

# Neurocognitive processing of inflected and derived words

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## Abstract

The representation of morphologically complex words in the mental lexicon and their neurocognitive processing has been a vigorously debated topic in psycholinguistics and the cognitive neuroscience of language. This thesis investigates the effect of stimulus modality on morphological processing, the spatiotemporal dynamics of the neural processing of inflected (e.g., ‘work+ed’) and derived (e.g., ‘work+er’) words and their interaction, using the Finnish language.

Overall, the results suggest that the constituent morphemes of isolated written and spoken inflected words are accessed separately, whereas spoken derived words activate both their full form and the constituent morphemes. The processing of both spoken and written inflected words elicited larger N400 responses than monomorphemic words (Study I), whereas the responses to spoken derived words did not differ from those to monomorphemic words (Study IV). Spoken inflected words elicited a larger left-lateralized negativity and greater source strengths in the left temporal cortices than derived words (Study IV). Thus, the results suggest different cortical processing for derived and inflected words. Moreover, the neural mechanisms underlying inflection and derivation seem to be not only different, but also independent—as indexed by the linear summation of the responses to derived and inflected stimuli in a combined (derivation+inflection) condition (Study III). Furthermore, the processing of meaningless, spoken derived pseudowords was more difficult than for existing derived words, indexed by a larger N400-type effect for the pseudowords. However, no differences were observed between meaningful derived pseudowords and existing derived words (Study II). The results of Study II suggest that semantic compatibility between morphemes seems to have a crucial role in a successful morphological analysis.

As a methodological note, time-locking the auditory event-related potentials/fields (ERP/ERF) to the suffix onset revealed the processes related to morphological analysis more precisely (Studies II and IV), which also enables comparison of the neural processes in different modalities (Study I).

## Tiivistelmä

Morfologisesti kompleksisten sanojen neurokognitiivinen käsittely sekä niiden edustus mentaalisisä leksikossa on ollut vilkkaan keskustelun aiheena jo pitkään psykolingvistiikassa. Tässä väitöskirjassa tarkasteltiin taivutettujen (esimerkiksi 'työ + tä') ja johdettujen (esimerkiksi 'työ + tön') sanojen hermostollista käsittelyä, niiden välistä vuorovaikutusta sekä aistipiirin vaikutusta morfologiseen prosessointiin.

Tutkimuksessa selvisi, että sekä visuaalisten että auditiivisten taivutettujen sanojen käsittelyn aikana sanan morfeemit ('työ'+ 'tä') käsitellään erikseen, kun taas auditiivisten johdosten prosessointi aktivoi sekä koko sanan edustuman ('työtön') että yksittäiset morfeemit ('työ'+ 'tön'). Sekä visuaalisten että auditiivisten taivutettujen sanojen käsittely aktivoi suuremman N400-jännitevasteen verrattuna yksimorfeemisiin sanoihin (Osatyö I), kun taas johdosten käsittely ei eronnut yksimorfeemisten sanojen käsittelystä (Osatyö IV). Auditiiviset taivutetut sanat aktivoivat voimakkaammin otsalohkon vasemman aivopuoliskon jännitevasteen sekä vasemman ohimolohkon hermostollisia lähteitä verrattuna johdoksiin (Osatyö IV). Tulosten mukaan taivutuksen ja johtamisen hermostolliset taustamekanismit ovat toisistaan erillisiä ja lisäksi myös toisistaan riippumattomia (Osatyöt III ja IV). Jälkimmäistä havaintoa tuki tulos, jonka mukaan jännitevasteet summautuivat lineaarisesti yhdistelmätilanteessa, jossa esiintyi sekä johtaminen että taivutus (Osatyö III). Lisäksi morfologisesti virheellisten johdettujen epäsanon käsittely oli vaikeampaa verrattuna oikeisiin johdoksiin, aiheuttaen suuremman N400-vasteen epäsanonille. Morfologisesti oikein johdettujen epäsanon synnyttämät jännitevasteet eivät puolestaan eronneet käytössä olevien johdosten synnyttämistä vasteista (Osatyö II). Tulosten mukaan johdoksissa sanan merkityksellä on ratkaiseva rooli morfologisessa prosessoinnissa. Väitöskirjan menetelmällinen kehitystyö osoittaa, että suffiksilukitut jännitevasteet ovat hyödyllinen keino erotella morfologiseen käsittelyyn liittyviä prosesseja (Osatyöt II ja IV) mahdollistaen myös hermostollisten mekanismien vertailun aistipiirien välillä (Osatyö I).

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## List of original publications

This thesis is based on the following original articles, which are referred to by their Roman numerals in the text:

**Study I:** Leinonen, A., Grönholm, P., Järvenpää, M., Söderholm, C., Laine, M., & Krause, C.M. (2009). Neurocognitive processing of auditorily and visually presented inflected words and pseudowords: Evidence from a morphologically rich language. *Brain Research*, 1275, 54–66.

**Study II:** Leminen, A., Leminen, M., & Krause, C.M. (2010). Time course of the neural processing of spoken derived words: An event-related potential study. *NeuroReport*, 21, 948–952.

**Study III:** Leinonen, A., Brattico, P., Järvenpää, M., & Krause, C.M. (2008). Event-related potential (ERP) responses to violations of inflectional and derivational rules of Finnish. *Brain Research*, 1218, 181–193.

**Study IV:** Leminen, A., Leminen, M., Lehtonen, M., Nevalainen, P., Ylinen, S., Kimppa, L., Sannemann, C., Mäkelä, J., & Kujala, T. (2011). Spatiotemporal dynamics of the processing of spoken inflected and derived words: A combined EEG and MEG study. *Frontiers in Human Neuroscience*, 5, 1-14.

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## Abbreviations

Ag/AgCl	silver/silver chloride
ANOVA	analysis of variance
CUP	complex uniqueness point
DP	deviation point
ECD	equivalent current dipole
EEG	electroencephalography
EOG	electro-oculogram
ERP	event-related potentials
ERF	event-related fields
fMRI	functional magnetic resonance imaging
ISI	inter-stimulus interval
ITI	inter-trial interval
LIFG	left inferior frontal gyrus
LSD	least significant difference
MCE	minimum current estimate
MEG	magnetoencephalography
PCA	principal component analysis
PET	positron emission tomography
RT	reaction time
SOA	stimulus onset asynchrony
SQUID	superconducting quantum interference device
TMS	transcranial magnetic stimulation
UP	uniqueness point

# 1 Introduction

In most languages, sentences can be broken down into words, which themselves can be further broken down into units that contain meaning of their own, i.e., morphemes. These smallest units of meaning can stand alone as an independent word (free morphemes such as *'joy'*), or must be attached to a stem (bound morphemes such as *'ful'*). Bound morphemes either attach to a stem to form a new lexeme (e.g., *'joy'+ 'ful'* = *'joyful'*), which is called derivation, or they attach to a stem to convey grammatical information (e.g., *'joy'+ 's'* = *'joys'*), a phenomenon called inflection. Inflectional affixes typically have a syntactic function, whereas the function of derivation is to form new words, or lexemes (Anderson, 1992; Haspelmath, 2002; Scalise, 1988; Spencer, 2000; Stump, 1998). Derivational affixes may change the syntactic category of their root (e.g., *'happy'* (adjective) → *'happiness'* (noun)), while inflectional affixes do not (*'boy'* (noun) → *'boys'* (noun)). Inflectional affixes are also usually more productive than derivational affixes, as the latter have more selectional restrictions (i.e., cannot be attached to every stem) and they tend to be semantically more transparent than derivations (Scalise, 1988; Stump, 1998). Nevertheless, these criteria may not be sufficient for a firm distinction between derivation and inflection (for a review, see e.g., (Stump, 1998). Furthermore, it has been argued that instead of being categorically represented and processed differently due to their different function in the language, the inflectional-derivational distinction can be accounted for by other properties of the complex words such as regularity, transparency, and productivity (McQueen & Cutler, 1998). However, aphasic patient data has shown that derivations and inflections involve at least some distinct mechanisms other than graded differences in such properties (Allen & Badecker, 2000; Badecker & Caramazza, 1989; Niemi et al., 1994). The relationship between inflection and derivation and, particularly, their underlying neural mechanisms, has remained unclear.

In some languages, grammar relies on strict word order in sentences, whereas in agglutinative languages such as Finnish most grammatical relations are realized morphologically. For instance, Finnish nouns have approximately 140 paradigmatic forms, while verbs can have approximately 260 paradigmatic forms (clitics excluded) (Hakulinen, 2004). The use of such extensive affixation would require an enormous

memory capacity if all the different forms were stored in their full form. The use of combinatorial computation instead of explicit storage and retrieval might thus be a more plausible alternative in morphologically rich languages (Hankamer, 1989; Sandra, 1994).

The present thesis addressed the question of the neurocognitive mechanisms that activate when native speakers of Finnish process derived and inflected words when they either read or listen to them and when they are presented either in isolation or in sentence contexts. In Studies I-IV, both behavioral and electrophysiological responses were measured simultaneously. Behavioral research, most often using lexical decision and priming tasks, has laid the foundation of for the current understanding of the processing of morphologically complex words. However, lexical decision, among other behavioral responses, is a measurement at the final stage of processing and may be sensitive to lexical and post-lexical processing as well as planning of the response (Balota & Chumbley, 1984; Fiorentino, 2006). Thus, it is difficult to know exactly what stages of processing the possible reaction time differences reflect. Neuroimaging methods such as electroencephalography (EEG) and magnetoencephalography (MEG), with millisecond-level resolution, provide a temporally finer-grained functional analysis of cognitive processes than that available from behavioral measures alone (Ford et al., 1980).

This thesis reviews first the most relevant psycholinguistic and electrophysiological studies of morphological processing (Chapter 2). The literature review is followed by presenting the particular aims of this thesis (Chapter 3), description of the research methods (Chapter 4) and the obtained results (Chapter 5). The results are followed by a general discussion and conclusions in Chapters 6 and 7.

## 2 Background

### 2.1 Theoretical accounts of morphological processing

Psycholinguistic research on morphological processing focuses on the representation and processing of morphologically complex words in the mental lexicon. Scientific discussion of morphological processing is mostly concentrated on where morphemic units can be represented within the architecture of the language system (Giraudo & Voga-Redlinger, 2007). Particularly, the question of whether complex words (e.g., ‘darkness’) are decomposed into their stems (‘dark’) and affixes (‘-ness’) or not during their recognition has attracted great interest among psycholinguists. Vigorous research on this topic has led to formulation of several models of morphological processing. Below, the models that are most influential and/or relevant to the present thesis will be briefly reviewed. Table 1 summarizes their key assumptions.

The *full-listing model* (Butterworth, 1983) suggests that all complex words, irrespective of their morphological structure, are accessed and processed in their full form (e.g., ‘joyness’ or ‘joys’) during recognition, and thus, individual morphemes do not play a role in how such words are stored or accessed. On the other hand, the *full-decomposition model* (Taft, 1979; Taft & Forster, 1975) suggests that during complex word recognition, affix-like units are first stripped prelexically from their stems (e.g., ‘unlock’ is accessed as ‘un’+‘lock’). Following affix stripping, the lexical representation of the stem (‘lock’) is searched for. If the stem is successfully accessed, the full-form is retrieved from the so-called master file, in which words with the same stem are clustered together. In more recent developments of this model, the notion of obligatory decomposition has been retained, but there are morpheme-based representations both at the form level and at the lemma level, i.e., abstract level of representation, which mediates between the form and the semantic-syntactic level (Taft, 2004; Taft & Nguyen-Hoan, 2010). In a similar manner, recent models based on masked priming results suggest at least two stages of morphological processing: a very early level of morpho-orthographic decomposition and a subsequent level of morpho-semantic analysis (Meunier & Longtin, 2007; Rastle & Davis, 2008).

The dual route or *hybrid* models assume that during the processing of morphologically complex words, both decompositional and full-form processing can take place. For instance, according to the *Augmented Addressed Morphology (AAM) Model* (Caramazza et al., 1988; Chialant & Caramazza, 1995), the decompositional route is assumed to run in parallel with the full-form route. Familiar words are accessed by the full-form route, which is assumed to be faster than the decompositional route, whereas novel words are accessed via their morpheme constituents. The full form (e.g., ‘walked’) also activates morpheme components (i.e., ‘walk’ and ‘ed’) and orthographically similar representations (‘talked’). According to the *Supralexical Account*, lexical access begins with whole word processing, with morpheme information following directly after the activation of the full form (Giraudo & Grainger, 2000). Diependaele et al. (2009), in turn, present a bimodal hierarchical model that assumes prelexical morpho-orthographic decomposition, followed by a level of full-form representations that mediates between the prelexical form level and the supralexical morpho-semantic level.

The *Morphological Race Model (MRM)* (Frauenfelder & Schreuder, 1992) postulates two parallel processing routes, with the base and word frequency as well as phonological and semantic transparency determining the selection of the route. The *Interactive Activation Race (IAR) Model* (Schreuder & Baayen, 1995) assumes full-form and decompositional routes that interactively converge on the desired meaning representation. The full-form route maps full-form access representations into their associated concept nodes, which in turn activate the corresponding semantic and syntactic representations. The decompositional route proceeds in three different but related stages: segmentation, licensing, and composition. Segmentation (access) first divides the speech or written input into form-based access representations (stems and affixes), which in turn activate their associated concept nodes. In the auditory modality, continuous mapping of the speech input into lexical representations, i.e., a cohort-like mechanism (Marslen-Wilson, 1987) would be initiated (Schreuder & Baayen, 1995). The licensing and composition stages assess whether activated representations can be integrated on the basis of their subcategorization (argument structure) properties and compute the meaning of complex words from the meaning of their constituents.

**Table 1.** Summary of the psycho- and neurolinguistic models of morphological processing.

Model	Lexical access route	Factors affecting decomposition	Different effects for inflection and derivation	Predictions for the neural correlates of the processing of inflected and derived words
Full listing	full-form access only	-	no	no
Full decomposition	pre-lexical decomposition	-	no*	no
Augmented Addressed Morphology	full-form and decomposition	familiarity	no	no
Supralexical model	full-form and decomposition	surface frequency	no	no
Morphological Race	full-form and decomposition activated in parallel	transparency, frequency	depends on the characteristics of the words	no
Interactive Activation Race	full-form and decomposition activated in interaction	transparency, frequency, affix homonymy	depends on the characteristics of the words	no
Stem Allomorph /Inflectional Decomposition	full-form or decomposition	word formation type, frequency	yes	no
Core Decompositional Network	full-form or decomposition	regularity	yes**	yes
Declarative-Procedural	full-form or decomposition	regularity	no	yes
Dual-Mechanism Model	full-form or decomposition	regularity	yes	no
Distributed-Connectionist accounts	no	N/A	depends on the characteristics of the words	no

\* However, despite postulating an obligatory early decomposition mechanism Taft & Nguyen-Hoan (2010) have recently proposed that transparent derived words must also have their own *lemma* level representations whereas fully transparent inflected words do not (Taft, 2004); see also (Crepaldi et al., 2010). \*\* not during *early* decomposition

The *Stem Allomorph/Inflectional Decomposition (SAID) Model* (Laine et al., 1994; Niemi et al., 1994) is based on neuropsychological and behavioral data in Finnish and suggests that the recognition of inflected words involves morphological decomposition at the modality-specific input level and subsequent meaning integration of the morphological constituents. In contrast, derived words, similarly to monomorphemic

nouns, only have full-form representations in the orthographic input and central lexicons. The decompositional route is activated during the processing of most inflected words except for the most frequent ones (Soveri et al., 2007), whereas during the processing of derived words the full-form route is always used.

Furthermore, the *Dual-Mechanism Models* (Clahsen, 1999; Pinker, 1991; Ullman, 2004) postulate different representations and processing mechanisms for regular and irregular inflectional forms. Irregularly inflected forms are assumed to have full-form representations, whereas regularly inflected forms are computed by rules from their constituent morphemes. Additionally, according to the refined Dual Mechanism model (Clahsen et al., 2003) productive inflections and derivations are both a result of combinatorial operations, however, productive derivations have full-form representations, as do irregularly inflected forms.

Table 1 indicates that most of the psycholinguistic models make few immediate predictions concerning the neural correlates of either the decompositional route or the full-form route. However, more recent models, such as the *Core Decompositional Network Model* (Marslen-Wilson & Tyler, 2007) and the *Declarative/Procedural Model* (Ullman, 2004) include proposed neural correlates of the processing of morphologically complex words. For instance, the Declarative/Procedural model (Ullman, 2004) claims that the decompositional route used for regularly inflected words is governed by a network including frontal, basal ganglia, parietal and cerebellar structures, whereas the full-form route employed for irregularly inflected words is governed by temporal lobe structures. The Core Decompositional Network model (Marslen-Wilson & Tyler, 2007) states that all regularly inflected words undergo morphological decomposition which is triggered by their morphophonological properties. According to this model, an early and blind segmentation also operates for derivationally complex forms, but they might not be subject to further combinatorial analysis (Marslen-Wilson & Tyler, 2007).

Finally, in contrast to many of these models, the Distributed-connectionist accounts claim that there are no decomposition or full-form procedures for lexical access (Gonnerman et al., 2007). Instead, morphological structures being assumed to arise from a system that learns to map between orthography, phonology and semantics across one or more weighted connections (Gonnerman et al., 2007; Joanisse & Seidenberg, 1999; Kiehl & Joanisse, 2010, 2011; Mirkovic et al., 2011; Seidenberg & Gonnerman,

2000). Within this framework, morphology is processed as a function of statistical regularities in sounds and meanings. Since morphologically related words are similar in both respects, they are connected in a systematic and structured way that influences the word recognition process (Kielar & Joanisse, 2010, 2011).

### **2.1.1 Behavioral studies on derivational and inflectional processing**

Most of the research on the processing of inflected vs. derived words has been conducted behaviorally. For instance, studies in Finnish, which the SAID model is based on, suggest that inflected and derived words are represented and processed differently. This evidence has been obtained by extensive investigation of two Finnish-speaking aphasics as well as behavioral and eye-tracking experiments with healthy participants. These experiments have shown that Finnish inflected words elicit longer reaction times (RTs) and higher error rates than derived or monomorphemic (non-affixed) words (Bertram et al., 1999; Laine & Koivisto, 1998; Laine et al., 1995; Laine et al., 1999b; Lehtonen & Laine, 2003; Soveri et al., 2007). Inflected words also show longer first and second fixations in comparison to monomorphemic words (Hyönä et al., 1995). This processing cost has been interpreted as reflecting morphological decomposition (Niemi et al., 1994). On the other hand, Finnish derived words have elicited similar error rates, RTs, and eye-fixation durations to monomorphemic words, and thus are assumed to be processed in their full form (Hyönä et al., 1995; Niemi et al., 1994; Vannest et al., 2002). More recently, structurally invariant Finnish derived forms (i.e., lack of suffix allomorphy) have shown base frequency effects, whereas for derived forms with suffix allomorphy only surface frequency effects have been observed (Järvikivi et al., 2006). The lack of suffix allomorphy increases affixal salience and therefore may enhance morphological decomposition of such derived forms (Järvikivi et al., 2006).

The findings of the behavioral studies in other languages than Finnish in which derivational and inflectional processes have been directly compared are not entirely conclusive. For instance, it has been reported that in overt priming paradigms inflected words show larger priming effects than derived words (Feldman, 1994; Stanners et al., 1979) and that inflected words prime other inflected words, while derived words do not

(Schriefers et al., 1992). It has also been reported that the inflected form of a stem homograph (e.g., '*spar-ivano*') inhibits an inflected stem ('*spar-are*'), but the derived form of a stem (e.g., '*spar-izion-e*') does not (Laudanna et al., 1992). This finding was interpreted as indicating that inflectional but not derivational affixes are represented in a decomposed form, and thus providing support for the representational distinction between inflection and derivation (Laudanna et al., 1992). However, some other studies have failed to observe differences between inflection and derivation. For instance, both inflected and derived words have shown similar effects in overt priming (Clahsen et al., 2003; Fowler et al., 1985; Raveh & Rueckl, 2000). However, although Clahsen et al. (2003) observed full priming for regularly inflected forms and productively derived forms; in an overt lexical decision task derived forms showed surface frequency effects, whereas regularly inflected forms did not. Some other unprimed lexical decision experiments also suggest distinct processing of inflection and derivation (Bertram et al., 1999; Bertram et al., 2000). Additionally, both derived and inflected English words have shown base and surface frequency effects during sentence reading (Niswander et al., 2000).

In summary, at a general level, there seems to be some consensus on morphological processing of (regularly) inflected words in psycholinguistics and the cognitive neuroscience of language, while the processing of derived words is still a debated issue. Whereas some authors suggest that derived words in general may not be decomposed at the access level (McQueen & Cutler, 1998), others propose that factors such as semantic transparency (Marslen-Wilson et al., 1994), suffix productivity (Burani et al., 1999), base and surface frequency (Vannest et al., 2002; Vannest & Boland, 1999), and suffix type (Vannest & Boland, 1999; Vannest et al., 2005) may affect the way a derivationally suffixed word is accessed and represented. The processing of derived words also seems to vary cross-linguistically (Vannest et al., 2002). Additionally, it has recently been proposed that, at least in English, regularly inflected words are accessed in a decomposable form, while derived words, after initial form-based decomposition, may not trigger decompositional processes in the same way due to their well lexicalized nature and less predictable complexity (i.e., their meaning may or may not be compositional with respect to the meaning of the constituents) (Bozic & Marslen-Wilson, 2010).

## **2.2 Time-course and localization of the processing of inflected and derived words**

The present thesis utilizes event-related potentials and fields (ERP/ERF), and the ERPs/ERFs in general and in association with language and morphological processing are discussed in what follows.

### **2.2.1 Event-related potentials and fields**

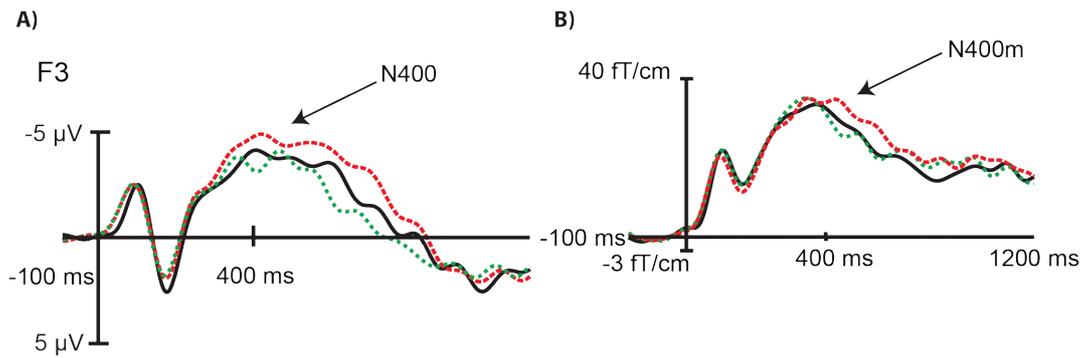
Electroencephalography (EEG) and magnetoencephalography (MEG) allow non-invasive measurement of the electric and electromagnetic neural activity in the brain with a time-scale of milliseconds (Hämäläinen et al., 1993; Hari et al., 2000). The EEG, recorded with electrodes attached to the scalp, shows the electric potential differences between two electrodes as a function of time (Luck, 2005). MEG measures the weak magnetic field produced by electric currents in the brain (Hämäläinen et al., 1993). Both EEG and MEG signals are generated by the same synchronized post-synaptic potentials in large groups of pyramidal cells (Hämäläinen et al., 1993; Lopes da Silva, 2010). MEG signals are sensitive to electric currents tangential to the skull, originating in the cortical sulci, while the EEG measures both radially and tangentially oriented electrical activity. Despite their excellent temporal resolution, the spatial resolution of EEG and MEG is limited. The EEG signal is distorted by the conductivity of the skull, making it difficult to separate the simultaneous activity of different sources. In contrast, MEG has an advantage in terms of localizing the source of the signal, as magnetic fields are not distorted as they pass through the brain, skull, and scalp (Hämäläinen et al., 1993).

The EEG and MEG signals are typically averaged across tens or hundreds of stimulus presentations to reveal the event-related potentials and fields (ERP and ERF, respectively) associated with the processing of a particular stimulus. Thus, ERP/ERFs reflect the electrical and electromagnetic activity both time- and phase-locked to the stimulus. The averaging procedure reduces noise associated with cortical activity unrelated to the processing of the stimulus as well as external magnetic and electric

noise. ERP components are peaks in ERPs that are recognized according to their polarity and latency, scalp distribution, location of the brain generators and/or in terms of the functional process with which they are associated (Luck, 2005; Otten & Rugg, 2005). The ERP components are named based on the approximate latency of the peak of the component in milliseconds (e.g., N400, occurring approximately 400 ms after stimulus onset (Figure 1), their function (e.g., mismatch negativity (MMN), occurring 150–200 ms after stimulus onset) or topographical distribution (e.g., left anterior negativity, LAN). The magnetic ERF components are denoted by the letter m to differentiate them from their ERP counterparts (e.g., N100m, N400m).

### **2.2.2 Event-related potentials/fields (ERP/ERFs) in language processing**

Several ERPs have been identified and associated with the processing of linguistic stimuli. The literature briefly reviewed below focuses only on ERPs relevant for Studies I–IV of the current thesis. The first and very well-known language-related ERP component is the so-called N400, a broad negativity peaking approximately 300–500 ms after the onset of a linguistic stimulus (Figure 1). The N400 was originally observed as an increased negativity in response to violations of semantic expectancy, e.g., ‘I like my coffee with cream and socks’ (Kutas & Hillyard, 1980). The N400/N400m is often associated with the processing of some semantic anomaly, but it is elicited by various meaningful stimuli, such as isolated words, pronounceable pseudowords, faces, and pictures (Kutas & Federmeier, 2011; Lau et al., 2008). The N400 purportedly reflects processes such as lexical access, initial access to long-term semantic memory, and a dynamic process of meaning construction (Kutas & Federmeier, 2000; Kutas & Federmeier, 2011; Lau et al., 2009; Lau et al., 2008), as well as semantic integration or unification (Hagoort et al., 2009). Several MEG studies have localized sources of the N400 to the left superior temporal cortices (Helenius et al., 2002; Uusvuori et al., 2008; Vartiainen et al., 2009b), the middle and anterior temporal areas, and the inferior frontal areas (Halgren et al., 2002).



**Figure 1.** Example of an N400 and its magnetic counterpart. The solid black line represents ERP/ERFs for monomorphemic words (e.g., *morsian*=‘bride’), dashed red line depicts ERPs/ERFs for inflected words (e.g., *uuni+ssa*=‘oven’+ ‘in’: ‘in the oven’), and dotted green line for derived words (e.g., *karvaton*=‘hair’ + ‘less’: ‘hairless’). A) Grand average ERPs from F3 electrode. Negative polarity is plotted upwards. The Y-axis represents voltage ( $\mu\text{V}$ ) and the X-axis time (ms). B) Grand average areal mean signals from five MEG gradiometer pairs in the left temporal area. The Y-axis represents magnetic field density (fT/cm), the X-axis depicts time (ms). (A) is modified from Study IV and (B) is adapted from unpublished data of Study IV.

The (early) left anterior negativity (E/LAN) and the P600 have generally been associated with syntactic processes (Friederici & Weissenborn, 2007). The ELAN has been observed at the left frontal electrodes at ~150–300 ms after stimulus onset in association with word category violations (e.g., \*The driver who is in the sleeping/The driver who is sleeping) (Isel et al., 2007; Kubota et al., 2004). It is suggested that the ELAN reflects an initial phase of local phrase-structure building (Friederici & Weissenborn, 2007). The ELAN has been localized to the inferior frontal and anterior temporal areas, with stronger activation in the left hemisphere (Friederici et al., 2000; Gross et al., 1998a). The left anterior negativity (LAN) is elicited approximately 300–500 ms after stimulus onset at the (left) frontal electrodes. The LAN has generally been observed in association with morphosyntactic violations (e.g., ‘The boy in the kindergarten \*sing a song’/ The boy in the kindergarten sings a song’) (Friederici, 2002; Friederici & Kotz, 2003; Friederici & Weissenborn, 2007; Rossi et al., 2005) but also with working memory cost (Fiebach et al., 2002; Kluender & Kutas, 1993). The neural sources of the LANm have been localized to the left superior temporal cortex (Service et al., 2007).

The P600 effect is a centro-parietal positivity, which occurs roughly at 500–700 ms after stimulus onset. The sources of the P600 have been localized to the bilateral posterior superior temporal cortices (Grodzinsky & Friederici, 2006; Service et al., 2007). The P600 has typically been identified as an increased positivity elicited during the processing of syntactically violated and syntactically complex stimuli (Coulson et al., 1998; Friederici, 2002; Friederici & Kotz, 2003; Friederici & Weissenborn, 2007; Münte et al., 1997). More recently, however, the P600 has also been reported in association with semantic violations, such as animacy and semantic-thematic violations (e.g., ‘The eggs wouldn’t eat’) (Kuperberg, 2007). This effect may reflect a repair, reanalysis, or continued combinatorial processes of complex or violated linguistic stimuli (Friederici & Weissenborn, 2007; Kuperberg, 2007). In general, different types of information (i.e., lexical-semantic and syntactic) are assumed to interact at this late processing stage (Friederici & Weissenborn, 2007).

The LAN, N400, and P600 have been reported in association with the processing of inflected and derived words, findings which are discussed in detail below.

### **2.2.2 Temporal processing of inflected and derived words: ERP/ERF findings**

The time course of inflectional processing has been investigated in a number of ERP studies across a variety of languages, many of which have used violation paradigms or priming tasks (Allen et al., 2003; Gross et al., 1998b; Linares et al., 2006; Lück et al., 2006; Morris & Holcomb, 2005; Münte et al., 1999; Newman et al., 2007; Penke et al., 1997; Rodríguez-Fornells et al., 2001; Weyerts et al., 1997). ERP studies using inflectionally violated stimuli have reported the LAN effect with over-regularized inflectional forms (e.g., *\*growed/grew*), whereas violations of irregular inflection (e.g., *\*sept/seeped*) have often elicited an increased N400 effect (Allen et al., 2003; Gross et al., 1998b; Linares et al., 2006; Lück et al., 2006; Morris & Holcomb, 2005; Münte et al., 1999; Newman et al., 2007; Penke et al., 1997; Rodríguez-Fornells et al., 2001; Weyerts et al., 1997). This distinction has been taken to support the dual-route models of morphological processing: regular inflection is governed by rules, whereas irregular inflection is assumed to have a full form representation (Clahsen, 1999; Pinker, 1991;

Ullman, 2004). Specifically, the LAN effect may reflect more demanding combinatorial processing related to morphological structure building (Rodríguez-Fornells et al., 2001), such as integrating an inflectionally violated word into its syntactic context (Morris & Holcomb, 2005). On the other hand, the increased N400 effect for violations of irregular inflected forms is assumed to reflect a more demanding memory scan of a full-form representation (Morris & Holcomb, 2005).

Compared to the large number of ERP studies on inflectionally violated stimuli, studies on correctly inflected words are few. One visual lexical decision study using isolated inflected Finnish words reported increased N400 effects for low- frequency inflected words than for matched monomorphemic words (Lehtonen et al., 2007). The increased N400 effect for inflected words may reflect the semantic integration of the decomposed stem and suffix. A recent MEG study reported stronger N400m responses for correctly inflected words than for monomorphemic words during silent reading (Vartiainen et al., 2009a).

ERP studies on derived words have shown a somewhat inconsistent pattern. Visual lexical decision studies on incorrectly derived words composed of existing morphemes elicited a larger N400/N400m effect as compared to existing derived words (Bölte et al., 2009b; Janssen et al., 2006). However, the processing of incorrectly derived words embedded in sentences elicited a LAN-type negativity (Bölte et al., 2009a). This effect was suggested to reflect demanding structural processes of recombination of constituent morphemes (Bölte et al., 2009a). On the other hand, derived words elicited a larger M170 effect than monomorphemic words, which was interpreted as indicating an early decomposition of derived words (Zweig & Pykkänen, 2008). Evidence of decomposition has also been observed for affixed words with free stems (*'taxable'*) and bound roots (*'tolerable'*) at the early processing stage, reflected in the M170 responses (Solomyak & Marantz, 2010). The relatively large variability between the findings of these ERP and MEG studies means that the exact electrophysiological correlates of derivational processing are still unclear. On the other hand, studies on inflected words using violated stimuli in sentence contexts indicate that combinatorial decomposition of regularly inflected words is indexed by the LAN-type negativity (Morris & Holcomb, 2005; Rodríguez-Fornells et al., 2001). Moreover, the very few studies on the processing of correctly inflected words to date have shown a centro-parietal N400-type

negativity during the recognition of inflected words (Lehtonen et al., 2007; Vartiainen et al., 2009a).

### **2.2.3 Localization of the processing of inflected and derived words**

In addition to investigating the temporal course of morphological processing, the recognition of inflected and derived words has been studied using hemodynamic methods, such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET). PET and fMRI can be used to localize metabolic changes in the active brain tissue with high spatial resolution. Several studies on visual and auditory comprehension of inflected words have observed that the left inferior frontal gyrus (LIFG) is involved in the processing of (regular) inflection (Tyler et al., 2005; Vannest et al., 2005). In Finnish, greater activation of LIFG was found for inflected words than for monomorphemic words (Laine et al., 1999a; Lehtonen et al., 2006b). In addition to LIFG, areas such as the basal ganglia (Vannest et al., 2005), superior temporal gyrus (Tyler et al., 2005), as well as the anterior cingulate (Tyler et al., 2005) have been mentioned in association with the recognition of inflected words. Using MEG, it has been observed that visually presented inflected nouns elicit stronger activation in the superior temporal areas than monomorphemic words (Vartiainen et al., 2009a). Tyler et al. (2005) have suggested that the LIFG indicates the segmenting of complex words into stems and affixes, whereas the superior temporal cortex might indicate lexical access of the stem.

With regard to the visual processing of derived words, localization findings are not entirely clear-cut. For instance, increased activity in the LIFG, bilateral temporo-occipital, and right parietal areas were recently observed for the processing of German written derived words with high complex internal structure, e.g., derived from the adjective to the noun via the verb (*Lesbarkeit*/'readability') as compared to those with low complex internal structure, e.g., derived from the verb or adjective (*Müdigkeit*/'tiredness') (Meinzer et al., 2009). Furthermore, increased activity in Broca's area and the basal ganglia were reported for decomposable derived words (e.g., '*dark+ness*') as compared to non-decomposable derived words (e.g., '*seren+ity*') (Vannest et al., 2005). Similarly, in an overt priming paradigm, morphologically related

pairs elicited significantly reduced activation in the left frontal areas regardless of the semantic transparency of these word pairs (Bozic et al., 2007). This priming effect was not found in orthographically related (e.g., ‘*scandal–scan*’) or semantically related (e.g., ‘*accuse–blame*’) word pairs. Two recent MEG studies reported activation in the temporal (Bölte et al., 2009b) and posterior occipito-temporal regions (Lehtonen et al., 2011) for the processing of derived forms. However, in one fMRI study, no differences between monomorphemic and derived words were observed in a synonym-monitoring task (Davis et al., 2004). Moreover, it has been recently reported that English derivational affixes do not selectively trigger activation in left-lateralized fronto-temporal areas as inflected affixes do (Bozic & Marslen-Wilson, 2010; Bozic et al., 2009).

To summarize, the processing of (regularly) inflected words seems to be governed by the fronto-temporal networks of the left hemisphere (Bozic & Marslen-Wilson, 2010). The processing of derived words activates the left inferior frontal areas (Bozic et al., 2007; Meinzer et al., 2009; Vannest et al., 2005), the basal ganglia (Vannest et al., 2005), left, right, or bilateral occipito-temporal areas (Gold & Rastle, 2007; Lehtonen et al., 2011; Meinzer et al., 2009; Solomyak & Marantz, 2010; Zweig & Pykkänen, 2008), the temporal (Bölte et al., 2009b), and right occipital areas (Meinzer et al., 2009). The larger distributed and bilateral cortical activation for the derived words has been interpreted as evidence that derivational affixes might not trigger decompositional processes in the same way as inflectional affixes (Bozic & Marslen-Wilson, 2010; Bozic et al., 2009).

### 3 The aims of the present thesis

The general aim of this thesis was to investigate the neurocognitive processing of morphologically complex words. The neural processing of isolated visual and auditory inflected and derived words was determined by using lexical decision and acceptability judgment tasks utilizing both EEG and combined EEG and MEG recordings. Furthermore, the similarities and differences in the processing and underlying neural mechanisms of inflected words (*spot+s*) and derived words (*spot+less*) were directly compared.

The specific aims of Studies I–IV were to examine:

- the neural processing of auditorily vs. visually presented inflected words (Study I)
- the time course of the neural processing of spoken existing derived words, novel but legally derived words, and illegally derived pseudowords (Study II)
- the interaction and independence between the neural processing of inflected and derived stimuli presented visually in sentences (Study III)
- the spatiotemporal dynamics of the neural processing of spoken inflected and derived words (Study IV)

The aim of Study I was to directly compare processing of inflected words in auditory as against visual modality, an issue with practically no investigation so far. It was of interest to see how the temporal unfolding as against immediate availability of *auditory vs. visual inflected* words would affect morphological decomposition. Behavioral and EEG responses were recorded simultaneously in order to investigate the neurocognitive processing of visually (Experiment 1) and auditorily (Experiment 2) presented inflected words. The processing of inflected nouns was contrasted with the processing of monomorphemic (non-affixed) words during a lexical decision task. Higher error rates, longer RTs, and larger N400 amplitudes were expected for both visual and auditory correctly inflected words than for monomorphemic words. It has been proposed that although visual and auditory words are processed by distinct neural systems at the early stages of processing, at the later stages word recognition is probably modality-

independent (Balconi & Pozzoli, 2005; Holcomb & Neville, 1990; Vartiainen et al., 2009b). Based on this assumption, similar recognition processes were expected for visual and auditory inflected words at the later stages of processing. In addition, one aim was to further examine morphological processing in inflected pseudowords, i.e., items with a pseudostem and a real suffix: are only real stems required for morphological analysis? Previous findings on this issue are relatively controversial, as some studies have observed a morphological processing cost for inflected or derived pseudowords (Laine, 1996; Lehtonen et al., 2006a), while others have not (Lehtonen et al., 2007).

In Study II, the time-course of the neural processing of *derived auditory* stimuli was investigated by simultaneously recording behavioral data and ERPs. A recent overt priming study has reported that meaningful derived pseudowords prime their stems, whereas incorrectly derived pseudowords do not (Meunier & Longtin, 2007). It is, however, still unclear whether this failure is due to their non-grammaticality or semantic non-interpretability (Meunier & Longtin, 2007). In order to elucidate which factors are crucial during neurocognitive processing of derived words, the processing of existing derived words was compared with novel but semantically highly interpretable (legal) derived pseudowords as well as semantically non-interpretability and illegal derived pseudowords. Furthermore, according to some models, (visual) morphological processing proceeds in two stages: form-based morphological decomposition and semantic integration of the morphemes (Hyönä & Laine, 2002; Longtin & Meunier, 2005; Meunier & Longtin, 2007; Niemi et al., 1994; Rastle & Davis, 2008; Schreuder & Baayen, 1995). In order to separate the ERP effects related to the processing of a base morpheme and suffix, the ERP responses were time-locked to the suffix onset. For illegally derived words, the semantic or grammatical analysis was expected to fail, which was expected to elicit a larger N400 (Janssen et al., 2006) or LAN (Bölte et al., 2009a) than the other stimuli. For legally derived pseudowords, despite their semantic interpretability, their novelty was expected to elicit a morphological cost, indexed by the longer RTs, higher error rates (Burani et al., 1999; Meunier & Longtin, 2007; Wurm, 2000) and by larger N400 effects as compared to existing derived words (but see McKinnon et al., 2003).

The aim of Study III was to investigate the possible interaction and independence between the neural processing of *visually presented inflected* and *derived* stimuli using ERPs. This question was addressed by presenting the participants with sentences containing derivationally violated (real stem and suffix, illegal stem+suffix combination), inflectionally violated (number agreement mismatch), and doubly violated stimuli (containing both a derivational and inflectional violation), in addition to correctly inflected and derived stimuli. Inflectionally violated stimuli were expected to elicit LAN and P600 effects (Newman et al., 2007). Derivationally violated stimuli were hypothesized to elicit larger N400 or LAN effects as compared to correctly derived words (Bölte et al., 2009a; Janssen et al., 2006). If the neural generators underlying inflectional and derivational processes are separate and independent, the language related ERP effects to these stimuli should linearly summate in the combined violation condition.

Study IV investigated the spatiotemporal dynamics of the neural processing of *spoken correctly inflected* and *derived* words using simultaneously recorded EEG and MEG responses. In this study, isolated inflected and derived words were contrasted with monomorphemic words. Additionally, to identify the timing of morphological processes more precisely, the ERP and ERF responses were time-locked to both stimulus onset as well as critical point (suffix onset for complex words and uniqueness point for monomorphemic words). Because of previous assumptions that Finnish derived words might be recognized in their full form (Bertram et al., 1999; Vannest et al., 2002), similar ERP responses were expected for monomorphemic words and derived words in Study IV. For inflected words, morphological analysis was assumed to be reflected in a larger N400 than for monomorphemic and, possibly, derived words as well. Inflected and derived words were expected to activate left or bilateral superior temporal areas (Bölte et al., 2009b; Vartiainen et al., 2009a).

## 4 Methods

### 4.2 Participants

All of the participants were healthy volunteers with normal hearing, normal or corrected-to-normal vision, and no record of neurological diseases. All participants were right-handed, verified by a Finnish version of Edinburgh Handedness Inventory (Oldfield, 1971) or an unpublished Finnish version of the Boston V.A. Handedness questionnaire. All of the participants gave their informed consent and received movie tickets for their participation. Study I was approved by the Ethics Committee of the University of Turku. Studies II and III were approved by the Ethics Committee of the Department of Psychology, University of Helsinki. Study IV was approved by the Coordinating Ethics Committee of the Helsinki University Central Hospital. Table 1 summarizes the participants in Studies I–IV.

**Table 2.** Participants in Studies I–IV

Study	N	Males	Age (mean) in years
I: Exp 1	10	4	20–44 (25)
I: Exp 2	10	6	19–26 (21)
II	14	5	18–27 (22)
III	15	4	19–64 (30)
IV	10	6	18–34 (26)

### 4.2 Stimulus materials

In Study I, stimulus frequencies were obtained from the *Turun Sanomat* lexical database with 22.7 million word tokens, using a computerized search program (Laine & Virtanen, 1999). In Studies II, III, IV and V, frequency information was obtained from the Finnish corpus (109,341,835 tokens) composed by the Research Institute for the Languages of Finland, the Finnish IT Center for Science, and the Department of General Linguistics, University of Helsinki. The corpus was accessed through WWW-

Lemmie 2.0 at the Finnish IT center for science (www.csc.fi). Table 3 summarizes the stimulus conditions used in Studies I–IV and provides examples of each condition. Auditory stimuli were used in Studies I, II, and IV. Visual stimuli were used in Studies I and III. All the inflectional and derivational suffixes selected for the Studies I–IV were those that have also been used in previous studies on Finnish morphological processing (e.g., Bertram et al., 1999; Brattico et al., 2007; Järvikivi et al., 2006; Laine, 1996; Lehtonen et al., 2007; Vannest et al., 2002).

**Table 3.** Stimulus characteristics in Studies I–IV and examples with approximate translations

Stimulus conditions	Examples
Study I	
Monomorphemic words	<i>morsian</i> =‘bride’
Inflected words	<i>talo+ssa</i> =‘house’ + ‘in’: ‘in the house’
Monomorphemic pseudowords	<i>vorsilo</i>
Inflected pseudowords	<i>käny+lle</i> =‘*käny’+ ‘allative case <i>-lle</i> ’
Study II	
Derived words	<i>melo+nta</i> =‘paddle’ + ‘V-doing’: ‘paddling’
Legal pseudowords	<i>elvy+ntä</i> =‘recover’ + ‘V-doing’: ‘recovery’
Illegal pseudowords	<i>heinä+ntä</i> =‘*hay’ + ‘V-doing’: ‘haying’
Study III	
Correctly inflected and derived stimuli	Mies, joka omistaa talon, <u>on talo+llinen</u> =(‘house’+ ‘own N <sub>SG</sub> ’) mies. (The man who owns a house, is a house-owning man)
Incorrectly inflected stimuli	Mies, joka omistaa talon, <u>on *talo+lliset</u> =(‘house’+ *‘own N <sub>PL</sub> ’) mies. (The man who owns a house, is a house-owning <sub>PL</sub> man)
Incorrectly derived stimuli	Mies, joka juoksee metsässä, <u>on juokse+llinen</u> =(‘*run’+ *‘ownN <sub>SG</sub> ’) mies. (The man who runs in the woods, is a run-owning man)
Incorrectly derived and inflected stimuli	Mies, joka juoksee metsässä, <u>on juokselli+set</u> =(‘*run’+ *‘ownN <sub>PL</sub> ’) mies. (The man who runs in the woods, is a run-owning <sub>PL</sub> man)
Study IV	
Monomorphemic word	<i>morsian</i> =‘bride’
Inflected word	<i>koodi+ssa</i> =‘code’ + ‘in’: ‘in a code’
Derived word	<i>karva+ton</i> =‘hair’ + ‘less’: ‘hairless’

In Study I, the visual and auditory stimuli in both Experiments 1 and 2 consisted of 100 Finnish case-inflected nouns and 100 monomorphemic nouns. The monomorphemic words consisted of nouns in nominative singular form. The inflected stimuli included nine different suffixes. Six were locatives (inessive ‘*-ssa*’, elative ‘*-*

*stA*’, illative ‘*-Vn*’, adessive ‘*-lla*’, ablative ‘*-lta*’, allative ‘*-lle*’), essive (‘*-nA*’), as well as genitive (‘*-n*’) and partitive (‘*-A*’ and ‘*-tA*’). Inflected pseudowords consisted of a pseudostem and a real inflectional case suffix. The experiments also included 100 monomorphemic and 100 inflected pseudowords, which complied with the phonotactic rules of Finnish.

In Study II, the auditory stimuli consisted of existing derived words, legal and illegal derived pseudowords (Table 3), with 80 stimuli per condition. All derived stimuli had the same suffix ‘*-ntA*’, which denotes ‘V-doing’ (*ammu+nta*=‘shoot’+‘V-doing’: ‘shooting’). Legal derived pseudowords were formed by combining the verbal base and derivational suffix ‘*-ntA*’, such that the resulting words did not violate the phonotactic, morphotactic or derivational rules of Finnish. The interpretability and novelty of the resulting combinations were verified by a pretest questionnaire. In the illegal pseudoword condition, the resulting pseudowords violated a selectional restriction, the suffix ‘*-ntA*’ being attached to a nominal base instead of a verbal base. These pseudowords did not violate the phonological rules of Finnish, but were semantically non-interpretable and non-existent, as verified by the pretest questionnaire.

The stimuli in Study III consisted of correctly derived and inflected stimuli, incorrectly inflected and derived stimuli as well as doubly violated stimuli (80 stimuli per condition). All stimuli had the same suffix ‘*-llinen*’, which denotes ‘N-owning’ (*talo+llinen*=‘house’ + ‘owns N’: ‘owns a house’). The critical stimuli were embedded in simple declarative sentences (Table 3). The inflectional violation consisted of a number agreement violation, the critical word being presented in the plural instead of singular form. The derivational violation comprised of adding an adjectival suffix to a verbal base instead of a nominal one, making these stimuli non-interpretable. In the combined violation condition, the suffix was attached to a verbal base and thereafter the stimulus was inappropriately embedded in a morphosyntactic context.

In Study IV, the stimuli consisted of monomorphemic words, inflected words, and derived words (75 stimuli per condition). The monomorphemic words consisted of nouns in nominative singular form. The inflected nouns included structural case suffixes such as genitive, partitive, and essive as well as locative suffixes. The derived words included derivational suffixes ‘*-kAs*’ (*äly+käs*=‘intelligence’ + ‘a property of N’: ‘intelligent’); ‘*-tOn*’ (*karva+ton*=‘hair’ + ‘less’: ‘hairless’) and ‘*-(i)stO*’ (*kone+isto*=

‘machine’ + ‘a collection of N’: ‘machinery’), which are all attached to nominal stems (Hakulinen, 2004). In order to balance the number of correct and incorrect responses, the study also included monomorphemic pseudowords as well as derivationally violated and inflectionally violated stimuli (the results are reported elsewhere, Leminen et al., in preparation).

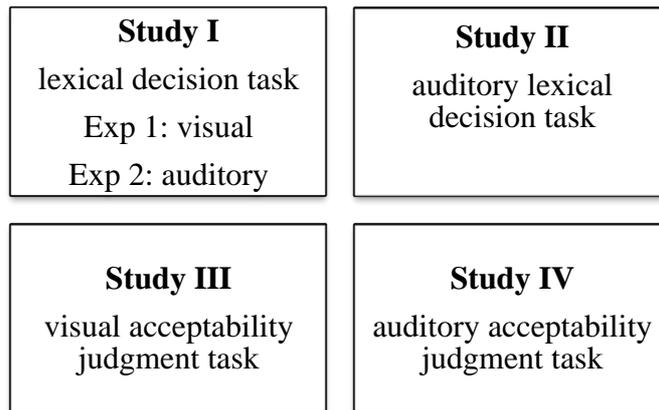
#### **4.2.1 Fine-grained temporal analysis of the stimuli**

In Studies II and IV, the ERP responses were time-locked to the onset of morphologically relevant information to avoid jitter in the signal due to variability in the base morpheme duration and suffix onset. In Studies II and IV the responses to morphologically complex words were time-locked to the suffix onset and in Study IV the responses to monomorphemic control words were time-locked to the uniqueness point (UP). The UP is the phoneme at which a word deviates from all other words that share the same phoneme up to and preceding the UP (Balling & Baayen, 2008). In Study II, the Complex Uniqueness Point (CUP) and Deviation Point (DP) were also controlled for. The CUP, which is related to morphologically complex words, is the point at which the morphologically complex word is unique; so that the CUP for ‘*kindness*’ is the second ‘n’, which deviates ‘*kindness*’ from e.g., ‘*kindly*’ (Balling & Baayen, 2008). The DP is the phoneme at which no unique word matches the stored material. In Studies II and IV the UP/DP and CUP were defined by an extensive corpus search. The precise time point of the suffix onset/UP/DP was marked by a trigger code in each auditory file of each stimulus.

### **4.3 Experimental procedures**

Figure 1 summarizes the experimental paradigms used in Studies I–IV. In Study I visual and auditory lexical decision tasks were employed. In the visual lexical decision task (Experiment 1), the participants were instructed to decide as quickly and correctly as possible whether a letter string was a Finnish word or not. The subject responded by

pressing either the button marked ‘word’ or the button marked ‘pseudoword’ on a response pad. The response was followed by a 3000 ms inter-trial interval (ITI), after which the next stimulus was presented. In the auditory lexical decision task (Experiment 2), the same procedure as in Experiment 1 was used, except that the stimuli were presented binaurally through earphones.



**Figure 2.** Experimental paradigms used in Studies I–IV.

In Study II, the auditory stimuli were presented binaurally through earphones. The participants were instructed to listen to the stimuli and press the corresponding button on a response pad according to whether the stimulus was a Finnish word or not as quickly and accurately as possible. Each trial began with a 2500 ms ITI, after which the next stimulus was presented. A fixation cross was presented in the middle of the screen throughout the trial. The stimulus presentation within the block and the order of the blocks were randomized separately for each participant.

In Study III, each trial began with a 1000 ms ITI; followed by a fixation cross, after which the first word of the experimental sentence was presented. The sentences were presented on a word-by-word basis. After showing the sentence, the text ‘Respond now’ appeared on the screen, prompting the participants to answer. After reading each sentence, the participants were instructed to press one of two response buttons if the sentence was acceptable in Finnish, and another if the sentence was unacceptable.

In Study IV, the stimuli were presented binaurally through plastic tubes at a comfortable sound level. The participants were instructed to listen to the stimuli and indicate whether the items were acceptable Finnish words or not by releasing their index

and middle fingers of the right hand from the optical response pad. The participants released their index finger of the right hand if the word was acceptable and middle finger if it was unacceptable. The ITI was 1500 ms, after which the next stimulus was presented.

#### 4.4 Data acquisition and analysis

Table 4 summarizes the details for the data acquisition and analysis. In Studies I–III, brain responses were recorded using EEG. In Study IV, the EEG and MEG signals were recorded simultaneously. In Study I, the EEG was measured using the Neuroscan 386 Scan 3.0 recording system (Neuroscan, USA) with a Braintronics CNV/ISO-1032 amplifier. Twenty Ag/AgCl electrodes were placed bilaterally on the participant's scalp using electrode paste and the 10/20 system of electrode placement. Two EOG electrodes were placed on the outer sides of the eyes.

**Table 4.** Details of the data acquisition and ERP/ERF analysis

	Study I	Study II	Study III	Study IV
Sampling rate	200 Hz	512 Hz	250 Hz	600 Hz
Reference during recording	Linked ears	Common Mode Sense (CMS) electrode	Nose	Nose
Re-referencing	No	Averaged mastoids	No	Averaged mastoids
Online filter	0.3–70 Hz	DC–128 Hz	0.1–50 Hz	0.1–200 Hz
Offline filter	0.5–45 Hz	0.1–30 Hz	0.5–20 Hz	0.2–45 Hz
Eye blink correction	no	PCA	ICA	PCA
Artifact rejection threshold	$\pm 100 \mu\text{V}$	$\pm 100 \mu\text{V}$	$\pm 100 \mu\text{V}$	$\pm 100 \mu\text{V}$ $\pm 1200 \text{ fT/cm}$
Epoch (ms)	-100–1400	SO*: -200–1500 SufO**: -1000–1000	-100–800	SO: -200–1200 CpO***: -200–700
Baseline (ms)	-100–0	SO: -200–0 SufO: -1000–700	-100–0	SO: -200–0 Cp: -200–0

\*SO = stimulus onset time-locked, \*\*SufO = suffix onset time-locked, \*\*\*CpO = critical point time-locked

In Study II, the EEG was measured using the BioSemi ActiveTwo recording system (BioSemi, Inc., The Netherlands), with 64 active scalp electrodes fitted onto an elastic cap and following the BioSemi ABC position system. Additionally, three active electrodes were placed at the tip of the nose and at the left and right mastoid sites. EOG was monitored by two bipolar leads.

In Study III, the EEG was recorded with the NeuroScan 4.3 system and SynAmps2 amplifier (Neuroscan, USA) with 28 Ag/AgCl electrodes mounted on an electrode cap. Left and right mastoids were also recorded. EOG electrodes were placed at the temples and above and below the right eye.

In Study IV, the EEG and MEG signals were recorded with the 306-channel helmet-shaped system (Elekta Neuromag, Finland), which consists of 102 sensor elements each comprising two orthogonal planar gradiometers and one magnetometer. The EEG was recorded with a 64-channel electrode cap using an amplifier designed and built for simultaneous EEG and MEG recordings (Virtanen et al., 1997; Virtanen et al., 1996). EOG electrodes were placed at the temples above and below the left eye. The continuous raw MEG data were pre-processed offline using the MaxFilter<sup>TM</sup> software (Elekta Neuromag, Finland), which minimizes the potential effects of magnetic sources outside the head as well as sensor artifacts, using a Signal Source Separation method (Taulu et al., 2004). MaxFilter was applied with spatiotemporal filtering and head-movement compensation, which corrected motion artifacts. The source locations of the MEG data were initially determined using L1 norm minimum current estimates (MCE) in order to acquire an overview of the spatial distribution of the activity and to subsequently compare it with sources obtained with equivalent current dipole (ECD) modeling. The MCE estimates current density across a large number of sources evenly distributed across the brain surface. The MCE requires no a priori information of the possible source configuration or restriction of the MEG channels included in the modeling. The measured signals are accounted for by a distribution of electric current that has the minimum total amplitude (Uutela et al., 1999). The MCEs were calculated for each participant, condition and time point (in 2 ms time-steps) and projected on the triangularized gray matter surface of a standardized brain. Cortical sources of the magnetic fields were then modeled as ECDs for the activity after the critical point. An ECD, performed by minimizing the difference between the calculated and measured

magnetic fields, represents the mean location, strength of activation, and orientation of the current flow in the designated brain area. All 204 gradiometers were used in the ECD analysis. Fit intervals and the number of sources modeled were selected using grand average magnetic field patterns and the principal component analysis (PCA) implemented in the BESA Research 5.3 software. The goodness of fit of the dipoles selected exceeded 80%.

## **4.5 Statistical analyses**

In Experiments 1 and 2 of Study I, RTs and error rates were analyzed with separate repeated measures analyses of variance (ANOVA) with two factors: Lexicality (two levels: words, pseudowords) and Morphology (two levels: monomorphemic, inflected). The mean amplitude comparisons for the ERP data of Experiment 1 were performed in the 400–500 ms and 750–900 ms time-windows for the factors: Lexicality (two levels: words, pseudowords), Morphology (two levels: monomorphemic, inflected), Region (three levels: anterior, central, posterior) and Hemisphere (three levels: left, central, right). In Experiment 2, ANOVA was performed for the same factors as in Experiment 1 but in the 650–750 time window.

In Study II, mean RTs and error rates measured from the stimulus and suffix onset were analyzed using separate one-way repeated measures ANOVA with one factor, Condition (three levels: existing derived word, legal pseudoword, illegal pseudoword). The mean amplitudes in the 805–885 ms time-window after stimulus onset, in the -200–0 ms before and the 274–314 ms after the suffix onset were analyzed with separate three-way ANOVAs with factors: Condition (three levels: existing derived word, legal pseudoword, illegal pseudoword), Anterior-Posterior axis (three levels: anterior, midline, posterior), and Laterality (three levels: left midline, midline, right midline). Post-hoc comparisons were performed using the least significant difference (LSD) test.

In Study III, the comparison of percentages of acceptability judgments for the four stimulus conditions (correct, inflectional violation, derivational violation, combined violation) was performed with a two-way repeated measures ANOVA with factors: Inflectional violation (two levels: yes/no) and Derivational violation (two levels:

yes/no). The mean amplitudes in the 450–550 ms, 600–800 ms, and 700–800 ms time-windows were analyzed by separate repeated measures analysis of variance (ANOVA) with factors: Derivational violation (two levels: yes/no), Inflectional violation (two levels: yes/no), Region (three levels: anterior, central, posterior), and Laterality (three levels: left, central, right). The additivity of the ERP responses to derivational and inflectional violations was tested by comparing the mean amplitudes from the observed and modeled difference waves. The observed difference wave was obtained by subtracting the correct condition (CC) from the combined violation condition (CV-CC). The modeled difference wave was obtained by subtracting the correct condition from the inflectional and derivational violation conditions and then adding them together [(IV-CC) + (DV-CC)]. The mean amplitudes from the modeled and observed difference waves were calculated in the 700–800 ms and 600–800 ms time-windows for the parietal electrodes using separate repeated measures ANOVAs with one factor: Summation (two levels: combined, modeled). Additionally, in the 450–550 ms time window, the mean amplitude comparisons between observed and modeled difference waves were examined with repeated measures ANOVA with factors: Summation (two levels: combined, modeled), Region (two levels: anterior, posterior) and Laterality (two levels: left, right).

In Study IV, mean RTs and error rates measured from the stimulus onset and from the critical point were analyzed using separate one-way repeated measures ANOVA with one factor Condition (three levels: monomorphemic, derived, inflected). Furthermore, the amplitude comparisons were performed for ERPs and equivalent current dipoles (ECD). The mean amplitudes for the ERPs were calculated in the 700–780 ms (stimulus onset time-locked), 80–120 ms, 170–210 ms, and 190–230 ms (critical point time-locked) time-windows. For both stimulus onset and critical point time-locked ERPs, the amplitudes were entered into separate ANOVAs with factors Condition (three levels: monomorphemic, inflected, derived), Anterior-Posterior axis (three levels: anterior, midline, posterior) and Laterality (four levels: left, left midline, right midline, right). The mean amplitudes for the midline electrodes were analyzed separately with factors Condition (three levels: monomorphemic, inflected, derived) and Site (three levels: Fz, Cz, Pz).

**Table 5.** The time windows in which the mean amplitudes for ERPs in Studies I–IV and ECDs in Study IV were measured.

<b>Study</b>	<b>Time-windows</b>
Study I	
Experiment 1 (SO ERPs)	450–550 ms 750–900 ms
Experiment 2 (SO ERPs)	650–750 ms
Study II	
SO ERPs	805–885 ms
SufO	-200–0 ms 274–314 ms
Study III	
SO ERPs and modeled ERPs	450–550 ms 600–800 ms 700–800 ms
Study IV	
SO ERPs	700–780 ms
CpO ERPs	80–120 ms
CpO ERPs	170–210 ms
CpO ERPs	190–230 ms
CpO ECDs	80–120 ms
CpO ECDs	170–210 ms
CpO ECDs	190–230 ms

For ECDs, separate ANOVAs were performed for critical point time-locked source waveforms in the 80–120 ms, 170–210 ms, and 190–230 ms time-window for the factors Condition (three levels: monomorphemic, inflected, derived). Post-hoc comparisons were performed using the least significant difference (LSD) test. In order to determine the differences in dipole location between the conditions, Euclidean distances (ED) in millimeters were calculated for the Cartesian coordinates x and y (left-right and anterior-posterior) of the dipole locations. EDs between the conditions were then tested against the baseline (0 mm) with the pair-wise t-tests. In order to address the possibility of accepting false positives, the p-values were Bonferroni corrected.

## 5 Results

### 5.1 Neural processing of written and spoken inflected words and pseudowords (Study I)

#### 5.1.1 Experiment 1: Visual experiment

Table 6 demonstrates the mean RTs and error rates in Experiment 1. Table 7 shows the statistically significant main effects and interactions for the behavioral and ERP data in Experiment 1. Error rate results showed a significant main effect for Morphology, with inflected stimuli eliciting higher error rates than monomorphemic stimuli. The reaction time data showed a significant main effect for Lexicality, as pseudowords elicited longer RTs than words. The main effect for Morphology was also significant, with inflected stimuli eliciting longer RTs than monomorphemic stimuli. Furthermore, there was a significant Lexicality  $\times$  Morphology interaction. Pair-wise comparisons showed longer RTs for inflected words than for monomorphemic words, but no significant differences in RTs between inflected and monomorphemic pseudowords.

**Table 6.** Mean RTs (SD) and error rates (SD) in Experiment 1

Stimulus type	Reaction time (ms)	Error rate (%)
Monomorphemic words	661 (136)	2.0 (2.1)
Inflected words	740 (172)	5.3 (3.4)
Monomorphemic pseudowords	801 (187)	3.5 (3.4)
Inflected pseudowords	827 (200)	5.1 (3.8)

The ERP results showed that there was a significant main effect for Lexicality in the 400–500 ms time window, as pseudowords elicited a significantly larger negativity than words (Figures 3 and 4). The negativity for pseudowords was most prominent at the centro-posterior electrodes of the right hemisphere, as Lexicality  $\times$  Region and Lexicality  $\times$  Hemisphere interactions reached significance. The main effect for Morphology was also significant, reflected in a larger negativity for inflected stimuli than monomorphemic stimuli. There was a significant interaction between Morphology

and Hemisphere, as the N400 effect for inflected stimuli in comparison to monomorphemic stimuli was larger in the right hemisphere than in the left. Subsequent analysis separately for words and pseudowords showed that the negativity was larger for real inflected words than for real monomorphemic words, but this effect was not observed for pseudowords. In the 750–900 ms time window, there were significant interactions between Lexicality and Morphology and between Lexicality and Hemisphere, as inflected stimuli elicited a larger positivity than monomorphemic over the right hemisphere. Separate analysis for words and pseudowords showed that only real words elicited a larger positivity than monomorphemic words at the right hemisphere electrodes.

**Table 7.** Statistically significant main effects and interactions (F-test, degrees of freedom, p-value) of Study I

<b>Factors</b>	<b>F-test, df, p-value</b>
<b>Experiment 1 (Visual)</b>	
<i>1) Error rate data</i>	
Morphology	F(1,9) = 28.86, p < 0.001
<i>2) Reaction time data</i>	
Lexicality	F(1,9) = 28.81, p < 0.001
Morphology	F(1,9) = 21.48, p = 0.001
Lexicality × Morphology	F(1,9) = 10.86, p = 0.009
<i>3) ERP results (450–550 ms)</i>	
Lexicality	F(1,9) = 15.17, p = 0.004
Morphology	F(1,9) = 11.66, p = 0.008
Morphology × Hemisphere	F(2,18) = 8.93, p = 0.002
Lexicality × Region	F(2,18) = 7.97, p = 0.003
Lexicality × Hemisphere	F(2,18) = 5.84, p = 0.036
Lexicality × Hemisphere × Region	F(4,36) = 7.37, p < 0.001
<i>4) ERP results (750–900 ms)</i>	
Lexicality × Hemisphere	F(2,18) = 5.8, p = 0.011
Lexicality × Morphology	F(2,18) = 5.7, p = 0.041
<b>Experiment 2 (Auditory)</b>	
<i>1) Error rate data</i>	
Morphology	F(1,9) = 20.21, p = 0.001
<i>2) Reaction time data</i>	
Lexicality	F(1,9) = 21.44, p = 0.001
Morphology	F(1,9) = 45.32, p < 0.001
Lexicality × Morphology	F(1,9) = 9.31, p = 0.014
<i>3) ERP results (650–750 ms)</i>	
Morphology	F(1,9) = 6.88, p = 0.028
Lexicality × Morphology	F(1,9) = 15.64, p = 0.003

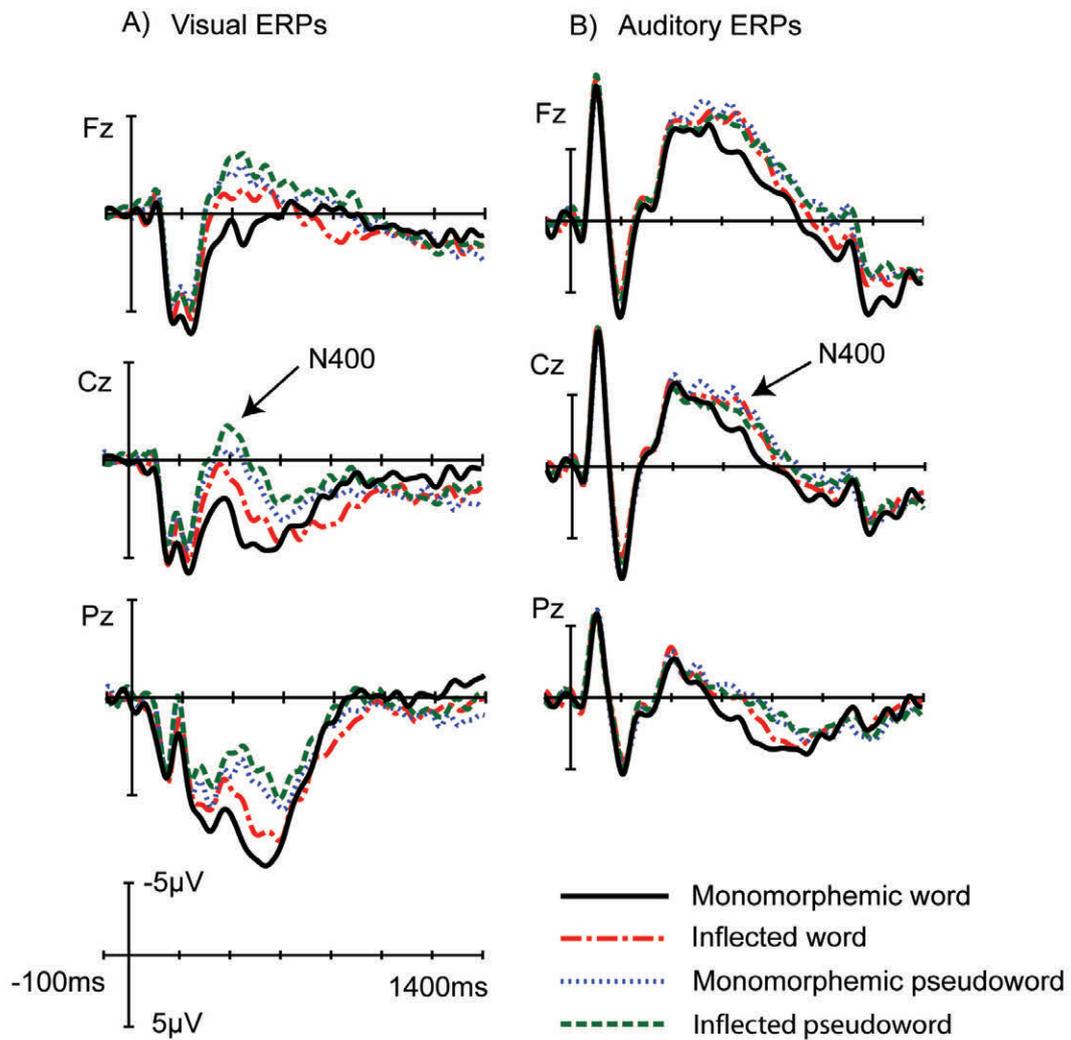
## 5.1.2 Experiment 2: Auditory experiment

Table 7 depicts the statistically significant main effects and interactions for the behavioral and ERP data in Experiment 2. Table 8 demonstrates mean RTs and error rates in Experiment 2. In line with the results from Experiment 1, error rates showed a significant main effect for Morphology, as inflected stimuli elicited higher error rates than monomorphemic stimuli. The RT data showed a significant main effect for Lexicality, seen as longer RTs for pseudowords than for words. The inflected stimuli elicited longer RTs than the monomorphemic stimuli, as the main effect for Morphology reached significance. The Lexicality  $\times$  Morphology interaction was significant. This was seen as longer RTs for inflected words than monomorphemic words, whereas the RTs for inflected pseudowords did not differ from those for monomorphemic pseudowords.

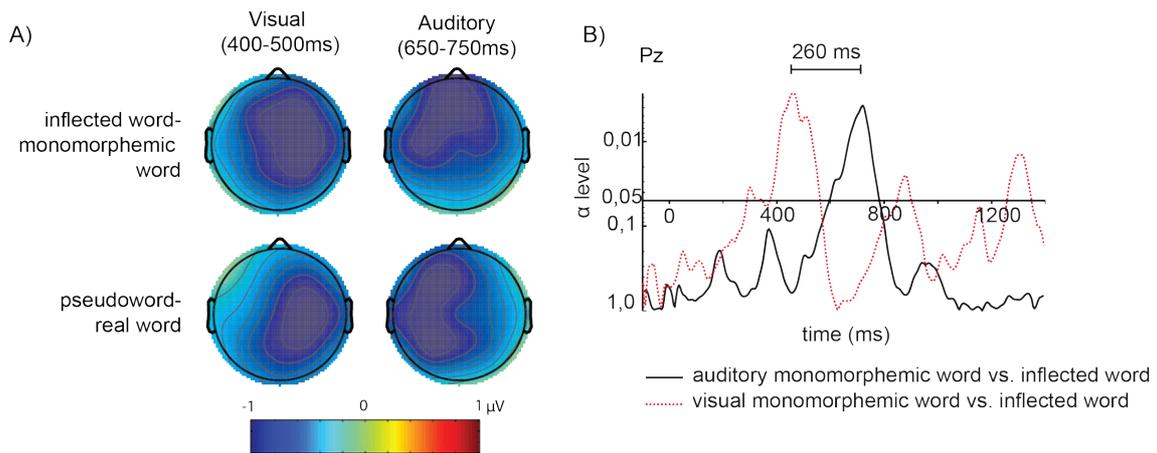
**Table 8.** Mean RTs (SD) and error rates (SD) in Experiment 2

Stimulus type	Reaction time (ms)	Error rate (%)
Monomorphemic words	957 (42)	2.3 (2)
Inflected words	1020 (64)	4.5 (1.9)
Monomorphemic pseudowords	1120 (120)	3.9 (5)
Inflected pseudowords	1130 (113)	5.9 (6.3)

The ERP results demonstrated that in the 650–750 ms time window, the main effect for Morphology reached significance, as inflected stimuli elicited a larger, widely distributed negativity than monomorphemic stimuli (Figures 3 and 4). There was a significant interaction between Lexicality and Morphology. Subsequent pair-wise comparisons showed that inflected words elicited a larger negativity than monomorphemic words, but there were no differences between inflected and monomorphemic pseudowords.



**Figure 3.** Grand average ERPs (10 participants) from 3 scalp sites (Fz, Cz, Pz) to A) visually and B) auditorily presented words. The lines depict ERPs for the monomorphemic words (black solid line), inflected words (red alternating dashed/dotted line), monomorphemic pseudowords (blue dotted line) and inflected pseudowords (green dashed line), after baseline correction in the 100 ms prestimulus interval. Time 0 is the onset of the stimulus. Negative polarity is plotted upwards. The X-axis represents time (milliseconds) and the Y-axis depicts voltage (microvolts,  $\mu\text{V}$ ). The arrowhead lines show the N400 effect for the visual and auditory stimuli. Modified from Leinonen, A., Grönholm-Nyman, P., Järvenpää, M., Söderholm, C., Lappi, O., Laine, M., Krause, C.M. (2009). Electrophysiological processing of auditorily and visually presented inflected words and pseudowords: Evidence from a morphologically rich language. *Brain Research*, 1275, 54-66, (Study I).



**Figure 4.** A) Topographical maps for the mean amplitudes in the 400–500 ms and 650–750 ms time windows (the erratum in Figure 2 of the original publication has been corrected) for the visually (left) and auditorily (right) presented stimuli. Maps are based on the vector scaled difference waveforms that resulted from subtracting the mean amplitude of grand average ERPs elicited by monomorphemic words from ERPs to inflected words and monomorphemic words from monomorphemic pseudowords. B) The results of the consecutive t-tests in a 100 ms moving average for the electrode Pz contrasting visually presented monomorphemic and inflected real words (red dotted line) and auditorily presented monomorphemic and inflected real words (black solid line). Serial t-tests on the difference waveforms were calculated against the null hypothesis of no difference from the baseline. Time 0 is the onset of the stimulus. The X-axis represents time (milliseconds) and the Y-axis depicts the uncorrected alpha level of significance. The purpose of the serial t-tests was to compare the time-windows in which the conditions differ from each other significantly. Modified from: Leinonen, A., Grönholm-Nyman, P., Järvenpää, M., Söderholm, C., Lappi, O., Laine, M., Krause, C.M. (2009). Electrophysiological processing of auditorily and visually presented inflected words and pseudowords: Evidence from a morphologically rich language. *Brain Research*, 1275, 54-66, (Study I).

## 5.2 Time course of the neural processing of spoken derived words (Study II)

Table 9 demonstrates the mean RTs and error rates in Study II. Table 10 demonstrates the statistically significant effects for the behavioral and ERP data in Study II.

**Table 9.** Mean RTs (SD) and error rates (SD) in Study II

Stimulus type	RT measured from the stimulus onset (ms)	RT measured from the suffix onset (ms)	Error rate (%)
Existing derived words	1456 (134)	787 (133)	4.3 (3.5)
Legal derived pseudowords	1591 (126)	941 (132)	47 (24)
Illegal derived pseudoword	1554 (125)	912 (133)	6.7 (7.8)

The error rate data demonstrated a significant main effect for Condition, seen as higher error rates for pseudowords than for existing derived words. Post-hoc tests showed that legal pseudowords elicited significantly higher error rates than existing words and illegal pseudowords. The RT data measured from both the stimulus and suffix onset showed a significant main effect for Condition, and post-hoc tests confirmed that legal pseudowords elicited longer RTs than existing words and illegal pseudowords.

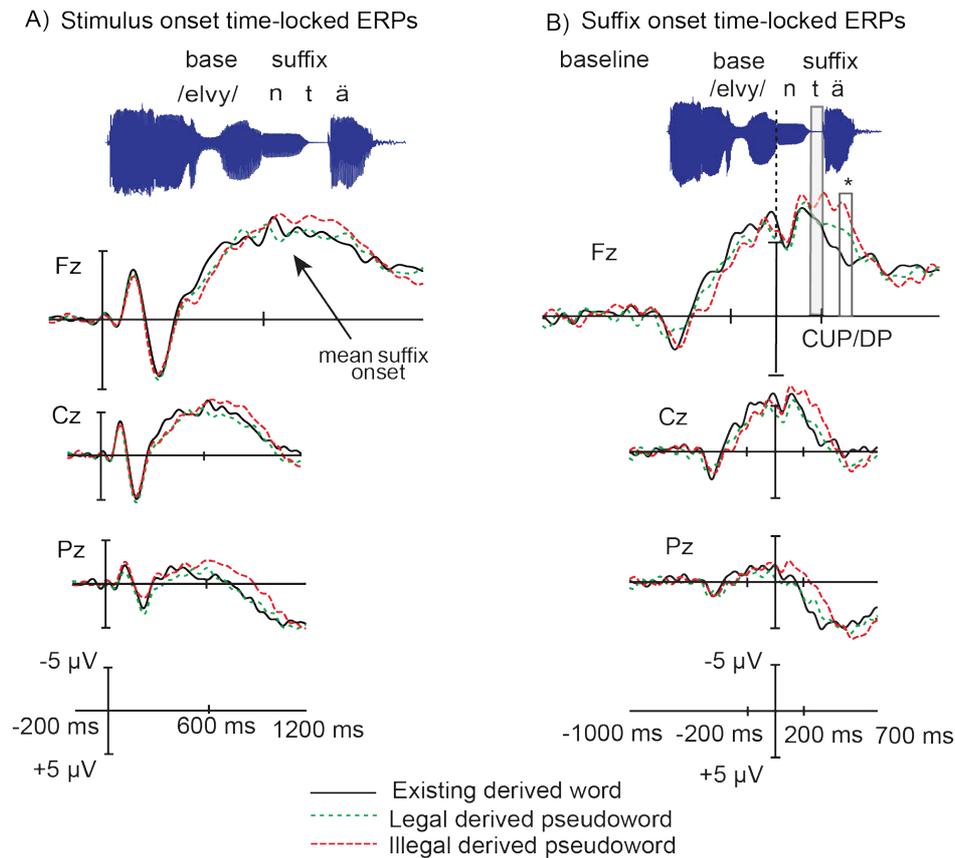
**Table 10.** Statistically significant effects (F-test, degrees of freedom, p-value) of Study II

Factors	F-test, p-value
<i>1) Error rate data</i>	
Condition	F(2,26) = 44, p < 0.001
<i>2) Reaction time data</i>	
Condition*	F(2,26) = 32.72, p < 0.001
Condition **	F(2,26) = 36.97, p < 0.001
<i>3) ERP results (274–314 ms)**</i>	
Condition	F(2,26) = 3.9, p = 0.032

\* measured from the stimulus onset, \*\* measured from the suffix onset

The ERP results showed no differences between the conditions in the stimulus onset time-locked data. The suffix onset time-locked ERPs revealed that the differences between the conditions emerged in the 274–314 ms time-window after the suffix onset

(Figure 5). There was a significant main effect for Condition, as pseudowords elicited a larger widespread negativity than existing derived words. Post-hoc tests showed that illegal pseudowords elicited a significantly larger negativity than existing words. There were no significant differences in the magnitude of the negativity between legal and illegal pseudowords or legal pseudowords and existing words.



**Figure 5.** A) Grand average ERPs (14 participants) from Fz, Cz, and Pz to existing derived words (black solid line), legal derived pseudowords (green dotted line), and illegal derived pseudowords (red dashed line), after baseline correction in the – 200 to 0 ms pre-stimulus interval. Time 0 is the stimuli onset. Negative polarity is plotted upwards. The X-axis represents time (milliseconds), the Y-axis depicts voltage ( $\mu\text{V}$ ). An example of an auditory file (legal derived pseudoword ‘elvyntä’) is depicted above Fz. B) Grand average event-related potentials from three sites (Fz, Cz, Pz) to existing derived words (black solid line), legal derived pseudowords (green dotted line), and illegal derived pseudowords (red dashed line), after baseline correction in the – 1000 to –700 ms pre-suffix interval. The complex uniqueness point (CUP)/deviation point (DP) is shaded in gray at Fz. The time window in which significant differences between conditions were observed is marked with a square (\* $p < 0.05$ ). Modified from Leminen, A., Leminen, M., Krause, C.M. (2010). Time course of the neural processing of spoken derived words: an event-related potential study. *NeuroReport*, 21, 948-952, (Study II).

### 5.3 Interaction and independence of derivational and inflectional processes (Study III)

Table 11 demonstrates the mean error rates in Study III. Table 12 shows the statistically significant main effects and interactions for the behavioral and ERP data in Study III.

**Table 11.** Mean error rates (SD) in Study III

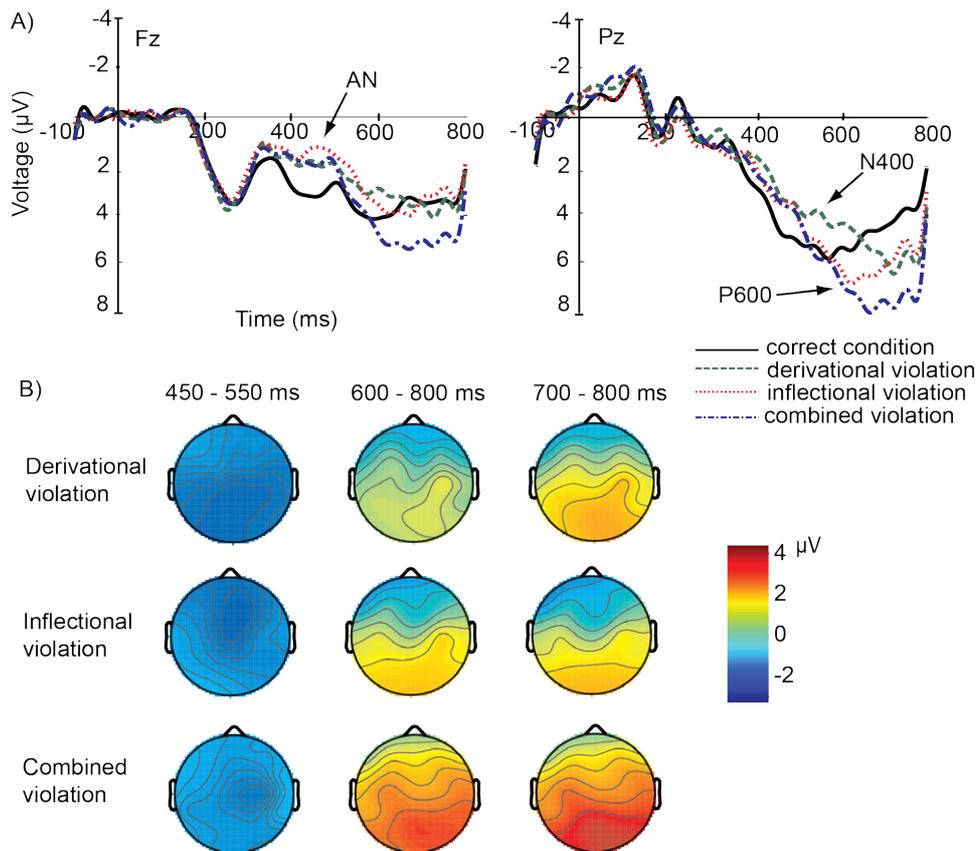
Stimulus type	Error rate (%)
Correct stimuli	4 (1.2)
Inflectionally violated stimuli	1.3 (0.9)
Derivationally violated stimuli	0.8 (1.3)
Doubly violated stimuli	1.5 (2.1)

The error rate data showed a significant main effect for Derivational violation and a significant Derivational violation  $\times$  Inflectional violation interaction, as derivationally and doubly violated stimuli elicited fewer errors than correct stimuli. There were no differences in error rates between inflectionally violated and correct stimuli.

**Table 12.** Statistically significant main effects and interactions (F-test, degrees of freedom, p-value) of Study III

Factors	F-test, df, p-value
<i>1) Error rate data</i>	
Derivational violation	F(1,14) = 17.14, p < 0.001
Derivational violation $\times$ Inflectional violation	F(1,14) = 24.18, p < 0.001
<i>2) ERP results (450–550 ms)</i>	
Derivational violation $\times$ Region	F(2,28) = 4.23, p = 0.023
<i>3) ERP results (600–800 ms)</i>	
Derivational violation	F(1,14) = 4.72, p = 0.048
Inflectional violation	F(1,14) = 9.52, p = 0.008
Inflectional violation $\times$ Region	F(1,16) = 5.79, p = 0.024
Derivational violation $\times$ Inflectional violation $\times$ Region	F(2,28) = 3.59, p = 0.041
<i>4) ERP results (700–800 ms)</i>	
Derivational violation	F(1,14) = 8.66, p = 0.01
Inflectional violation	F(1,14) = 6.51, p = 0.023
Derivational violation $\times$ Region	F(1,28) = 6.9, p = 0.006
Inflectional violation $\times$ Region	F(1,18) = 5.69, p = 0.025
Derivational violation $\times$ Inflectional violation $\times$ Region	F(2,28) = 5.84, p = 0.008

The ERP data showed that a Derivational violation  $\times$  Region interaction reached significance in the 450–550 ms time window, since the derivationally violated stimuli showed a larger centro-parietal negativity than correct stimuli. The Inflectional violation  $\times$  Region interaction was marginally significant, but pair-wise comparisons showed that inflected stimuli elicited a significantly larger anterior negativity than the correct stimuli (Figure 6).

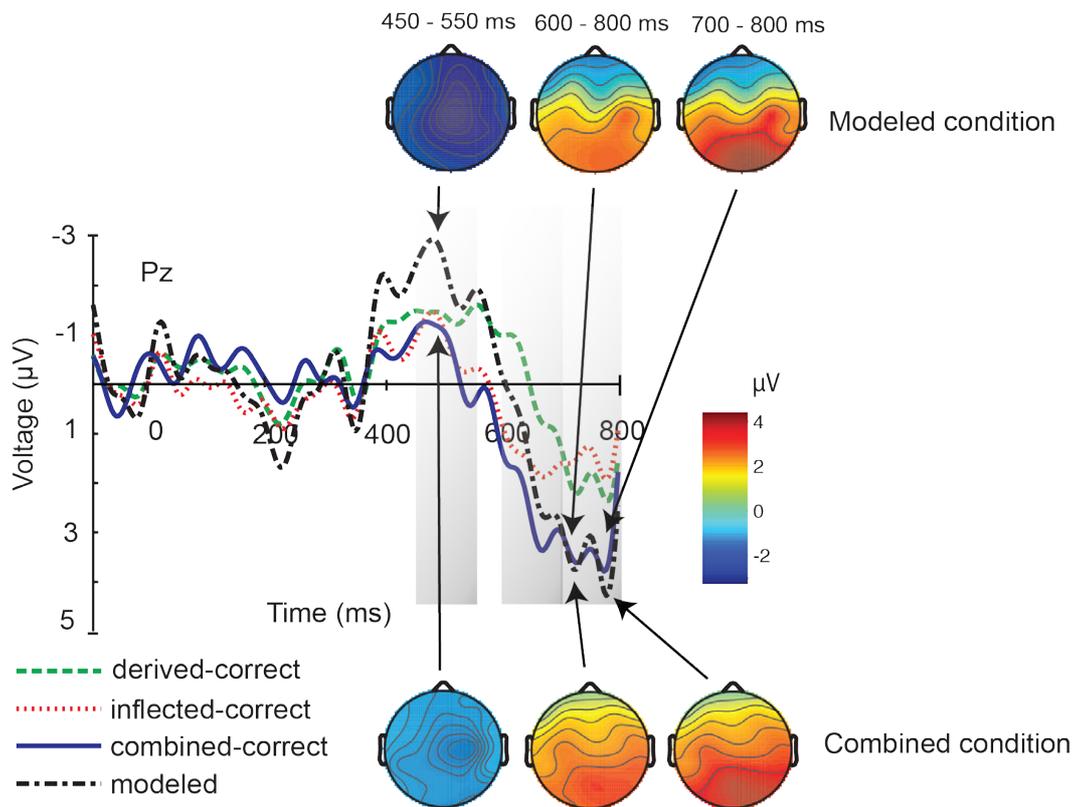


**Figure 6.** A) Grand average ERPs from electrodes Fz and Pz to correct stimuli (solid line), inflectionally violated (dotted line), derivationally violated (dashed line) and doubly violated stimuli (alternating dashed/dotted line), after baseline correction in the 100 ms pre-stimulus interval. Time 0 is the onset of the critical stimulus. The X-axis represents time (milliseconds), the Y-axis depicts voltage (microvolts,  $\mu\text{V}$ ). B) Grand average topographical maps of the 450–500 ms, 600–800 ms and 700–800 ms after critical word onset. Maps are based on difference waveforms resulting from subtracting the correct condition from the mean amplitude in the time windows of grand average ERP for the derivational, inflectional, and combined violations. Modified from Leinonen, A., Brattico, P., Järvenpää, M., Krause, C.M. (2008). Event-related potential (ERP) responses to violations of inflectional and derivational rules of Finnish. *Brain Research*, 1218, 181-193, (Study III).

In the 600–800 ms time window, there were significant main effects for Derivational violation, Inflectional violation, and the interaction between Inflectional violation and Region. The interaction of Derivational violation  $\times$  Inflectional violation  $\times$  Region was also significant. That is, derivational, inflectional, and combined violations elicited a larger positivity effect than correct stimuli, and in the inflectional and combined violation conditions this positivity was parietally distributed.

Finally, in the 700–800 ms time-window, there was a significant main effect for Derivational violation and a significant Derivational violation  $\times$  Region interaction, since derivationally violated stimuli elicited a larger parietal positivity effect than correct stimuli. In addition, there was a significant main effect for Inflectional violation and a significant interaction between Inflectional violation and Region, with inflectionally violated stimuli eliciting a parietally distributed positivity. The doubly violated stimuli also elicited a parietal positivity, seen in the significant interaction between Derivational violation and Inflectional violation and Region.

Furthermore, the linear sum for the P600 effects showed no differences between the observed and modeled mean amplitudes either in the 450–550 ms, 600–800 ms or 700–800 ms time windows, showing that the effects in the combined violation condition were additive (Figure 7).



**Figure 7.** Observed difference wave from electrode Pz to inflectional and derivational violations ([inflectional violation minus correct], [derivational violation minus correct]), combined violation (combined minus correct), and the modeled difference wave calculated as the sum of the difference waves for each single violation ([derivational violation minus correct] + [inflectional violation minus correct]). (above the ERP waveform): Observed topographical maps to combined violation (combined minus correct) (below the ERP waveform): Modeled topographical maps calculated as the sum of the difference waves for each single violation ([derivational violation minus correct]+[inflectional violation minus correct]) for the time windows of 450–550 ms, 600–800 ms and 700–800 ms. Modified from Leinonen, A., Brattico, P., Järvenpää, M., Krause, C.M. (2008). Event-related potential (ERP) responses to violations of inflectional and derivational rules of Finnish. *Brain Research*, 1218, 181-193, (Study III).

## 5.4 Spatiotemporal dynamics of spoken derived and inflected words (Study IV)

Table 13 demonstrates the mean RTs and error rates in Study IV. Table 14 depicts the statistically significant main effects and interactions for the behavioral and ERP data in Study IV. The error rate data showed the significant main effect for Condition, seen as higher error rates for inflected words than for monomorphemic and derived words. The RT data<sup>1</sup> measured from the critical point showed a significant main effect for Condition. According to post-hoc tests, both inflected and derived words elicited longer RTs than monomorphemic words, but no differences in RTs were found between inflected and derived words. The stimulus onset ERP data showed a significant main effect of Condition and a significant interaction for Condition and Anterior-Posterior Axis in the 700–780 ms time-window. Post-hoc tests confirmed that inflected words elicited a larger centro-parietal negativity than monomorphemic and derived words.

**Table 13.** Mean RTs (SD) and error rates (SD) in Study IV

Stimulus type	RT measured from the critical point (ms)	Error rate (%)
Monomorphemic words	671 (176)	2.8 (2)
Inflected words	769 (168)	6.2 (3.1)
Derived words	729 (190)	4.1 (2.8)

The critical point time-locked ERP data showed that, inflected words elicited a larger left-lateralized negativity than monomorphemic and derived words in the 190–230 ms time window, when the interactions between Condition  $\times$  Anterior-Posterior Axis and Condition  $\times$  Laterality reached significance at the lateral electrodes (Figure 8). In the 170–210 ms time-window, the interactions between Condition  $\times$  Anterior-Posterior Axis and Condition  $\times$  Laterality were significant at the lateral electrodes. At the midline electrodes, the main effect for Condition and the Condition  $\times$  Site interaction were significant. These lateral and midline effects were due to a smaller negativity for derived words than for monomorphemic words at all electrode sites.

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<sup>1</sup> The RTs are rather suggestive, since the participants were explicitly instructed to judge the words as acceptable/unacceptable as accurately as possible, but not as quickly as possible.

**Table 14.** Statistically significant main effects and interactions (F-test, degrees of freedom, p-value) of Study IV

<b>Factors</b>	<b>F-test, df, p-value</b>
<i>1) Error rate data</i>	
Condition	F(2,18) = 9.69, p = .001
<b>EEG</b>	
<i>2) ERP results, lateral electrodes (700–780 ms)*</i>	
Condition	F(2,18) = 5.64, p = .013
Condition × A-P Axis	F(4,36) = 4.14, p = .024
<i>3) ERP results, midline electrodes (700–780 ms)*</i>	
Condition	F(2,18) = 4.95, p = .04
<i>4) ERP results, lateral electrodes (170–210 ms)**</i>	
Condition × A-P Axis	F(4,36) = 4.18, p = .038
Condition × Laterality	F(6,54) = 4.44, p = .016
<i>5) ERP results, midline electrodes (170–210 ms)**</i>	
Condition	F(2,18) = 3.91, p = .039
Condition × Site	F(4,36) = 3.8, p = .011
<i>6) ERP results, lateral electrodes (190–230 ms)**</i>	
Condition × A-P Axis	F(4,36) = 4.37, p = .027
Condition × Laterality	F(6,54) = 3.2, p = .04
<i>7) ERP results, midline electrodes (190–230 ms)**</i>	
Condition × Site	F(4,36) = 3.3, p = .042
<b>MEG</b>	
<i>1) Source amplitudes, (Source pattern 1), 80–120 ms, Right hemisphere**</i>	
Condition	F(2,14) = 5.4, p = .018
<i>2) Source amplitudes (Source pattern 2), 170–210 ms, Left hemisphere**</i>	
Condition	F(2,12) = 3.9, p = .049
<i>3) Source amplitudes (Source pattern 2), 190–230 ms, Left hemisphere**</i>	
Condition	F(2,12) = 3.95, p = .048

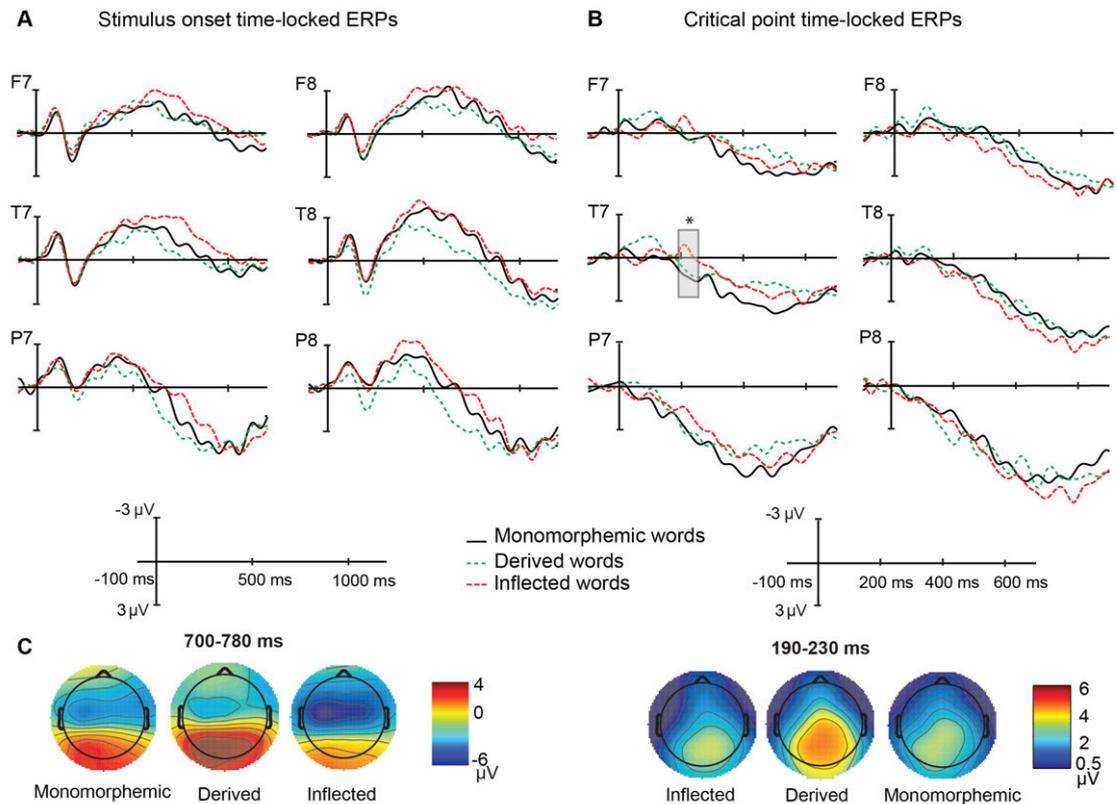
\*after the stimulus onset, \*\* after the critical point

In the critical-point time-locked MEG data, the overall magnetic flux at ~0–150 ms after the critical point showed similar stable flux patterns across conditions. However, the magnetic flux pattern changed and stabilized at ~150 ms after the critical point (Figure 9). ECD modeling of the critical point time-locked MEG data revealed one bilateral source (2 dipoles) fitted into the 80–120 ms time-window (Source pattern 1). In the 170–210 ms after the critical point, the MEG activity was modeled by a bilateral pair of dipoles (Source pattern 2), in addition to Source pattern 1. All sources were localized to the temporal cortices (Figure 10).

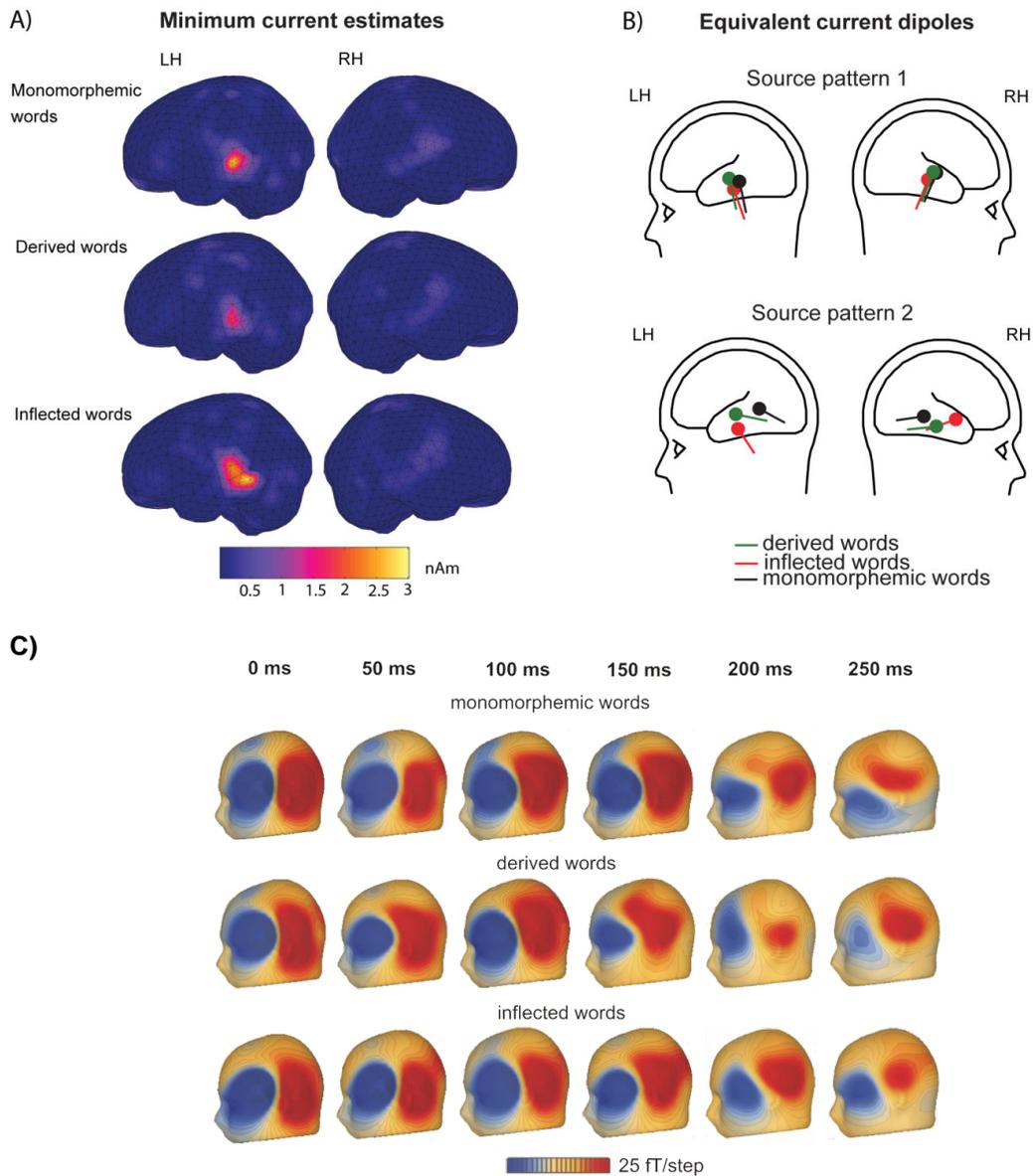
For Source pattern 1, there was a significant main effect for Condition in the right hemisphere, since derived words elicited larger source amplitudes than inflected and

monomorphemic words in the 80–120 ms time window. For Source pattern 2, the main effect for Condition reached significance in the 170–210 ms and 190–230 ms time-windows, as inflected words elicited larger source amplitudes than derived (but not monomorphemic) words in the left hemisphere (Figure 11). The results from the minimum current estimates also showed predominance of the left temporal area in the 170–210 ms time-window after the critical point (Figure 9).

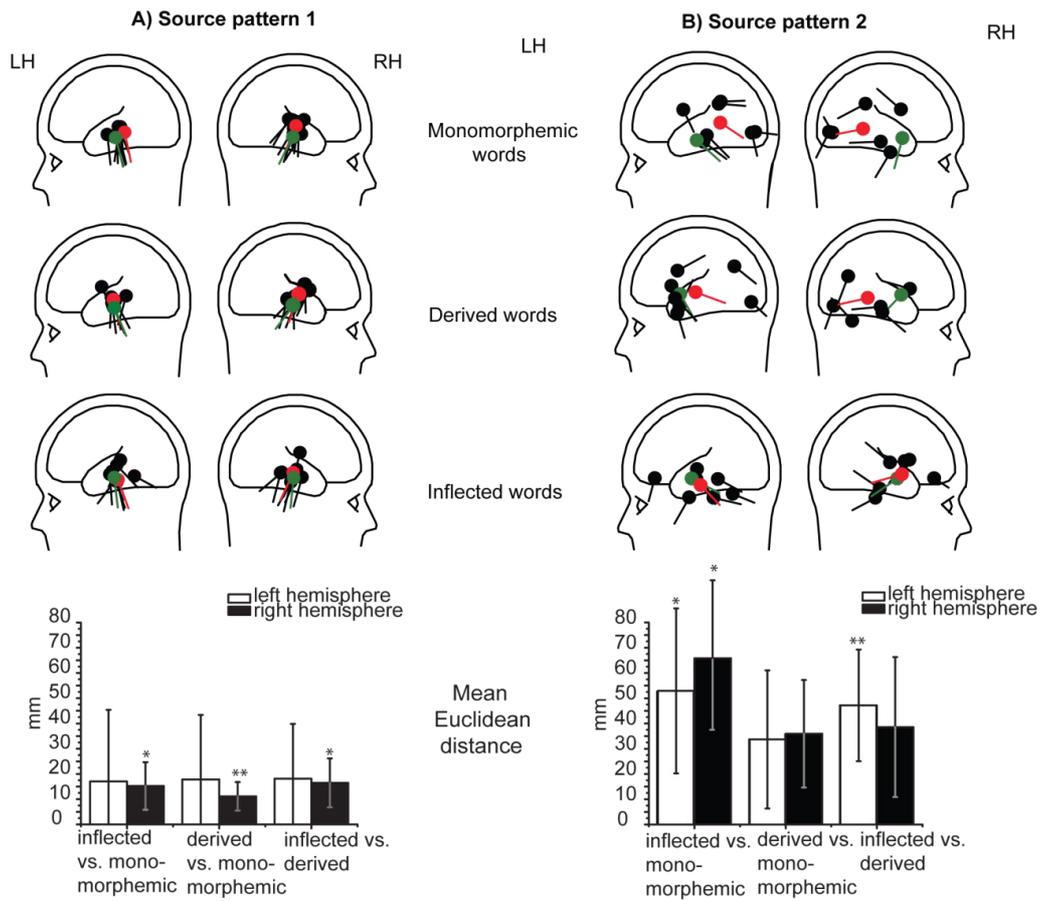
To investigate the differences in dipole locations between the conditions, Euclidean distances (ED) were calculated and tested against the baseline of zero millimeters. ED analysis showed that for Source pattern 1, there were significant differences in dipole locations in the right hemisphere between inflected and derived words, derived and monomorphemic words, as well as monomorphemic and inflected words (Figure 10). For Source pattern 2, in the left hemisphere, there were significant differences in dipole locations between inflected vs. derived words and between inflected vs. monomorphemic words. In the right hemisphere, there were significant differences only between inflected and monomorphemic words (Figure 10).



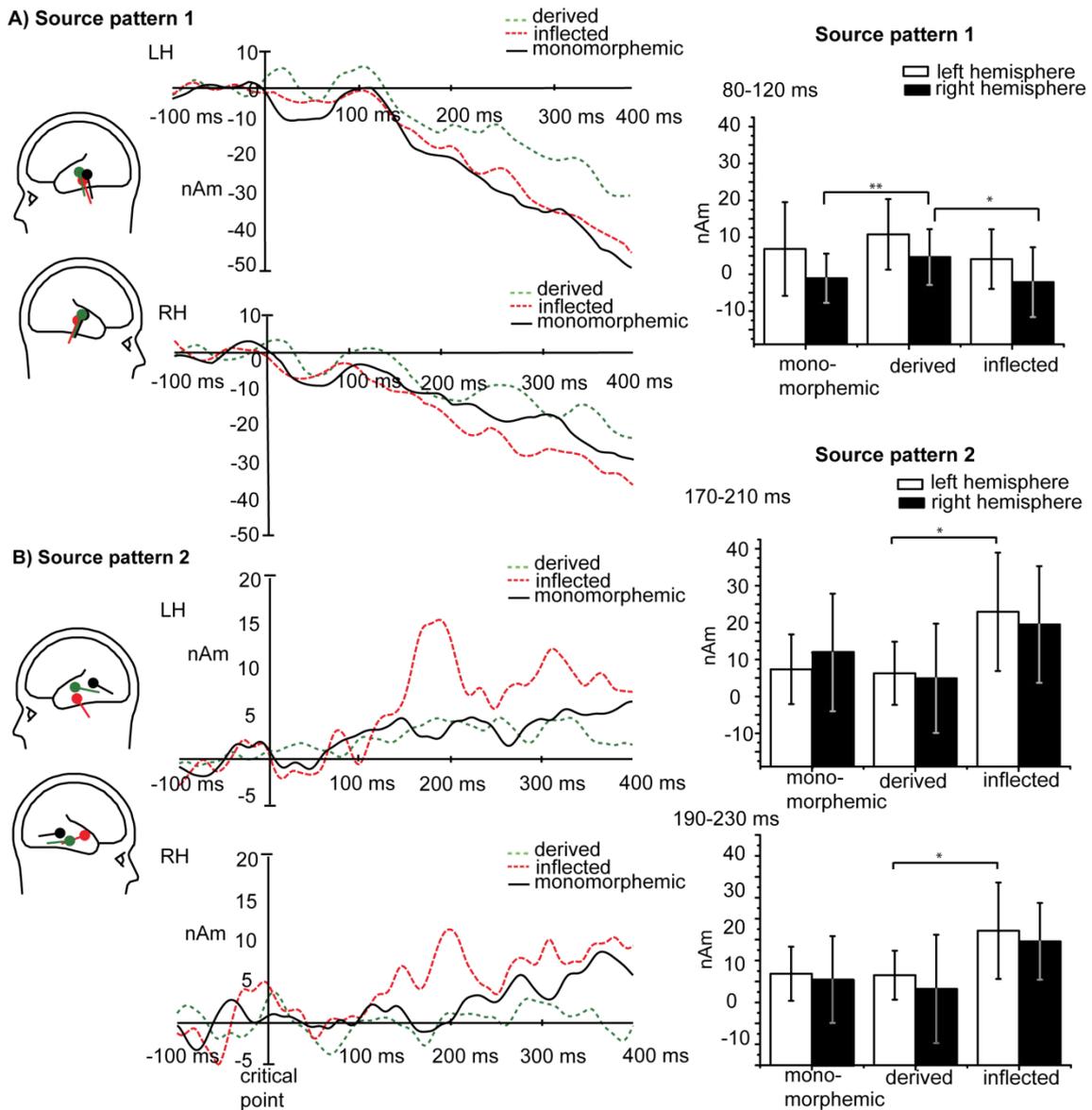
**Figure 8.** (above) Grand average (10 participants) ERPs from 6 electrodes (F7, F8, T7, T8, P7, P8) A) time-locked to the stimulus onset, and B) time-locked to the critical point (i.e., uniqueness point for monomorphemic words; suffix onset for affixed words). The lines represent ERPs to monomorphemic words (black solid line), derived words (green dotted line) and inflected words (red dashed line). Baseline is corrected in the -100 0 ms interval A) before the stimulus onset B) before the critical point. Time 0 is the onset of the stimulus. Negative polarity is plotted upwards. The X-axis represents time (milliseconds), the Y-axis depicts voltage (microvolts,  $\mu\text{V}$ ). The time interval in which significant differences between conditions were observed is marked with a square ( $*p < 0.05$ ). C) Grand average topographical maps for A) the 700–780 ms time-window after the stimulus onset and B) the 190–230 ms time-window after the critical point. Modified from Leminen, A., Leminen, M., Lehtonen, M., Nevalainen, P., Ylinen, S., Kimppa, L., Sannemann, C., Kujala, T., Mäkelä, J. (2011). Spatiotemporal dynamics of the processing of spoken inflected and derived words: a combined EEG and MEG study, *Frontiers in Human Neuroscience*, 5, 1-14 (Study IV).



**Figure 9.** A) Grand average minimum current estimates (MCE) averaged across 10 subjects calculated in the 170–210 ms time-window after the critical point. B) Mean dipole locations for Source patterns 1 and 2 for inflected, derived, and monomorphemic words in the left and right hemispheres are depicted as red, green, and black dipoles respectively. C) Grand average magnetic flux patterns for monomorphemic, derived, and inflected words for 0–250 ms after the critical point presented in 50 ms time steps (magnetic flux density 25 fT/step). Blue indicates magnetic flux directed into the brain (negative flux), while red shows flux directed out of the brain (positive flux). Modified from Leminen, A., Leminen, M., Lehtonen, M., Nevalainen, P., Ylinen, S., Kimppa, L., Sannemann, C., Kujala, T., Mäkelä, J. (2011). Spatiotemporal dynamics of the processing of spoken inflected and derived words: A combined EEG and MEG study, *Frontiers in Human Neuroscience*, 5, 1-14 (Study IV).



**Figure 10.** (Above) Individual subject dipole locations (black) for A) Source patterns 1 (80–120 ms after the critical point) and B) Source pattern 2 (170–210 ms after the critical point) in the left and right hemisphere for monomorphemic, derived, and inflected words. Mean source locations and grand average (10 subjects) locations are displayed as red and green dipoles respectively. (Below) Mean Euclidean distance (columns) and standard deviations (error bars) in millimeters between conditions for Source pattern 1 (left) and Source pattern 2 (right). Asterisks display significant differences between conditions against the baseline of 0 mm (\*\* =  $p < .01$ ; \* =  $p < .05$ ). Modified from Leminen, A., Leminen, M., Lehtonen, M., Nevalainen, P., Ylinen, S., Kimppa, L., Sannemann, C., Kujala, T., Mäkelä, J. (2011). Spatiotemporal dynamics of the processing of spoken inflected and derived words: A combined EEG and MEG study, *Frontiers in Human Neuroscience*, 5, 1-14 (Study IV).



**Figure 11.** Grand average ECD source waveforms for the critical point time-locked MEG data. (Middle) A) Source pattern 1 is depicted above and B) Source pattern 2 below, in the left and right hemisphere for monomorphemic, derived, and inflected words. (Right) Mean source amplitudes (columns) and standard deviations (error bars) for monomorphemic, derived, and inflected words for Source pattern 1 and Source pattern 2. Asterisks display significant differences in source amplitudes between conditions (\*\* =  $p < .01$ ; \* =  $p < .05$ ). (Left) Mean dipole locations for inflected, derived, and monomorphemic words in the left and right hemispheres are depicted as red, green, and black dipoles respectively. Modified from Leminen, A., Leminen, M., Nevalainen, P., Lehtonen, M., Ylinen, S., Kimppa, L., Sannemann, C., Kujala, T., Mäkelä, J. (2011). Spatiotemporal dynamics of the processing of spoken inflected and derived words: A combined EEG and MEG study, *Frontiers in Human Neuroscience*, 5, 1-14 (Study IV).

## **6 Discussion**

The present thesis explored the neurocognitive processing of inflected and derived words. More specifically, four topics were addressed: 1) how written and spoken inflected words are processed in the brain, 2) the time-course of the neural processing of spoken derived words, 3) the interaction between the neural processes of inflection and derivation in sentence contexts, and 4) the spatiotemporal dynamics of the neural processing of spoken inflected and derived words. The main finding was that at the cortical level, inflected and derived words are processed differently, indexed by the differences in ERP effects and by the differences in activation of neural sources (MEG evidence). The results suggest that both written and spoken inflected words are decomposed into their morphological constituents, whereas for spoken derived words both morpheme-based and full-form processing seems to be activated. The implications of Studies I–IV are discussed in detail below.

### **6.1 Neurocognitive processing of written and spoken inflected words**

The neurocognitive processing of written and spoken correctly inflected single words vs. monomorphemic words were investigated using EEG in Study I. The results revealed that at the behavioral level, both spoken and written inflected words elicited longer RTs and higher error rates than monomorphemic words (Experiments 1 and 2). These results are in line with several previous findings with Finnish inflected words, which have suggested that longer RTs and higher error rates reflect morphological decomposition of Finnish inflected words (Bertram et al., 1999; Laine & Koivisto, 1998; Laine et al., 1999b; Lehtonen & Laine, 2003; Niemi et al., 1994; Soveri et al., 2007). The behavioral results from Experiment 2 are in line with Experiment 1, suggesting that both spoken and written inflected words show a morphological processing cost during their recognition.

The ERP results in Experiment 1 showed that the differences between inflected and monomorphemic words started to emerge approximately 300 ms after stimulus onset,

showing a larger N400-type negativity for the processing of written inflected words as compared to monomorphemic words. The results of Experiment 2 showed that spoken inflected words also elicited a larger long-lasting and widespread N400 than monomorphemic words. The duration of the processes reflected in the N400 was relatively similar in both the visual and auditory experiments, suggesting a uniform morphological processing in both modalities. It should be noted that in Study IV, stimulus onset time-locked inflected words also elicited a larger centro-parietal N400 than monomorphemic words (the results of Study IV are discussed in more detail in section 6.4). Overall, these results support previous ERP and MEG studies, which reported increased N400/N400m responses in association with the processing of written correctly inflected words pitted against matched monomorphemic words (Lehtonen et al., 2007; Vartiainen et al., 2009a). Although some recent MEG studies using visual stimuli have observed early morphological effects (< 200 ms after the stimulus onset) (Solomyak & Marantz, 2010; Zweig & Pylkkänen, 2008), the differences between monomorphemic and complex words were not observed earlier than 300 ms in Study I (see also Lehtonen et al., 2007; Vartiainen et al., 2009a). These earlier effects (< 200 ms) were thought to reflect obligatory pre-lexical decomposition of morpheme constituents (Solomyak & Marantz, 2010).

Recent studies have suggested that the N400 effect might reflect lexical access (Lau et al., 2009; Lau et al., 2008) and, possibly, semantic integration processes (Hagoort, 2005; Lau et al., 2008). The N400 might also reflect the dynamic creation of a conceptual representation in a multimodal long-term memory system and may thus be affected both by factors influencing the feedforward processes of the stimulus input (e.g., orthographic neighborhood), as well as those having an impact on the state of the semantic system (e.g., attention) (Kutas & Federmeier, 2011). As the lexical decision task can be sensitive to both lexical and post-lexical factors (Balota & Chumbley, 1984), the larger N400 effects observed for inflected words in Study I might reflect a dynamic lexical-semantic access process and possible integration of the morphemes. The observed larger N400 for inflected than for monomorphemic words, in combination with the behavioral findings (longer RTs and higher error rates), support previous findings in Finnish that composition/integration of the morphological constituents causes more costly processes at the semantic-syntactic stages of complex word

recognition (Hyönä & Laine, 2002; Lehtonen et al., 2007; Lehtonen et al., 2006b; Vartiainen et al., 2009a).

In addition to existing words, Study I examined the neurocognitive processing of inflected pseudowords consisting of pseudostems and real suffixes pitted against “monomorphemic” pseudowords. The aim was to assess whether an existing stem is required for initiating decompositional processes, since previous findings on this issue are rather inconsistent (Laine, 1996; Lehtonen et al., 2007; Lehtonen et al., 2006b). In the visual modality, pseudowords elicited larger N400 effects than existing words (lexicality effect). However, no such lexicality effect was observed in the auditory modality. In the auditory modality, the rejection of unsuitable lexical candidates might be easier when the stimulus unfolds gradually, in contrast to the situation when the whole pseudoword is presented at once. Alternatively, activation of the lexical candidates, reflected by the N400, might be distributed over a longer period of time, indexed by a smaller N400 for pseudowords. Importantly, in inflected pseudowords, a morphological processing cost was not observed in either the visual or auditory modality. Inflected pseudowords did not elicit higher error rates, longer RTs or larger N400 amplitudes than monomorphemic pseudowords. These results are in line with those previous findings, which did not observe significant differences in error rates, RTs, or ERPs between visual monomorphemic pseudowords and inflected pseudowords composed of a non-existent stem and a real suffix (Lehtonen et al., 2007). The current results thus suggest that only inflected forms with an existing stem initiate morphological decomposition, regardless of the stimulus modality. At least in the lexical decision task, the recognition of a stem as a pseudoword seems to halt further morphological processing of an inflected pseudoword. This result gives further support to previous findings that lexical-semantic access is governed by the stem irrespective of its position in a phrase or word (Laine, 1999; Laine et al., in preparation).

## **6.2 Neurocognitive processing of derived words**

One central aim of the present thesis was to investigate the neural processing of derived stimuli (Studies II–IV). In Study II, derivationally correct and incorrect word forms were presented to the participants auditorily, whereas in Study III derived word forms

were presented visually embedded in sentence contexts. In Study IV, correctly derived words were presented auditorily in word lists, and their neural sources were investigated using MEG recordings.

Study II investigated the time-course of the neural processing of spoken derived words and pseudowords by simultaneously recording behavioral data and ERPs. In the auditory stimuli, the suffix-related information becomes available only after the stem, possibly giving a head start to morphological decomposition. Furthermore, in order to separate the ERP effects related to the processing of a base morpheme and suffix, the ERP responses were time-locked to both the stimulus and the suffix onset. The stimuli included existing derived words as well as legal and illegal derived pseudowords. The results showed that legal derived pseudowords elicited higher error rates and longer RTs than existing words and illegally derived pseudowords. This suggests that their high interpretability (as verified by a paper-pencil pretest) made them harder to reject as non-words than illegal pseudowords (Burani et al., 1999; Meunier & Longtin, 2007; Wurm, 2000). The ERP results showed that there were no differences in the magnitude of the widespread negativity (elicited in the 274–314 ms time-window after the suffix onset, resembling an N400) between existing words and legal pseudowords. Thus, despite the fact that there was no existing full-form lexical representation for these pseudowords, their word-likeness and high interpretability affected the ERP responses, suggesting successful decomposition of the morpheme combination (for similar findings with written prefixed derived pseudowords, see McKinnon et al., 2003). The lack of differences in ERPs between existing derived words and legal derived pseudowords may further imply that existing derived words also have a preserved marking of morphological structure (Bozic & Marslen-Wilson, 2010; Clahsen et al., 2003; Marslen-Wilson, 2007).

In contrast to legal derived pseudowords, derived pseudowords with an illegal stem+suffix combination in Studies II and III elicited a larger negativity than correctly derived words. In Study II, spoken illegal pseudowords elicited a larger, widespread negativity ~300 ms after the suffix onset. In Study III, visual incorrectly derived stimuli showed a larger, centro-parietal negativity than correct stimuli ~500 ms after the stimulus onset. Both responses resemble the N400-type negativity by their latency (Study III) and/or topography (Studies II and III). Auditory N400 effects may be more

frontally or evenly distributed across the scalp, as compared to visual N400s, where a clearer centro-parietal maximum is observed (Hinojosa et al., 2001; Kutas & Federmeier, 2000; Kutas & Federmeier, 2011). The N400-like negativities for illegally derived words in Studies II and III might reflect difficulty with the semantic integration of the morpheme combination and/or detection of a mismatch between the stem and suffix (Bölte et al., 2009b; Janssen et al., 2006). Furthermore, as the ERPs in Study II were time-locked to the onset of the derivational suffix, it was possible to monitor the time-course of morphological processing more precisely. The widespread negativity elicited during the processing of illegal pseudowords began to increase shortly after the deviation point. The increased N400-like negativity elicited at ~100 ms after the deviation point may reflect morphological analysis, including an attempt to integrate the constituent morphemes semantically. In the case of legal pseudowords, the morpheme combination is semantically compatible, which may have affected the successful analysis of novel root+suffix combinations.

Recent studies have raised the question of what factors are relevant at the later stages of morphological processing: semantic interpretability or grammaticality (Burani et al., 1999; Meunier & Longtin, 2007)? What factors can explain the lack of overt priming between the illegal derived pseudoword and its stem and the existence of priming between the legal derived pseudoword and its stem (Meunier & Longtin, 2007)? In Studies II and III, the stem+suffix category violation of a derived form was indexed by the increased N400-like effect. The results especially from Study II suggest that the licensing/integration of these illegally derived stimuli may not have been successful. This also suggests that semantic interpretability seems to have a crucial role in successful analysis of derived forms. The evidence for this assumption comes from an increased N400 effect to illegally derived stimuli and no differences in the N400 amplitude between existing derived words and legally derived pseudowords.

Study IV examined the neural processing of existing derived words pitted against monomorphemic words. It was of interest to elucidate the processing of existing derived words further: do they undergo simultaneous full-form access and morpheme-based activation or are they accessed solely in their full form? There were no differences in ERP effects between derived and monomorphemic words. However, MEG source analysis showed larger source amplitudes for derived words than for monomorphemic

and inflected words in the right hemisphere ~100 ms after the critical point. There were also significant differences in source locations between monomorphemic and derived as well as inflected and derived words. These differences suggest that in addition to the full-form activation, existing derived words may at least initially activate their suffixes, and, perhaps, suffix allomorphs. This assumption is compatible with the view that derived words have stored full-form representations but have also the preserved marking of their morphological structure (Bozic & Marslen-Wilson, 2010; Clahsen et al., 2003; Marslen-Wilson, 2007). As briefly mentioned above, the possible preserved marking of morphological structure in derived words might also explain the lack of electrophysiological differences between existing derived words and legal derived pseudowords in Study II, since the morphemes are activated in both stimulus types. Nevertheless, the processing of legal pseudowords seems to require additional analysis as compared to existing words, indexed by the lack of differences in the magnitude of the N400-type negativity between legal and illegal derived pseudowords.

### **6.3 On the interaction between derivational and inflectional processes**

Studies I, II, and IV investigated the neural processing of morphologically complex words presented in isolation. The agglutinative nature of Finnish means that derived words frequently appear in an inflected form (Vannest et al., 2002). Moreover, inflected words are rarely presented without a sentence context. In order to address these issues, Study III was designed to examine the neural processing of inflected and derived forms embedded in sentence contexts and whether their underlying neural mechanisms are interactive or independent. The ERP results showed that derivationally violated stimuli elicited a larger N400, whereas inflectionally violated stimuli elicited an anterior negativity (AN) in the 450–550 ms time-window after the stimulus onset. These observations are in line with the previous findings reporting the N400 in association with the processing of derivational stem+affix category violations (Janssen et al., 2006). The findings are also in line with those studies which reported (left) anterior negativities elicited during the processing of stimuli with agreement violations (Linares et al., 2006; Newman et al., 2007). Additionally, derivationally, inflectionally, and doubly violated

stimuli elicited a posterior positivity, the P600, which has been observed during the processing of inflected stimuli presented in sentences (Allen et al., 2003; Lück et al., 2006; Morris & Holcomb, 2005; Rodríguez-Fornells et al., 2001; Roll et al., 2010) and in isolation (Lehtonen et al., 2007; Morris & Holcomb, 2005). The P600 might reflect combinatorial reanalysis of the violated inflected and derived stimuli (Friederici & Weissenborn, 2007; Morris & Holcomb, 2005).

The combined violation showed a parietal positivity, the magnitude of which approximated the linear sum of the P600 in the single derivational and inflectional violation conditions. This suggests that the mechanisms underlying inflectional and derivational processes do not interact in the 600–800 ms and 700–800 ms time-windows but are initiated independently and possibly in parallel. In addition, in the 450–550 ms time-window, inflected and derived stimuli elicited distinct responses, i.e., (L)AN and N400 respectively. The additivity analysis showed that these responses approximated also a linear sum. Overall, these results suggest that during visual presentation of derivational and inflectional suffixes, the derived and inflectional suffixes are processed separately. Morphological parsing for real derived words with an inflectional suffix might proceed in a left-to-right manner by accessing the stem related information first (as shown in for instance, Study I, and Laine, 1999) and then retrieving the derivational and inflectional suffixes in parallel.

## **6.4 Spatiotemporal dynamics of spoken derived and inflected words**

The results from Study III suggested that visual inflectional and derivational processes are governed by independent neural mechanisms. Study IV directly compared the time-course and neural sources of spoken inflected and derived word processing. In contrast to Study III, inflected and derived words were presented in the auditory modality, in isolation, and contained no violation. Similarly to the results from Study I, the stimulus onset time-locked ERPs for inflected words in Study IV showed a larger centrally distributed negativity than other conditions, but this negativity was not lateralized. However, the precise ERP effects related to morphological processing are difficult to

disentangle relying only on average stimulus onsets, as this does not eliminate the variability in the suffix onsets due to the large number of stimuli with different stem durations used (Pulvermüller et al., 2009). Thus, in Study IV, the onset of the suffix for each spoken inflected and derived word (and the uniqueness point for monomorphemic words) was calculated precisely. This method allowed separation of the suffix-related effects from those related to the processing of the stem. For the critical point time-locked ERPs, an increased negativity was observed for inflected words as compared to derived and monomorphemic words, approximately 200 ms after the critical point. However, in contrast to the stimulus onset time-locked negativity, the critical point time-locked negativity was left lateralized and did not resemble the N400 effect. It is worth noting that the left-lateralized negativity observed in study IV is well in line with the finding in Study III, where inflected words were presented in declarative sentences, violating the morphosyntactic context. Previously, the LAN in association with inflectional processing has been proposed to reflect morphological structure building processes (Morris & Holcomb, 2005; Penke et al., 1997; Rodríguez-Fornells et al., 2001). The left-lateralized negativity in Study IV emerged in the absence of any sentence context and violation. If the LAN reflects combinatorial morphosyntactic structure building and, possibly, (morpho)syntactic licensing, this finding suggests that these processes may also take place during morphological processing of natural inflected stimuli.

The ECD modeling of the critical point time-locked MEG data of Study IV revealed one bilateral source in the superior temporal cortices (Source pattern 1) approximately 100 ms after the critical point. This activation of the superior temporal network during spoken word processing is in line with several previous MEG studies (Helenius et al., 2002; Pulvermüller & Shtyrov, 2009; Uusvuori et al., 2008; Vartiainen et al., 2009b). In general, the superior temporal network has been involved in accessing the meaning information from speech (Bozic et al., 2010; Tyler et al., 2005), choice among activated representations (Solomyak & Marantz, 2009), and the retrieval of lexical-syntactic information (Indefrey & Cutler, 2004). Source pattern 1 was localized highly systematically in all conditions, suggesting a process common to both morphologically simple and complex words. This process might consist of the mapping of incoming

phonological information onto stored meaningful units, which is reflected in the activity of the superior temporal cortices.

Furthermore, a bilateral middle/inferior temporal source was active approximately 200 ms after the critical point, in addition to the superior temporal source. The activity of the middle/inferior source was localized systematically only in the inflected word condition, reflecting a neural process possibly specific to inflected words. This source activity was stronger in the left hemisphere, where inflected words elicited larger source amplitudes than derived words. For the derived and monomorphemic words, there was considerable variability in source locations. In these conditions, the processes activating this source may be relatively small or even non-existent. This assumption is in accordance with a recent fMRI finding that derivational affixes in English do not selectively activate left-lateralized fronto-temporal areas in contrast to inflected words (Bozic & Marslen-Wilson, 2010; Bozic et al., 2009). This suggests that derivational affixes in English do not trigger decompositional processes in the same way as inflectional affixes (Bozic et al., 2009). Moreover, recent fMRI findings in Polish also show that only words with purely inflectional affixes elicit a coherent pattern of inferior-frontal activation, as compared to words with mixed derivation-inflection affixes, which elicit a heterogeneous pattern of activation (Szlachta et al., 2011). In Study IV, the activity of the middle/inferior temporal source was generated in the same time-window as the left-lateralized negativity in the critical point time-locked ERP data (190–230 ms), suggesting that this source activity was involved in generating the left-lateralized negativity. This is in accordance with previous studies, which have localized the LAN to the left temporal cortices (Friederici et al., 2000; Service et al., 2007). This systematic and temporally short-lived activity in the middle/inferior temporal cortices indicates that inflected words undergo morphosyntactic analysis of the morpheme combination, e.g., building a morphosyntactic frame in order to provide meaning for a morpheme combination. The simultaneous activation of the superior and middle/inferior temporal sources implies that lexical access and morphosyntactic licensing/structure building processes may be activated simultaneously and in parallel; suggesting continuous use of any relevant linguistic information as soon as it becomes available (Pulvermüller et al., 2009; Van den Brink & Hagoort, 2004).

All in all, the results from Study IV as well as from Study III suggest that derived and inflected words are processed differently in Finnish at the cortical level. These findings are in line with the previous behavioral data on Finnish written complex words (Niemi et al., 1994) as well as behavioral and hemodynamic evidence in other languages such as English and German (Bozic & Marslen-Wilson, 2010; Clahsen et al., 2003).

## **6.5 Theoretical considerations**

In general, the findings from Studies I, III, and IV with regard to inflected words are in line with hybrid models of morphological processing such as the IAR model (Schreuder & Baayen, 1995), the SAID model (Laine et al., 1994; Niemi et al., 1994), and with the Core Decompositional model (Marslen-Wilson & Tyler, 2007), as the current results provide further neurocognitive evidence for morphological decomposition of inflected words.

The current evidence is largely compatible with the Stem Allomorph/Inflectional decomposition (SAID) model of Finnish morphologically complex words (Laine et al., 1994; Niemi et al., 1994). However, this model does not make explicit predictions concerning the neural mechanisms of morphological decomposition. The findings of this thesis complement previous research compatible with the SAID model, particularly the findings concerning the neural processing of spoken inflected and derived words. Moreover, the current results converge with the previous findings on the recognition of visual inflected words as well as providing new evidence on the processing of written inflected and derived words in sentence contexts. In general, behavioral and neural evidence from Studies I, III, and IV confirms the assumption of the SAID model that most Finnish inflected words are decomposed into their morphological constituents during recognition, and most have no stored full-form representations. Morphological analysis of spoken inflected words was reflected in the ERPs by the N400 and LAN-type negativities. Additionally, the processing of spoken inflected words simultaneously activated two neural sources in the superior and middle/inferior temporal cortices. In the visual modality, the processing of isolated inflected words was indexed by the centro-

parietal negativity, whereas violating the morphosyntactic context elicited the (left) anterior negativity.

Furthermore, in line with the assumption of the SAID model, the results in the current thesis suggest that inflected and derived words are processed differently in the brain (Studies III and IV). The independence of the neural mechanisms of inflected and derived word processing was indexed by the distinct responses for the anomalous inflected and derived stimuli ((L)AN and N400) as well as by the linear summation of the P600 responses to inflectionally and derivationally violated stimuli in the combined violation condition (Study III). The results of Study IV provided additional evidence for the differential cortical processing of derived and inflected words. During the processing of derived words, a full-form representation is probably activated along with initial activation of the suffix representation. This would be in line with Core Decompositional model, which suggests that although the constituent morphemes of a derived form may be identified early in the processing, this may not lead to further combinatorial analysis of derived forms (Marslen-Wilson, 2007; Marslen-Wilson & Tyler, 2007). The current results also corroborate the assumption that inflections and productive derivations are both a result of combinatorial operations, but productive derivations also have stored entries (with preserved combinatorial structures) (Clahsen et al., 2003). In addition to being lexicalized and having less semantic transparency than inflected forms (Bozic & Marslen-Wilson, 2010), most derivational affixes in Finnish have more suffix allomorphs than structurally invariant inflectional suffixes (Järvikivi et al., 2006). These factors may complicate their decomposition and it might be rather effortful to parse a derivational form each time it is encountered (Vannest et al., 2002).

The results from Studies II and IV allow construction of a tentative model for the neurocognitive processing of (auditory) inflected and derived words. Morphological analysis would begin from the initial activation of phonological/orthographic features, after which incoming phonological information is mapped into stored meaningful representations. The base morpheme access is reflected in the activation of the superior temporal cortex and is seen as a sustained negativity in ERPs (resembling the N400). After base morpheme activation, the suffix begins to unfold. Most Finnish inflected words are not assumed to have full-form representations and, during suffix access, the processing of a decomposed morpheme combination may include evaluation of its

semantic-syntactic compatibility (Schreuder & Baayen, 1995). In the case of isolated words, morphological analysis processes may include building a morphosyntactic context in order to construct a proper meaning for a morpheme combination. These morphosyntactic processes are reflected in the left-lateralized negativity responses in ERPs, which seem to be generated in the cortical networks of the temporal lobe. On the other hand, if the lexical representation for the morpheme combination exists (as seems to be the case with the derived words), the full-form representation is activated along with the possible activation of the suffix and its allomorphs. If the full form is available then there may be no need for further analysis of the morphemes. This is seen as the smaller ERP responses and smaller activation in the cortical networks of the temporal lobe for the derived words than for the inflected words. Study II showed a widespread N400-like negativity for illegal derived pseudowords. Thus, when a novel derived form is encountered, it undergoes morphological decomposition, in which the semantic compatibility of the stem and suffix is crucial.

Regarding visual morphological decomposition, the results in Study I with the comparison of visual and auditory processing of inflected words indicate that a similar type of decomposition takes place for written inflected words, with latency differences (~300 ms delay) in the negativity being attributed to the gradual unfolding of auditory stimuli. These latency differences do not seem to be due to the differences in morphological processing but rather to the differences in the availability of information in the visual vs. auditory systems. In general, base morpheme-related information in visual inflected words seems to be accessed prior to suffix-related information (Laine, 1999) as indicated by the lack of a morphological processing cost for inflected pseudowords with a nonexistent stem in Study I.

## 6.6 Future directions

The results of Studies I and IV provide electrophysiological evidence on the morphological decomposition of inflected words. However, inflected words are rarely presented in isolation in naturalistic contexts. The issue of the spatiotemporal dynamics of neurocognitive processing of correctly inflected words should be further studied by embedding inflected words into sentence contexts. These neurocognitive processes could be studied more thoroughly by for instance, recording concurrently the EEG/MEG responses and eye-movements (for a methodological discussion, see Dimigen et al., 2011). Time-locking the ERP/ERF responses to eye-fixations and modeling neural sources of these responses should provide more exact information concerning the neural correlates of reading of inflected and derived stimuli.

In the current thesis, the N400-like negativity was observed in all studies in association with different tasks and stimuli. However, this negativity also varied in latency and topography between and within studies. Thus, the current thesis does not provide a conclusive answer to a question whether this negativity represents one N400 component or several, possibly overlapping, N400 components, belonging to the so-called N400 family of effects. An attempt towards a possible separation of stem access and suffix access-related negativities was made in Studies II and IV, by time-locking responses to the suffix onset. Future studies should investigate this issue further by modeling the sources of the N400 associated with different types of stimuli. For instance, the sources of the N400s associated with lexicality vs. morphological complexity effects could be distinguished by contrasting monomorphemic real words vs. pseudowords as well as monomorphemic vs. polymorphemic real words. If the effects for these different contrasts are best modeled by distinct or at least partially distinct neural sources, then it will be plausible to assume that different neural populations generate these N400 components.

As a methodological point, time-locking of the responses to the suffix onset and uniqueness point revealed temporal features of lexical and/or morphological processing in Studies II and IV. Thus, this method should be used in future studies on spoken complex words, and the (complex) uniqueness point could be determined even more

precisely using a method like the gating paradigm (Marcus & Frauenfelder, 1985). In this paradigm, the subjects are presented with words that are interrupted before their offset and the subject's task is to guess the identity of the full word. By varying the locus of the interruption, one can establish how much of the word must be heard for it to reach reliable recognition (Mattys, 1997).

Furthermore, the neural processing of inflected and derived forms differed on a general level in the current thesis. However, a further theoretically important question is whether these observed differences between the two word types are due to their functional role or to their stimulus characteristics (Gonnerman et al., 2007; McQueen & Cutler, 1998; Schreuder & Baayen, 1995). In other words, is their distinction due to the differences in their typical characteristics, such as semantic transparency, suffix productivity, or the degree to which a word-formation process alters meaning, rather than due to the grammar specification as against lexeme formation functions? Addressing this question could also distinguish between some psycho- and neurolinguistic models of morphological processing, such as the IAR (Schreuder & Baayen, 1995) vs. the SAID (Laine et al., 1994) or the Core Decompositional (Marslen-Wilson & Tyler, 2007) models. According to the IAR model, the processing of derived vs. inflected forms might differ due to the differences in their typical characteristics, such as semantic transparency. In addition, the distributed-connectionist models (Gonnerman et al., 2007; Joanisse & Seidenberg, 1999; Kielar & Joanisse, 2010, 2011; Mirkovic et al., 2011; Seidenberg & Gonnerman, 2000) might be able to explain the different effects for inflected and derived words by different form-meaning correspondences while assuming a single mechanism for processing both of them. On the other hand, the SAID model makes an explicit distinction between derived and inflected words with respect to the processing and representation. The Core Decomposition model proposes that both inflected and derived forms may be decomposed at the initial stages of processing, however, only inflected forms would be subject to further morphological analysis. Also according to Taft (2004, 2010), inflected words do not have their own lemma representations, as all functional information about them can be entirely generated from their constituents. On the other hand, affixed words whose function cannot be entirely predicted from its morphemic constituents, such as most derived words, need to be represented at the lemma level.

The results of Study III and Study IV suggested that different cortical processes govern the comprehension of derived and inflected words. However, the tasks used in these studies called direct attention to the stimuli, and thus, involvement of strategic factors on decomposition cannot be excluded. Therefore, the extent to which visual and auditory morphological decomposition is dependent on attention should be studied further, perhaps by manipulating the focus of visual and/or auditory attention (Leminen et al., in preparation).

Finally, the results from Study IV showed activated sources for inflected words, particularly in the left temporal cortex. Numerous hemodynamic studies (for a recent review, see Bozic & Marslen-Wilson, 2010) have observed activation in the inferior frontal areas during the processing of morphologically complex words. However, several MEG studies on morphological processing have reported activation in the temporal or occipito-temporal areas (Bölte et al., 2009b; Lehtonen et al., 2011; Solomyak & Marantz, 2010; Vartiainen et al., 2009a; but see Pulvermüller & Shtyrov, 2009). This discrepancy most probably stems from a methodological difference. A recent study directly contrasting the neural activation patterns revealed by fMRI and MEG during reading, with the same participants and tasks, found weaker frontal but stronger temporal effects in MEG than fMRI (Vartiainen et al., 2011). This suggests that MEG responses and fMRI BOLD signals are likely to have different generation mechanisms (Vartiainen et al., 2011). Future studies should further investigate the functional significance of the neural sources involved in the processing of inflected and derived words using a combination of neuroimaging methods, such as EEG and fMRI and/or EEG and transcranial magnetic stimulation (TMS). A more comprehensive view may provide further important information for understanding the neural mechanisms underlying these basic building blocks of language.

## 7 Conclusions

This thesis investigated the neural processing of visual and auditory morphologically complex words. The aim was to assess the similarities and differences in the processing and underlying neural mechanisms of inflected ('spot+s') and derived ('spot+less') words and to elucidate the effects of stimulus modality on complex word recognition. Overall, the results show differences in the neural processing of derived and inflected words. Both written and spoken inflected words elicited larger N400 effects than monomorphemic words. When time-locked precisely to the critical point (suffix onset for complex words and UP for monomorphemic words), the increased negativity for the inflected words was left lateralized, resembling the left anterior negativity (LAN). This negativity is likely to reflect lexical access to morphological constituents as well as syntactic-semantic analysis of the morpheme combination, suggesting that inflected words do not have stored full-form representations. Spoken derived words seem to initially activate their suffix-related information; however, differences from inflected words suggest that they also have a full-form representation. As soon as this representation is activated, there is no need for further combinatorial analysis of the morpheme combination. This is reflected in a smaller negativity for derived words than inflected words. The processing of spoken derived and inflected words shows that incoming speech material is mapped onto stored meaningful units as the speech unfolds temporally. This mapping is indexed by the sustained widespread N400-like negativity. As a methodological note, the method of time-locking the EEG/MEG responses to the point at which the critical information takes place, such as suffix onset and recognition point, was proved to be important in revealing the effects reflecting morphological and/or lexical access processes. When studying speech material consisting of several meaningful components, it is necessary to analyze the data directly from the onset of the critical information.

Taken together, this thesis shows that despite the fact that inflected and derived forms using the same formal operation, i.e., affixation, they are processed differently in the brain. Furthermore, inflection and derivation are governed by at least partially distinct and independent neuronal networks active in the temporal cortical areas.

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