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Research paper

Neural mechanisms underlying word- and phrase-level morphological parsing

Alina Leminen [a, b, *], Sini Jakonen [b], Miika Leminen [a, b], Jyrki P. Mäkelä [c], Minna Lehtonen [b, d]

[a] Center of Functionally Integrative Neuroscience, Department of Clinical Medicine, Aarhus University, 8000, Aarhus, Denmark
[b] Cognitive Brain Research Unit, Cognitive Science, Institute of Behavioural Sciences, University of Helsinki, 00014, Helsinki, Finland
[c] BioMag Laboratory, HUSLAB, Hospital District of Helsinki and Uusimaa, 00029, Helsinki, Finland
[d] Department of Psychology, Abo Akademi University, 20500, Turku, Finland

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ABSTRACT

How is morphological and morphosyntactic information processed during sentence reading? Are the neural mechanisms underlying word- and phrase-level combinatorial processing overlapping or distinct? Here, electroencephalography (EEG) and magnetoencephalography (MEG) responses were recorded simultaneously during silent reading of Finnish sentences. The experimental conditions included 1) well-formed grammatical sentences (correct condition), 2) sentences containing morphosyntactic violations (adjective–noun number agreement violations), 3) morphological violations (incorrect stem allomorph and inflectional suffix combination), and 4) combined violations, containing both morphosyntactic and morphological violations. Signal space and source modeling results showed that morphosyntactic violations elicited a left anterior negativity effect, generated particularly in the left inferior frontal area. Morphological violations elicited a widespread negativity, resembling the N400. The neural sources of this negativity were localized most prominently to the right temporal cortical networks. Furthermore, all violations elicited P600 effects with similar widespread bilateral fronto-temporal neural generators that did not differ between morphosyntactic and morphological conditions. Our findings suggest at least partially distinct subnetworks in the fronto-temporal cortices for morphological and morphosyntactic parsing during the earlier stages of processes (~400 ms post stimulus onset) and shared neural generators for the later processing stages.

1. Introduction

Comprehension of a sentence requires understanding individual words, as well as accessing information encoded in the relations between words (i.e. syntactic structure). Sentences can be broken down into words and even further meaningful units, i.e. morphemes within words. Morphemes constitute a building block of natural languages by enabling production of complex words, such as regular plural nouns (boy + s) or verbs in past perfect simple form (walk + ed). However, languages differ in regard to the role that inflectional affixes versus word order play in assigning syntactic structure to sentences.

* Corresponding author. Center of Functionally Integrative Neuroscience/MINDLab, Department of Clinical Medicine, Aarhus University, 8000 Aarhus C, Denmark.
E-mail address: alina.leminen@cfin.au.dk (A. Leminen).

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The present study uses Finnish as its target language. Finnish is a Finno-Ugric agglutinative language with a complex inflectional system, where most grammatical relations are realized at morpheme level. This is reflected in the number of inflectional suffixes that are actively used; in Finnish, nouns can take up to 15 different inflectional cases. Finnish is also a language susceptible to morphophonological changes, such as consonant gradation,[1] and thus correct inflection of words often involves attaching an inflectional suffix to a correct stem allomorph (e.g., *lau**t**a* 'a board', *lau**t**a* + *an* 'to a board', *lau**d**a* + *lla* 'on a board'). Each noun can have up to 140 possible inflectional forms (clitics excluded), making Finnish a particularly interesting language to investigate complex combinatorial processing. At the phrasal level, adjacent elements must follow the same inflectional form. For instance, not only subject and verb must agree e.g. in number, but also a preceding adjective must agree with the noun in both number and case (e.g., Surffaaja osti $uuden_{GEN.SG}$ $laudan_{GEN.SG}$ lomamatkaa varten. '*The surfer bought a new board for a vacation trip*'). To sum up, reaching the final inflectional form in Finnish sentences, as in many other languages, requires integrating morphological and morphosyntactic information.

Morphosyntactic agreement has been defined as the covariation of inflectional morphology between related words (Molinaro, Carreiras, & Dunabeitia, 2012). Thus, it operates at the phrasal level, while morphological processing takes place at the word level, between morpheme boundaries. Processing of complex syntactic structures and regular inflectional structures typically activates left-fronto-temporal cortical networks (Bozic & Marslen-Wilson, 2010; Marslen-Wilson & Tyler, 2007). Parsing of inflected words is often assumed to involve both morphological parsing, which decomposes complex forms into stems and affixes,[2] and grammatical processing elicited by the grammatical functions of inflectional affixes.[3] Hence, an interesting question arises – are there spatiotemporal differences in brain activation between morphosyntactic and morphological parsing? Despite abundant research on the neural correlates of morphological and morphosyntactic processing, the exact relationship between the two – the time-course of phrase and word level processes and their possible interactions – have not yet been thoroughly investigated. Therefore, we asked here if the neural mechanisms of parsing sequences of morphemes (i.e. word-level agreement) are similar to those of parsing words connected in sequences and what the mechanisms behind these processes are.

Phrase and sentence level parsing have been extensively investigated using event-related potentials (ERP) and their magnetic counterparts (event-related fields, ERF), as ERP/ERFs allow parsing processes to be tracked with a time-scale of milliseconds. Studies of phrase- and sentence-level processing have, in many cases, reported the N400 component, the left anterior negativity (LAN), and the P600 (for a review, see e.g., Friederici & Wartenburger, 2010; Friederici & Weissenborn, 2007). The N400 has been typically observed during various lexical-semantic violations (for a review, see e.g., Federmeier, Segal, Lombrozo, & Kutas, 2000; Kutas & Federmeier, 2011) and its neural sources have been localized to the left and right superior temporal cortices (Helenius et al., 2002; Uusvuori, Parviainen, Inkinen, & Salmelin, 2008; Vartiainen, Parviainen, & Salmelin, 2009), the middle and anterior temporal areas, the inferior frontal areas (Halgren et al., 2002), and posterior frontal regions (Kielar, Panamsky, Links, & Meltzer, 2014). The N400 presumably reflects lexical or semantic processes such as lexical access, initial access to long-term semantic memory, a dynamic process of meaning construction (Kutas & Federmeier, 2000, 2011; Lau, Almeida, Hines, & Poeppel, 2009; Lau, Phillips, & Poeppel, 2008), as well as semantic integration or unification (Hagoort, Baggio, & Willems, 2009). Phrase-level morphosyntactic violations have typically elicited the left anterior negativity (LAN) (Friederici, 2002; Friederici & Kotz, 2003; Friederici & Weissenborn, 2007; Rossi, Gugler, Hahne, & Friederici, 2005) and P600 effects (Friederici & Wartenburger, 2010; Friederici & Weissenborn, 2007), although P600 effects have also been observed in semantic (Kuperberg, 2007) and morphological (derivational, i.e. word formation) processes (Leinonen, Brattico, Järvenpää, & Krause, 2008). The P600 has been proposed to reflect repair, reanalysis, or continued combinatorial processes of complex or violated linguistic stimuli (Friederici & Weissenborn, 2007; Kuperberg, 2007), where lexical-semantic and syntactic information is assumed to interact (Friederici & Weissenborn, 2007). With MEG, the sources of LAN have been localized to the left superior temporal cortex (Leminen et al., 2011; Service, Helenius, Maury, & Salmelin, 2007). The sources of the P600 have been localized to bilateral posterior superior temporal cortices (Grodzinsky & Friederici, 2006; Service et al., 2007) and to bilateral frontal, posterior temporal, and parietal regions (Kielar et al., 2014). With particular importance to our study, agreement violations (e.g., *The old waiter *serve with inattentive expression/The old waiter serves with inattentive expression*) have frequently elicited the LAN effect (typically together with the P600) (Angrilli et al., 2002; Molinaro, Barber, & Carreiras, 2011; Palolahti, Leino, Jokela, Kopra, & Paavilainen, 2005; Roehm, Bornkessel, Haider, & Schlesewsky, 2005). For instance, number agreement in case inflection (Leinonen et al., 2008), person and number agreement violations (Linares, Rodriguez-Fornells, & Clahsen, 2006), and clause-level past tense violations (*Yesterday I *frown*) (Newman, Ullman, Pancheva, Waligura, & Neville, 2007) have all yielded anterior negativities. The LAN in agreement violations has been suggested to reflect a violation of expectancy (elicited by e.g., a subject noun phrase) for the target functional morphology (e.g., the following verb) (Molinaro et al., 2011). If the inflectional morphology of the target constituent does not match with the value expressed in the trigger constituent, then a LAN is observed (Molinaro et al., 2011; see

[1] Consonant gradation is a type of consonant mutation, in which consonants alternate between various "grades", for example the word kukka 'flower' undergoes consonant gradation, when inflected to genitive case: kukka > kuka + n.

[2] Our basic assumption here was that most Finnish inflected words are decomposed into stem and suffix during recognition. This assumption is based on extensive research on recognition of recognition of Finnish inflected words (see, e.g., Lehtonen & Laine, 2003; Niemi et al., 1994; Soveri, Lehtonen, & Laine, 2007).

[3] Note that there are also accounts which do not assume that inflected words are processed via decomposition into morphological constituents (see, e.g., Baayen, Milin, Durdevic, Hendrix, & Marelli, 2011; Gonnerman, Seidenberg, & Andersen, 2007).