus hypothesized to reflect the strength of the existing neural memory trace for the whole form of the complex word. Equivalently, lexical MMN for compound words has been found to reflect the strength of the lexical representation for the stem combination (MacGregor and Shtyrov, 2013) and even particle verbs (Cappelle et al., 2010), reinforcing the notion of whole-form lexicalized (even supra-lexical) representations for this type of morphology. Lower response amplitudes for complex inflected forms, in turn, suggest the absence/weakness of a whole-form representation implying a step-wise parsing route for such items.

1.2 Structure of neural lexicon and its development in children

Children use inflectional rules already during their first years of life (Stolt et al., 2009; Toivainen, 1980), although they tend to over-extend regular inflections and incorrectly apply those to irregular words (e.g. '*goed') (Clahsen, Aveledo, & Roca, 2002). Sometimes suffixes can even help language comprehension. For instance, children can guess the word meaning based on a highly productive derivative suffix (Bertram, Laine, & Virkkala, 2000). However, children's explicit knowledge about morphological elements of complex words continues to develop during school years even after 8 years of school (Tyler and Nagy, 1989). It is, however, unclear whether it is due to the development of neurocognitive resources needed in morphological parsing during online comprehension, or to explicit cognitive skills in linguistic reasoning. Neuroimaging evidence has shown that fronto-temporal brain networks are maturing slowly (Gogtay et al., 2004). For instance, an fMRI study showed that while semantic and syntactic networks were distinct in the

adult brain, five-year-old children showed more similar activation patterns for both types of experimental manipulations (Wu et al., 2016). This indicates that while first signs of adult-like lexical-semantic processing develop already during the first 2 years of life (Stolt et al., 2009; Toivainen, 1980), combinatorial mechanisms needed in syntactic and morphological processes are dependent on neural resources that begin to be available slightly later (Friederici, 2005). These combinatorial skills modulate morphosyntactic processing in a continuous manner over the years of development (Clahsen et al., 2002; Friederici, 2005).

Only few studies have investigated differences in the processing of different types of complex words in children. Using morphological priming with both derived and inflected words, Rabin & Deacon (2008) found no differences in visual priming effects (response accuracy) when children in first and fifth grades were compared. In another study, 5- to 8-year-old children were asked to spell word endings (Deacon and Bryant, 2005). Spellings were more correct for inflected than derived words, and interestingly, again the effect was similar in both age groups. This suggests that children were more aware of inflectional rules than derivational rules, and this distinction remained similar during the development in these age groups. However, there are no studies on younger children (<5 years when the semantic and combinatorial systems begin to diverge). With most studies focused on reading, an acquired “add-on” for the language system, more evidence is required in the auditory modality, the “native” modality of language in which most of the acquisition takes place during the early childhood.

1.3 Memory trace formation and learning of word forms

Word learning in adults includes components some of which are hippocampus-dependent (e.g. so-called explicit encoding), whereas some rely on cortical mechanisms (Davis and Gaskell, 2009; Warren and Duff, 2014). Focused attention has also been found to be important in learning the contextual meaning of a word (see de Diego-Balaguer et al., 2016 for a proposed developmental link between attention and linguistic skills) and integrating it into a semantic network (for a review, see Smith et al., 2010), although the effect is modulated by individual differences, such as experience related to music expertise (Dittinger et al., 2017, 2016). Explicit encoding (with focused attention) tasks have been used to study learning of word forms with

or without meaning, the latter sometimes being called form-only words (for a recent fMRI study, see e.g., Takashima et al., 2017). In contrast, implicit learning of word forms may give important details on the core neural mechanisms behind initial stages of word learning. For example, Szmalec et al. (2012) found that implicit statistical learning of novel word forms through reading led to interference with existing phonological neighbor words in an auditory task, making the reaction times slower due to larger lexical competition. This suggests that implicitly acquired word forms (without learned meaning) are not independent of the neural lexicon, but instead interact with modality independent lexical processing. In a recent study, Sandoval et al. (2017) showed that implicit statistical learning paradigm can also be applied to acquisition of morphological rules of an unfamiliar language. To sum up these views, word learning is typically assessed via explicit learning, where attention is directed to the to-be-learned material. The learning process involves hippocampus-dependent distributed networks to store the meaning of a word as well as the word form, which gradually become consolidated in neocortical circuits. Implicit learning paradigms in which the new word forms are to be inferred from context rather than introduced via a direct instruction, are thought to induce a learning effect in cortical networks, independently of the hippocampus (Shtyrov et al., 2019).

The first study showing neurophysiological evidence of fast memory-trace buildup of monomorphemic words found that, only after 14 minutes of passive exposure, novel words had created their real-word-like memory-traces in perisylvian language cortices (Shtyrov, Nikulin, & Pulvermuller, 2010). After these initial findings, similar results have been found by several other studies using different languages, stimuli, and exposure sequences. These studies have shown that this rapid memory trace formation is specific to speech sounds (Shtyrov, 2011) and native phonology (Kimppa et al., 2015), is modulated by the previous experience in language acquisition (Kimppa et al., 2016), and is independent of locus of attention (Kimppa et al., 2015). The first and only study conducted in children (6- to 13-year-olds) showed that the response increase indicating memory trace build-up was evident much faster that previously shown in adults, already after 4 minutes of exposure (Partanen et al., 2017). Additionally, this study also found that, unlike in adults, the memory trace was strengthened even for phonologically non-native words and non-speech sounds. In

these cases, the response growth was bilateral indicating contribution of a wider neural network than the typical left-lateralized circuits in native language processing and acquisition. However, these previous studies used only monomorphemic words and not morphologically complex stimuli. A previous study investigating acquisition of new morphologically complex words in adults showed that new memory traces for novel combinations of two morphemes (novel suffix combined with an existing/non-existing stem) can be formed also during passive listening (Leminen et al, 2016). However, the developmental perspective of new morpheme acquisition remains unexplored.

1.4 The current study

Here, we aimed at elucidating neural underpinnings of morphological processing in young children at pre-reading stage, at the ages of 3 to 4 years. This age group was chosen because only few studies have approached this topic with pre-school-aged children during the most active stages of language development, and even fewer studies have addressed groups at pre-reading age. More specifically, we wanted to focus on the dynamics of memory trace formation and its development in this age range. Such young children are a challenging participant group for active tasks and, hence, potential unwanted variance can be minimized with a passive listening paradigm. We therefore employed the passive paradigm and stimuli previously successfully used with adult participants (Alina Leminen et al., 2013). The change in neural responses over the course of an 11-minute-long block was analysed in three experimental conditions including an existing derived word, an existing inflected word, and a novel complex word combining a novel stem with an existing suffix (see Methods section for more details). The chosen technique of passive listening paradigm with repeating stimuli is a particularly suitable and reliable method for revealing automatic activation of word-specific memory traces.

In line with previous studies using similar methodology, the enhanced responses would suggest reorganization of neural activity and thus formation of new memory traces (Kimppa et al., 2015, 2016; Partanen et al., 2017; Shtyrov, 2011; Shtyrov, Nikulin, & Pulvermuller, 2010). As the stimuli consist of morphologically complex words, the response strength in this study will reflect the memory trace of the

whole form, i.e., the stem and suffix combination. If the responses change during experiment differently to derived, inflected, and novel words, it would indicate that the original representations of these words differ, and thus, shape the ability to strengthen neural memory traces. Presumably the initial strength of the memory trace is weaker for the whole-form of the inflected word than that of derived complex word (based on previous findings with passive listening). According to this hypothesis, the inflected word is mainly processed via the parsing route. If repetitive exposure to existing morphemes in an inflectional combination increases the response amplitude, it would indicate that the neural link between these two morphemes has been created, connecting them into a whole-form representation with a unified memory trace. Further, it would indicate that the brain is capable of lexicalizing even familiar inflections if massively exposed to them, to facilitate their processing. The complex pseudo-word with pseudo stem and existing suffix will show whether similar whole-form acquisition is possible in parallel with the acquisition of the stem.

To track the developmental change during the 3rd and 4th years of life, the correlation with age and event-related potential amplitudes was calculated. It is unclear whether general statistical learning abilities improve, deteriorate, or remain stable during childhood (Arciuli, 2017). Studies contrasting morphologically complex words with somewhat older children (age range of 5 to 10 years), suggest no fundamental developmental change in the neural learning dynamics (Deacon and Bryant, 2005; Rabin and Deacon, 2008). However, as discussed above, in the present age group the neurolinguistics system is at its most plastic, undergoing rapid development. Therefore, we can hypothesize that if our results in 3-to-4-year-old children show age-related decrease in the ability to form memory traces, it will suggest that memory trace formation for morpheme combinations declines with overall decrease of brain plasticity in children. If we instead find response dynamics enhancement with age, it will suggest that the memory system supporting storage of morpheme combinations relies on more complex linguistic brain mechanisms that are still maturing in 3-to-4-year-old children (Skeide and Friederici, 2016).

2 Material and methods

2.1 Participants

16 young 3-to-4-year-old monolingual Finnish speaking children (mean age of 52.7±5.1 Months, range 45.2-59.7 Months, 14 boys[1]) participated in the study. None of the participants had any diagnosed neurological or developmental disorders, including language development disabilities, or hearing impairments. Two additional children were also recruited, but their data had to be rejected from the analyses due to massive movement artefacts and low data quality.

The experiment was conducted in accordance with the Declaration of Helsinki with the permission from the Ethical Board of Helsinki University Hospital (approval reference number: § 248/2012). Written informed consents were obtained from all adult participants and child participants' parents.

2.2 Experimental design and procedures

EEG recording was conducted using an active electrode system (Biosemi Active Two, Biosemi B.V., Netherlands) in an acoustically and electrically shielded chamber. The EEG was recorded with 66 channels (64 standard 10-20 system and two electrodes at mastoids), mounted in a cap. Participants chose a film which they watched without sound during the experiment. To make the recording session more comfortable for the children, the stimuli were presented through 2 loudspeakers (and not headphones), which were located on both sides of the display in approximately 45 degrees angle, at the distance of about 150 cm from the participants' head. The sound level at the head position was fixed to be comfortable (about 65 dB(A) SPL). Most of the children sat alone in a comfortable chair during the experiment (2 participants sat on the lap of their caretaker). The children's caretaker was present in the same chamber. All the participants were given a possibility to have small breaks between the experiment blocks (every 12 minutes) when needed and were served with refreshments.

The paradigm was a traditional oddball sequence (with a 1000 ms stimulus onset asynchrony (SOA)), including a frequently presented (79%) monomorphemic word and an occasionally occurring rare (21%)

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

complex form of the same word, which was created by adding a '-ja' suffix to the word stem. This suffix was chosen because, rather uniquely, in Finnish it represents the same surface form for an inflection (plural partitive) and derivation (profession, occupation) allowing for a strict matching of phonology and acoustics between different morphological conditions. Three different Finnish word stems were used in the current study; 'laula' (sing), 'laulu' (song), and 'raulu' (pseudo word). To control the acoustics of the word-final affix and avoid co-articulatory bias, stems and suffixes were obtained separately and cross-spliced together. The stems were used as such as the frequent ("standard") monomorphemic stimuli. The '-ja' suffix was taken from a separate word, in which the final phoneme was neither 'a' nor 'u', but 'i' ('tutki+ja'). To create the deviant stimuli, the same '-ja' suffix was cross-spliced to each stem with a natural 12 ms silent gap between the offset of stem and onset of a suffix. The stem length was 409 ms and, thus, a suffix onset was at 421 ms in all the conditions. The complex words constructed by combining stems with '-ja' suffix, resulted in three different morphological conditions; 'laulaja' ('singer', a real derived word), 'lauluja' ('songs', a real inflected word, the partitive plural form), and 'rauluja' (unfamiliar complex word, consisting of a pseudostem and a real suffix; see Figures 1A and 1B). The surface frequencies were 24.93 and 26.46 per million for derived and inflected words respectively (frequencies were obtained from the Finnish corpus composed by the Research Institute for the Languages of Finland, the Finnish IT Centre for Science and the Department of General Linguistics, University of Helsinki). However, surface frequencies are based on written language sources and more suitable for adult language processing measures, but most probably both stems and morphologically complex forms are familiar to all 3-to-4-year-old Finnish children. Due to carefully preserved phonotactics, the unfamiliar complex word sounds like a plural inflection to the native ear. Originally there were also a 'raulaja' condition (to act as a "derived" pseudo stem) in the paradigm (Leminen et al., 2013), but it was deemed necessary to leave it out from the current study to shorten the already one hour long recording session. The stimuli were uttered by a female native speaker of Finnish. The recordings were stored with a 44.1 kHz sampling frequency and 16-bit quantization. All stimulus items had matching fundamental frequency (F0) and duration. They were normalized to have the same peak sound energy (for more details, see Leminen et al., 2013). The stimuli were presented by NBS Presentation

software (Neurobehavioral Systems, Inc., USA). A pseudo-randomized stimulus sequence was used so that there were always at least two standard stimuli after any deviant. The stimuli were presented in 3 blocks (one condition per block), and the order of the blocks was counter-balanced across the participants using a Latin square design.

EEG data were recorded with a sampling rate of 512 Hz, signal bandwidth of DC-104 Hz, and a resolution of 31 nV. The PO1 electrode site was used as the reference electrode during the recording (CMS electrode of Biosemi's standard 64 channel layout). The EEG data were offline processed in BESA (Besa Research 6.1, Besa GmbH, Germany) and Matlab (R2016a, Mathworks Inc., USA). First, the eye movements and eye blinks were cleaned with automated PCA algorithm (Berg and Scherg, 1994) and the result was visually monitored. After interpolating bad channels, offline filtering (0.5-45 Hz, 48dB/oct), and epoching (from -100 ms to 1000 ms, based on word onsets), the single trial data were exported to Matlab (540 standards and 119 deviants per condition). Thereafter the data were re-referenced to the average of all channels, baseline corrected (with 100 ms pre-word baseline), and trials exceeding ±100 µV amplitude criteria were rejected. After rejection, 450/98 epochs (for standards and deviants, respectively; minimum of 308/65) were re-referenced to the average of mastoids and forwarded to analysis. These remaining trials were divided to two averages separately for each condition and stimulus type to first half and second half of the block, with equal number of trials (i.e. median split, see Figure 1C). Split half method was chosen as a compromise between signal to noise ratio of averages (with less epochs than usually acceptable in ERPs) and sensitivity to neural dynamics.

Figure 1 about here [width: 2 columns]

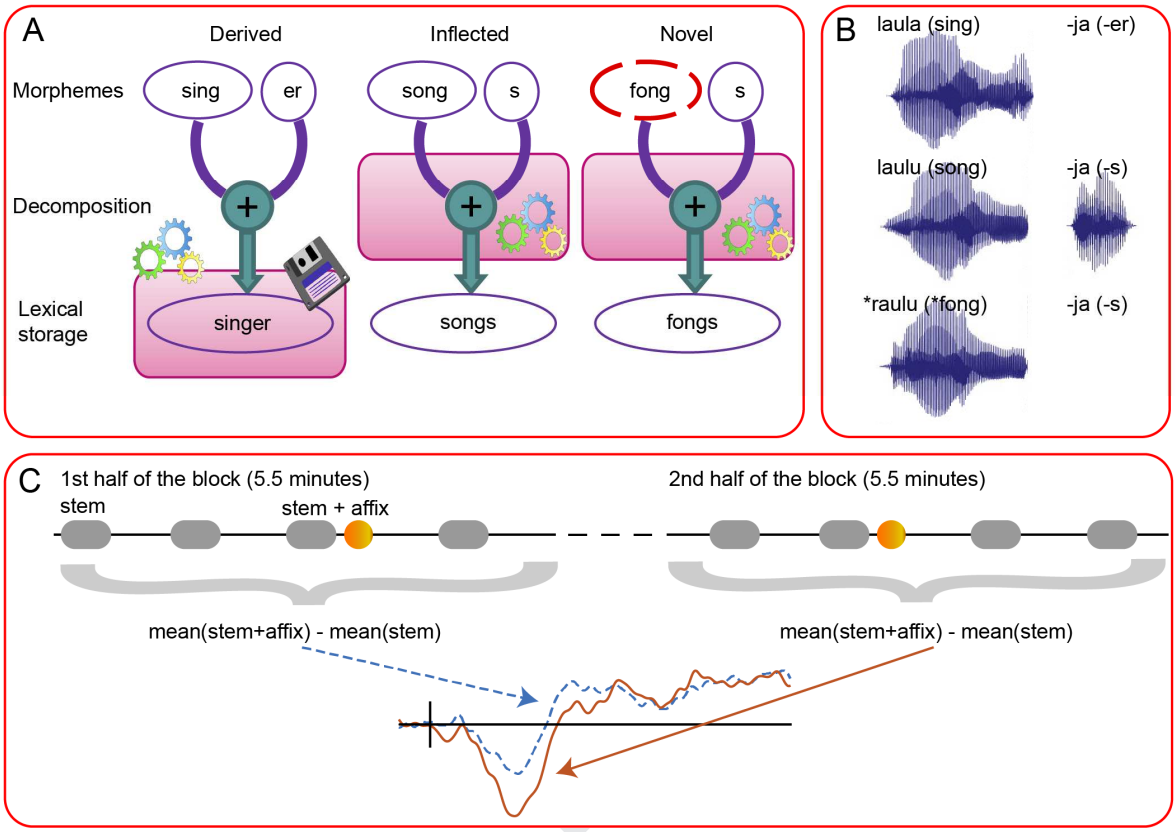


Figure 1. Details of the stimuli, paradigm, and the experimental design. A) Stimulus categories and the visualization of the storage vs. decomposition model of morphologically complex words. B) Stimulus waveforms. C) Visualization of the stimulus paradigm and how the response change during the experiment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

The areal means were used to improve the signal to noise ratio (which was lower than usual due to the overall lower quality of the child data and the smaller number of trials because of splitting into sub-averages to trace their dynamics during the exposure). These regions of interest (ROIs) were left (FC3, FC5, C3, and C5) and right (F4, F6, FC4, and FC6) fronto-temporal clusters in children (see Figure 2). ROIs were placed based on the topographic maps indicating activity maxima.

Statistical analyses were conducted for difference waveforms in IBM SPSS Statistics for Macintosh (version 23, IBM Corp., NY). The repeated measures ANOVA was calculated with within-subject factors of Condition (3 levels; Derived, Inflected, and Novel complex word), Exposure (2 levels; Initial and Final), and Laterality (two levels; Left and Right ROI). Mauchly's Test for Sphericity did not show any violations of sphericity assumptions. Effect sizes for statistical comparisons are reported as the means of partial eta-squared (η_P^2). Significant effects were followed with Bonferroni corrected simple pair-wise t-tests. The alpha level of 0.05 was used in all the statistical tests and accurate p values are reported.

To test the developmental aspect of changes in the responses, an additional repeated measures ANOVA was calculated by adding a continuous covariate of age in months. Significant effects were followed with condition-specific correlation analyses (two-tailed Pearson's correlation).

3 Results

In the time window of 120-160 ms after the suffix onset, repeated measures ANOVA showed a significant interaction of Condition × Exposure for the MMR responses ($F(2,30) = 5.30$, $p = .011$, $\eta_P^2 = 0.261$). Post-hoc analyses (tests of simple effects) showed that the response enhancement during the experiment was significant only in the Inflected condition (from 3.9±1.1 μV to 6.8±1.0 μV, p=.013). Furthermore, Inflected and Novel conditions differed from each other only in the second half of the experiment (p=.020), showing larger amplitudes for the Inflected condition than for the Novel condition (6.8±1.0 and 4.2±1.1 μV respectively) whereas other simple contrasts between the conditions were insignificant (see Figure 2). Note

that MMN responses were positive in polarity, which is typical with for young children (Kujala and Leminen, 2017).

Figure 2 about here [width: 2 columns]

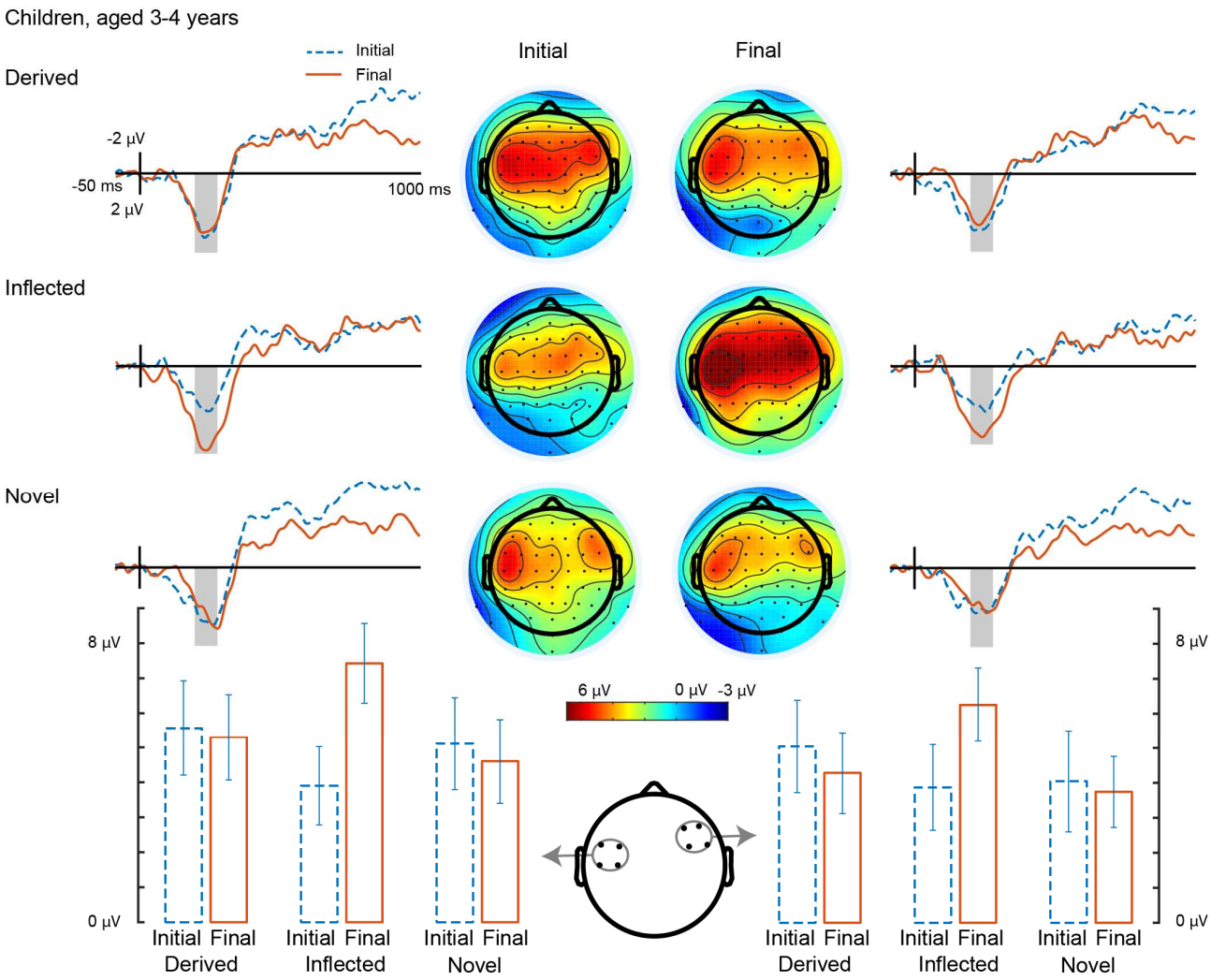


Figure 2. Scalp maps and difference wave ERPs (response for deviants minus response for standards). ERPs and scalp maps are shown separately for the first half (Initial) and the second half (Final) of the exposure. Bar diagrams show mean amplitudes (and their standard errors) of regions of interest (shown in a ROI scalp) within the time window of interest (shown as grey box on ERPs). Blue dashed line: Initial. Red solid line: Final.

When Age was added to the model as a covariate, the results showed significant interaction of Condition × Exposure × Age (F(2,28) = 4.20, p = .025, η_P^2 = 0.231). The post-hoc correlation tests showed that the Exposure-related change in the response amplitude was linearly increasing with the age in Inflected condition (r = 0.49, p = .055) whereas in the other two conditions the relationship was less clear (Derived: r = -2.2, p = .417; Novel: r = -0.14, p = .614; see Figure 3).

Figure 3 about here [width: 2 columns]

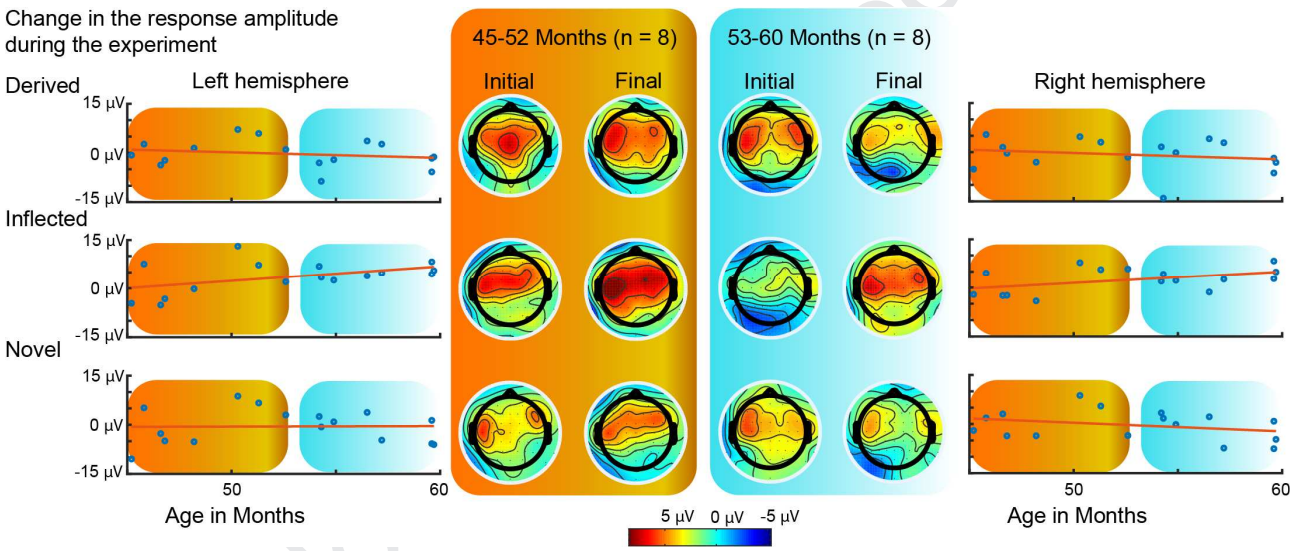


Figure 3. The effect of age on ERP dynamics. Scalp maps separately for younger and older children along with the ERP change during the experiment as a function of age. The zero line represents the case with no change during the experiment, while positive values represent response enhancement. Red line is a linear fit for all the data.

4 Discussion

In the current study, we aimed at elucidating the neural mechanisms involved in the early, most automatic stages of online processing and acquisition of morphologically complex words in young children. Furthermore, we investigated whether development during the age range of 3-4 years affects these

abilities. Our participants passively listened to derived, inflected, and novel complex words, which allowed tracking the different aspects of linguistic representations in the neural lexicon, and their dynamics during the passive stimulus exposure. Our results showed differential response dynamics depending on the experimental conditions and on the age of the children.

4.1 Derivation vs. Inflection in children

Typically developing native Finnish-speaking children are known to use inflections before they reach the age of 2 years (Stolt et al., 2009; Toivainen, 1980). There is also some evidence of distinct developmental trajectories for processing of inflected and derived complex words in English, as 5- and 8-year-old children showed an awareness of inflectional mechanisms in spelling, but not of derivations (Deacon and Bryant, 2005). Similarly, German-speaking children showed an adult-like behavioral cross-modal morphological priming effect for irregular inflections, evident in 10-year-olds, but still missing in 8-year-olds (Clahsen & Fleischhauer, 2013). In that study, regular inflections were similarly primed in all age groups. These findings were interpreted such that neural mechanisms for combinatorial inflections are developing earlier in life, while irregular inflections may be at least initially stored as full-forms in the neural lexicon and their parallel parsing route develops later. However, while the relationship between derivations vs. inflections and regular vs. irregular inflections in some languages is not straightforward, similar distinctions have been found in both contrasts.

Our results in 3-to-4-year-old children clearly show distinct processing of derived and inflected complex words. The response for the derived word did not change during the course of the experiment. This suggests that the neural representation of the derived word does not change due to passive exposure. The effect is similar that has been found earlier in adults with existing monomorphemic words (e.g., Shtyrov, Nikulin, & Pulvermuller, 2010) and indicates that the word most probably already has an existing memory trace for the whole form. However, the response for the inflected word condition was enhanced during the experiment. It suggests an enhancement of the neural memory trace for this type of complex word, similarly to what has been found for novel monomorphemic words in adults (Shtyrov, 2011) and in older

children (Partanen et al., 2017). The effect can be explained if we assume that children initially had lacking (or weaker) whole-form representation for the plural inflected form of the word, with its processing chiefly relying on decomposition, in line with the main findings for regular inflection processing. The magnitude of the lexical MMN response for monomorphemic words, occurring about 120-200 ms after the recognition point, has been shown to reflect lexicality and lexical frequency, so that existing high frequency words show larger amplitudes than low frequency words, and existing words show larger amplitudes than pseudowords (Bakker et al., 2013; Garagnani et al., 2009; Shtyrov et al., 2011). One could thus also hypothesize that repeating the same auditorily presented complex word for about 100 times during the experiment artificially increases word's surface frequency and leads to the build-up of a new or enhanced whole-form representation by linking two existing morphemes into a single memory circuit. Importantly, in the current study this effect was prominent only for the inflectional condition, which suggests that in the derived condition the existing memory trace was most likely already saturated and any further development of the response to it suppressed. Similar findings have been found in adults, for which processing of newly (explicitly) learned high frequency inflectional affixes showed less activation in brain structures underlying decomposition, in comparison to low frequency affixes or applying newly learned affixes into new stems (Nevat et al., 2017).

4.2 Development of language acquisition skills

We found that the ERP response enhancement for inflectional word ending increased from 3 to 4-year-olds. This could indicate that the maturation of neural networks involved in this response enhancement is in active phase during this age range[2]. It has been hypothesized that while the bottom-up language processing skills develop rapidly during the first 3 years of life, the neural capacity for top-down processing, needed for processing of syntactical hierarchies, develops later (Skeide and Friederici, 2016). It is possible that partly the same networks are also involved in morphological processes. Despite the fact that large scale linguistic networks are somewhat differently organized in 5-year-olds compared to adults, the resting state

[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.

connectivity between temporal and frontal areas in the left hemisphere correlate with skills to comprehend complex sentences (Xiao et al., 2016). The same inferior frontal gyrus area has also been shown to be specifically activated during an auditory morphological awareness task in 7-13-year-old children (Arredondo et al., 2015).

Furthermore, functional connectivity between the left posterior superior temporal gyrus (pSTG) and the left inferior frontal cortex (IFC) has been found already in 3- and 6-year-olds for syntactic processing (Vissiennon et al., 2017). Interestingly, however, these age groups were different: 3-year-olds had stronger functional connectivity with Brodmann area (BA) 45 whereas 6-year-olds had a stronger functional connectivity with BA 44. Authors linked this group difference to maturation of ventral and dorsal pathways. The ventral pathway linking pSTG to BA 45 is present already at birth while the dorsal pathway (also called the arcuate fasciculus, AF) linking pSTG to BA 44 matures later during childhood (Brauer et al., 2013, 2011). Especially the AF has been shown to be crucial for syntactic processing (Wilson et al., 2011). Moreover, the dynamic changes during the repetition of syntactic structures have been found in these same cortical areas. More specifically, the repetition of novel syntactic structures led to activation increase at both ends of the dorsal pathway, namely in posterior temporal and inferior frontal cortices while the repetition of initially known syntactic structures led to repetition suppression in the same cortical areas (Weber et al., 2016). However, it is debatable whether the same neural mechanisms are involved in the combinatorial processing of single-word-level morphology and multiple-word-level syntax (Marantz, 2013). One could still speculate whether memory traces for morpheme combinations are also partly dependent on the maturation of the dorsal pathway.

The findings of the current study suggest that young children have the ability to store new memory traces for streams of existing morphemes in passive listening. This is in line with a recent study on monomorphemic novel words with native and non-native phonology (Partanen et al., 2017). In that study, in contrast to previous findings in adults, Danish children showed response enhancement even when non-native phonology or non-speech sounds were used. Overall, these two studies demonstrate the increased

versatile flexibility of children's brain to form neural memory traces in passive listening for different types of auditory input, including both monomorphemic and bimorphemic words.

4.3 Morphological processing of non-words

In the current study, the third experimental condition included a novel complex word made of a pseudo word stem and an existing suffix (acoustically/phonologically identical suffix to that used in the other two conditions). Contrary to our expectations, the results did not show response enhancement during the exposure to this stimulus. This does not follow the findings with monomorphemic words in adults (Kimppa, Kujala, Leminen, Vainio, & Shtyrov, 2015; Kimppa, Kujala, & Shtyrov, 2016; Partanen et al., 2017; Shtyrov, 2011; Shtyrov, Nikulin, & Pulvermuller, 2010). The discrepancy between the previous and current findings might result from differences in morphological structure of the stimulus words. It has been found that morphologically complex words that contain either a real stem with pseudo-suffix or a pseudo stem with a real suffix, are more difficult to reject in lexical decision task than pseudowords without embedded real morphemes (Caramazza et al., 1988; see also Post et al., 2008). This indicates that the parsing route is at least partly activated even if one of the morphemes is non-existing. The ignited decomposition might indeed be a potential explanation, why in the current study pseudo words were not processed and lexicalized like monomorphemic words. On the other hand, and critically, they were neither lexicalized as a pair of existing morphemes. So, for existing inflections, it might be easier to boot-strap the two existing representations into a single one within the short exposure time employed here. For the pseudo stem + real affix combination this process may be more difficult, as the process requires both the construction of a new trace for the stem and its linkage with the affix, for which 11 minutes may be too short as a learning period. The order of pseudo and real morphemes may play a critical role especially in the auditory domain, i.e. the first morpheme (the pseudo stem in the current study) modulates the way how forthcoming morphemes are processed (see also Leinonen et al., 2009).

5 Conclusions

We examined the online neural processing and acquisition of combinations of morphemes in young children. Neural responses showed bilateral increase for the inflected complex words towards the end of the experiment. This enhancement increased with age, indicating development of automatic morphological processing circuits in age range of 3 to 4 years. No response change was observed for the derived words. Hence, it is possible that young children have an automatic ability to quickly and flexibly form memory traces for the combination of existing morphemes even without focusing their attention on the stimuli.

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Figure colors: for online only.

Figure legends

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.

Figure 2. Scalp maps and difference wave ERPs (response for deviants minus response for standards). ERPs and scalp maps are shown separately for the first half (Initial) and the second half (Final) of the exposure. Bar diagrams show mean amplitudes (and their standard errors) of regions of interest (shown in a ROI scalp) within the time window of interest (shown as grey box on ERPs). Blue dashed line: Initial. Red solid line: Final.

Figure 3. The effect of age in ERP dynamics. Scalp maps separately for younger and older children along with the ERP change during the experiment as function of age. The zero line represents the case with no change during the experiment, while positive values represent response enhancement. Red line is a linear fit for all the data.