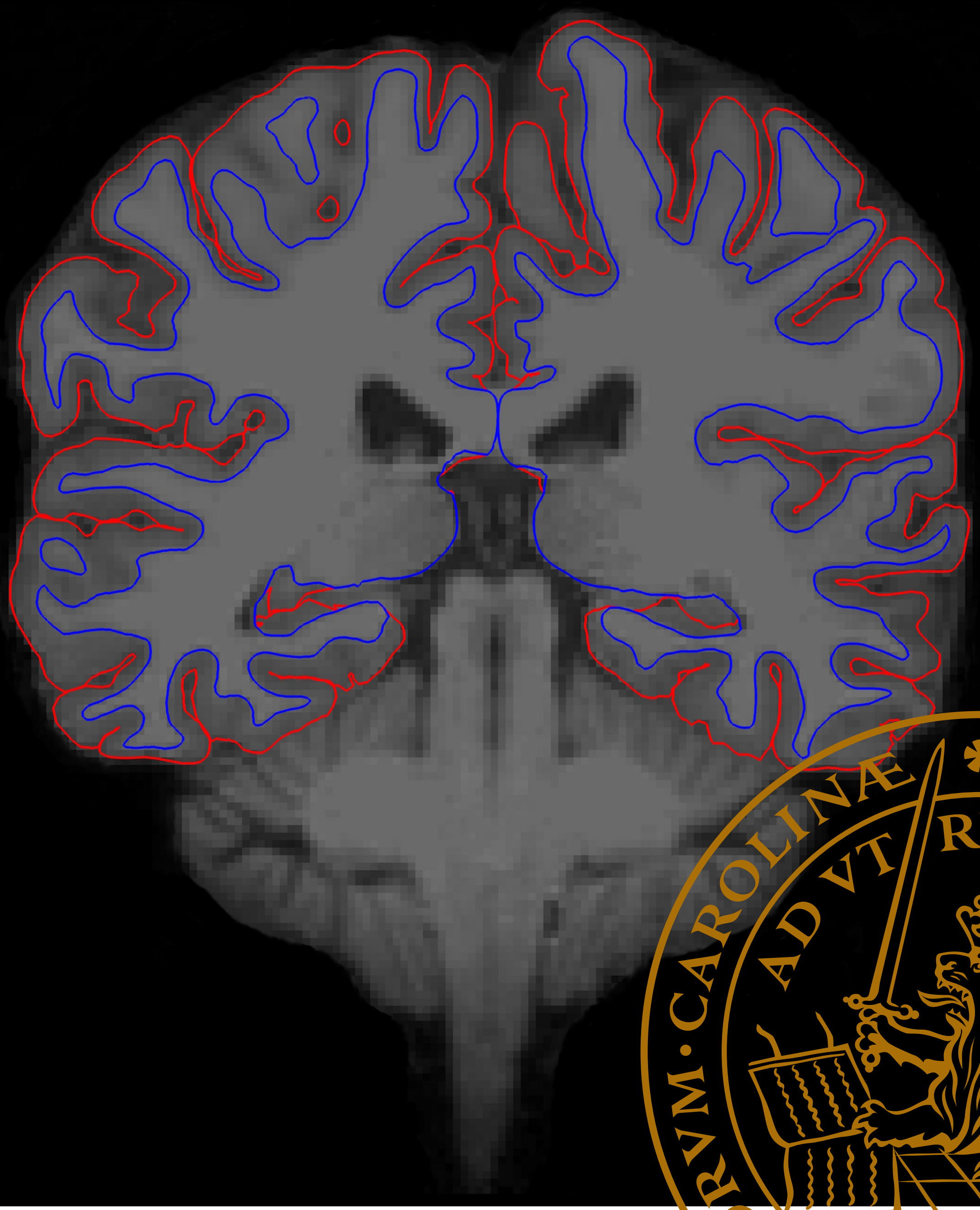
Cognitive and neural mechanisms of inflectional morphology processing

Studies of native speakers and second language learners of Swedish

ANDREA SCHREMM

CENTRE FOR LANGUAGES AND LITERATURE | LUND UNIVERSITY



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Abstract

The present dissertation investigates inflectional morphology processing in native speakers and second language (L2) learners of Swedish. Results of Study 1 suggest that two separate neural mechanisms might be available for native comprehension of inflected words, as reflected in event-related brain potentials obtained for visually presented verb forms. Overregularized verbs (e.g. **bär+de* ‘bear + past tense’) yielded a left anterior negativity (LAN), indicating decompositional processing of the regular tense inflection versus whole-word retrieval of correct irregular verb forms (e.g. *bär* ‘bore’). Enhanced long-range neural oscillatory phase synchrony observed for familiar irregular words potentially reflected increased engagement of the ventral language processing stream during whole-word access. As Swedish is characterized by a predictive association between specific word stem tones and upcoming suffixes, facilitating speech processing, Study 2 examines the integration of tonal cues into the native morphological system. Correlational analysis was conducted between cortical thickness in selected brain regions and individual participants’ response time patterns for suffix recognition following the tonal cue in real words (e.g. *hatt*$_{\text{Accent 1}}$*+en* ‘hat+sg’) and pseudowords (e.g. *kvut*$_{\text{Accent 1}}$*+en* ‘kvut+sg’). Results suggest that the left planum temporale might play a role when tones are accessed as part of whole-word memory representations, whereas the pars opercularis of the left inferior frontal gyrus could potentially support rule-based decompositional analysis of cued suffixes when no stored full-form representations are present. Study 3 focuses on the L2 acquisition of the tonal aspects of Swedish inflectional morphology. Response time patterns to inflected verbs indicate facilitated processing of word endings validly cued by the preceding stem tone in proficient L2 learners of Swedish, who had not received any explicit information about the tested L2 regularity. As these results suggested gradual and slow implicit acquisition of tone-suffix associations through exposure to L2 input, Study 4 explores possibilities of training the L2 feature at earlier stages of learning. Performance data collected during a two-week-period of training with a game prototype show gradually faster and more accurate responses to suffixes cued by preceding tones, indicating that low proficient learners start to integrate Swedish word accents into their L2 morphological processing system.

Key words: morphology, inflection, linguistic tone, ERP, cortical thickness, oscillatory phase synchrony, left anterior negativity, second language acquisition, response times, implicit learning, computer assisted learning

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Contents

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Abstract

The present dissertation investigates inflectional morphology processing in native speakers and second language (L2) learners of Swedish. Results of Study 1 suggest that two separate neural mechanisms might be available for native comprehension of inflected words, as reflected in event-related brain potentials obtained for visually presented verb forms. Overregularized verbs (e.g. **bär+de* ‘bear + past tense’) yielded a left anterior negativity (LAN), indicating decompositional processing of the regular tense inflection versus whole-word retrieval of correct irregular verb forms (e.g. *bär* ‘bore’). Enhanced long-range neural oscillatory phase synchrony observed for familiar irregular words potentially reflected increased engagement of the ventral language processing stream during whole-word access.

As Swedish is characterized by a predictive association between specific word stem tones and upcoming suffixes, facilitating speech processing, Study 2 examines the integration of tonal cues into the native morphological system. Correlational analysis was conducted between cortical thickness in selected brain regions and individual participants’ response time patterns for suffix recognition following the tonal cue in real words (e.g. *hatt*$_{\mathit{Accent\ 1}}$*+en* ‘hat+sg’) and pseudowords (e.g. *kvut*$_{\mathit{Accent\ 1}}$*+en* ‘kvut+sg’). Results suggest that the left planum temporale might play a role when tones are accessed as part of whole-word memory representations, whereas the pars opercularis of the left inferior frontal gyrus could potentially support rule-based decompositional analysis of cued suffixes when no stored full-form representations are present.

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List of original papers

Study 1

Schremm, A., Novén, M., Horne, M., & Roll, M. (manuscript). Brain responses to morphologically complex verbs: an electrophysiological study of Swedish regular and irregular past tense forms.

Study 2

Schremm, A., Novén, M., Horne, M., Söderström, P., van Westen, D., & Roll, M. (2018). Cortical thickness of planum temporale and pars opercularis in native language tone processing. *Brain and Language, 176*, 42-47.

Study 3

Schremm, A., Söderström, P., Horne, M., & Roll, M. (2016). Implicit acquisition of tone-suffix connections in L2 learners of Swedish. *The Mental Lexicon, 11*(1), 55-75.[1]

Study 4

Schremm, A., Hed, A., Horne, M., & Roll, M. (2017). Training predictive L2 processing with a digital game: Prototype promotes acquisition of anticipatory use of tone-suffix associations. *Computers & Education, 114*, 206-221.

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1. Introduction

The combinatorial nature of language underlies its unique expressive power. By arranging a limited set of building blocks into a practically unlimited number of combinations, language enables us to flexibly communicate meanings and even produce completely novel utterances (Chomsky, 1965; Jackendoff, 2003; von Humboldt, 1836). This combinatorial property is expressed across several levels of linguistic representation: phonemes are combined into morphemes; words are assembled into phrases, which are organized in turn to form sentences. In an attempt to understand the cognitive mechanisms and brain structures involved in such fundamental processes of language, research has often looked at the production and comprehension of complex word forms. The phenomenon the present thesis focuses on, inflectional morphology, has specifically been argued to capture important aspects of the general combinatorial property within the word level (Pinker, 1999). For example, regularly inflected words such as *walked* can be viewed as combinations of smaller building blocks, e.g. *walk* plus the past tense suffix *-ed*. The sequencing and choice of elements are clearly not arbitrary but appear to follow some underlying pattern, which might be expressed as rules. By contrast, many irregular words such as *went* seem to be simple word units rather than assemblies of morpheme parts. From this perspective, regularly inflected items could be produced and comprehended by combining the component parts "on the fly", based on some specific regularities, whereas irregular words would have to be retrieved in their full form from memory. The question whether these descriptive differences between the two types of word forms actually translate into two separate processing routes in the brain has constituted one of the core issues of psycholinguistic literature on language processing (e.g. Pinker & Ullman, 2002; Regel, Opitz, Müller, & Friederici, 2015).

A unique property of Swedish adds an extra dimension to the investigation of inflectional morphology processing. Thus, in Swedish, each prosodic word carries a tonal pattern, a so-called word accent. Even though word accents are realized on word stems, they are associated with specific suffixes attached to the stem (Riad, 2014; Rischel, 1963), which enables native speakers to anticipate possible upcoming endings already as they hear the beginning of the word (Roll, 2015; Roll, Horne, & Lindgren, 2010; Roll, Söderström, & Horne, 2013; Roll et al., 2015; Söderström, Horne, & Roll, 2016b; Söderström, Roll, & Horne, 2012). Such endings include inflectional suffixes, a fact which makes word accents an important part of Swedish inflectional morphology. Still, it is unclear how the interaction between tones signaling upcoming suffixes and the morphological processing system is implemented during on-line language comprehension in a way that enables predictive speech processing. Furthermore, the fact that the word accent-suffix association is largely unique to Scandinavian languages raises another important question: the acquisition of this feature by second language (L2) learners of Swedish. It is as yet not known whether adult L2 learners can integrate tonal information into their L2 morphological processing system and use word accent cues predictively. A related issue concerns the nature of the learning mechanisms that might facilitate L2 acquisition of word accent-suffix associations, which in turn carries important practical implications for effective L2 training strategies.

The present thesis investigated inflectional morphology processing in native speakers and L2 learners of Swedish. The first aim was to establish the nature of the processing routes available to native speakers for the comprehension of complex word forms and to identify brain structures and mechanisms that enable the integration of word accents as predictive cues into this system. Next, we addressed the question as to whether L2 learners can acquire this unique property of Swedish inflectional morphology, i.e. the tone-suffix associations and their predictive use, and how the learning processes might be supported with training. Four empirical studies were carried out, using a range of methodological approaches. Electrical activity of the brain, i.e. electroencephalography (EEG), was recorded from Swedish native speakers in order to gain insights into modulation of online neural activity during the processing of different types of inflected word forms. Thickness of the cerebral cortex was also measured in magnetic resonance (MR) images, to identify neuroanatomical correlates of processes involved in using stem tones as cues to morphological structure. With L2 learners of Swedish, the main approach was the measurement of response times to complex word forms. Patterns of response latency and accuracy to word endings cued by tones shed light on the way with which tone-suffix associations are processed after longer or shorter exposure to the L2 and were used to evaluate the efficiency of focused training in the L2 feature using a digital game.

Study 1 examined the general processing mechanisms involved in the comprehension of inflected words, by recording EEG as Swedish native speakers read regular versus irregular verb forms. Event-related potentials (ERP) and neural oscillatory patterns, extracted from the EEG, were analyzed to establish whether regular morphological patterns would trigger decompositional analysis and if familiar irregular items would be accessed as stored whole word forms in memory. Study 2 introduced the dimension of word accents, employing auditory stimuli, and looked at the way word accents might interact with the two proposed processing routes for inflected word forms. Therefore, the reliance on tonal cues to facilitate suffix processing was examined in two contexts: in real words, where retrieval of stored memory representations might play a role, and in inflected pseudowords, where comprehension depends on the extraction of the grammatically meaningful element, the suffix, which could be expected to engage morphological parsing mechanisms. In order to identify specific brain regions that support morphological processing, individual differences in cortical thickness measurements were correlated with the degree to which participants used tonal cues predictively on the different word forms. A meaningful relation between variation of cortical structure and tone processing performance would point to the involvement of the specific brain region as a neuroanatomical substrate. The two brain areas examined were the pars opercularis of the inferior frontal gyrus and the planum temporale, which have previously been implicated in inflectional morphological analysis and tone processing on familiar lexical items, respectively.

Study 3 and 4 focused on the L2 acquisition of Swedish tone-suffix associations. Predictive features in language rely on co-variations between an anticipatory cue (e.g. the stem tone) and a target (e.g. a suffix attached to the stem). A powerful domain-general learning mechanism for picking up co-variations in the input is statistical learning, which is assumed to proceed like implicit learning, i.e. incidentally and without conscious awareness of the regularity to be learned (Perruchet & Pacton, 2006). Study 3 thus investigated the assumption that L2 learners at higher levels of proficiency in Swedish might have implicitly acquired the predictive use of word accents during a relatively long period of exposure to the L2. In order to assess the degree of learning that has taken place without any explicit instruction, we examined whether these advanced learners would show a processing advantage in their response times to verbal inflections that were cued by the preceding word accent, in the same way as it was observed in native speakers. Study 4 focused on L2 acquisition at earlier stages of learning. Since implicit learning might proceed relatively slowly, and low proficient L2 learners do not show signs of acquiring the predictive use of word accents (Gosselke Berthelsen, Horne, Brännström, Shtyrov, & Roll, 2018), we investigated possibilities of providing focused training in Swedish tone-suffix associations with the help of a digital game. L2 learners at a low proficiency level in Swedish played a prototype of the game, which combined features of explicit and implicit learning conditions. The task constituting the core of the game mechanics required participants to make a correct choice between two alternative inflectional suffixes, one of which was validly cued by a previously presented word accent. Game performance measures as well as accuracy improvements in tone production were analyzed in order to assess the effectiveness of the training method and to gain insights into important aspects of learning an L2 predictive strategy facilitating morphological processing.

2. Background

2.1 Inflectional morphology

The morphology of a language concerns the structure of words, including the way new words are formed (e.g. *player* from *play*) or how various forms of a given word are constructed (e.g. *play*, *played*). The focus of the present thesis is on the brain processes associated with the latter phenomenon, inflectional morphology. Morphemes constitute basic linguistic units in the internal analysis of words, often defined as the smallest linguistic elements with a lexical or grammatical meaning (Booij, 2007). Morphemes might be free or bound: free morphemes can appear on their own as separate words, whereas bound morphemes always need to attach to a base morpheme, a 'stem'. In case a free (e.g. *play*) or bound morpheme (e.g. *-ful* in *playful*) has a meaning of its own, which is not tied to the grammar of the language, it is referred to as a lexical morpheme. Other types of morphemes have a grammatical function instead, and these may also be either bound or free, for example the past tense affix *-ed* (e.g. *played*) and the preposition *of* (e.g. *apple of Eve*), respectively. An affix added after the stem is called a 'suffix' (e.g. *-ed* in *played*), and an affix preceding the word stem is a 'prefix' (e.g. *re-* in *replayed*). The part of the stem that cannot be subdivided into further morpheme units is called the 'root' (e.g. *play* is the root and the stem at the same time, whereas *replay*, to which *-ed* is added, is a stem).

A further central concept in inflectional morphology is the 'lexeme', which denotes the word as an abstract entity, e.g. APPLE. The actual word realizing a lexeme is referred to as a 'grammatical word' (Booij, 2007; Stump, 2001), e.g. *apple* (the singular of APPLE) or *apples* (the plural of APPLE). The same lexeme might be therefore spelled out as different word forms, depending on the specific syntactic context in which the word appears, or the information that the speaker intends to express (e.g. *one apple, three apples*). Rules of inflection specify how such different forms of a lexeme might be created, a process which involves marking the word for specific morphosyntactic properties. Morphosyntactic properties encode relations among different constituents of the sentence via morphological marking. For instance, nouns in many languages can be inflected by the morphosyntactic category 'number'. In English, 'number' has two values, singular and plural, where plural is regularly expressed with the inflectional suffix *-s*. If the noun is in a subject-predicate relation with another constituent of the finite sentence, this relation is expressed through ‘agreement’ in English, via co-variation of the inflectional feature of the constituents involved: a finite verb with a singular subject thus gets an *-s* suffix (e.g. *One apple taste+s good*), whereas with plural subjects the verb carries no overt inflection (e.g. *Three apples taste good*). Another example of a morphosyntactic category is ‘tense’, which marks the temporal reference of a finite verb. Verbs and nouns in many languages can be grouped into different inflectional classes, called ‘declensions’ for nouns and ‘conjugations’ for verbs. Members of the same class share a specific pattern concerning the way the various forms of the word are created by inflection (Booij, 2007).

Another relevant notion for the present dissertation is that of the ‘lexicon’. The lexicon of a language is an abstract entity, listing idiosyncratic word-related information: existing words as well as other established expressions of the language, such as idioms or affixes. Information specified in the lexicon concerns arbitrary signs (Aronoff & Anshen, 2001), where the forms and/or the form-meaning pairings are unpredictable to some extent, hence the need to list these in a repository. The representation of (part of) this lexical repository in the brain of an individual speaker of the language is called the ‘mental lexicon’ (Booij, 2007).

2.2 Dual route model of inflectional morphology processing

A general distinction between regular and irregular inflectional classes is a well-known property of the morphological description of various languages, notably English, a language that has often dominated the focus of psycholinguistics research (Clahsen, 2016). It is no wonder therefore that the most influential psycholinguistic theories on inflectional morphology processing were formulated with specific focus on accounting for the production and comprehension of these two types of complex words. Proponents of the so-called dual-system model assume two qualitatively different morphological processing mechanisms (Clahsen, 1999; Pinker, 1999; Pinker & Ullman, 2002): regularly inflected words are suggested to be processed through productive rule-governed compositional operations whereas irregular items are assumed to rely on full-form representations in the mental lexicon. From this perspective, the production of an inflected word form involves access to the mental lexicon as well as engagement of grammatical operations. If the inflected form is stored in memory, together with the relevant morphosyntactic property as part of its lexical specification, the word is retrieved and further rule-based computations are blocked. In the absence of a stored representation a default morphological rule applies, combining the word stem with the regular inflectional suffix (Pinker & Ullman, 2002). Alternatively, connectionist single system approaches reject a distinction along the regular/irregular dimension (e.g. Rumelhart & McClelland, 1985) and argue that the same information, phonological and semantic regularities, would underlie the production of all inflected word forms (e.g. Joanisse & Seidenberg, 1999). From this perspective, apparent processing distinctions between regular and irregular words would stem from a solely qualitative difference: phonology plays a relatively greater role in the processing of regulars, where the verb stem and the base of the inflected form tend to be identical and the form of the inflection is often phonologically conditioned, as compared to irregulars, which rely more on semantic relations among words (Joanisse & Seidenberg, 1999).

The dual-system approach originally received support in studies that uncovered differences in priming effects for regular versus irregular word forms (e.g. Münte, Say, Clahsen, Schiltz, & Kutas, 1999; Sonnenstuhl, Eisenbeiss, & Clahsen, 1999; Stanners, Neiser, Hernon, & Hall, 1979). The observation that regularly inflected items (e.g. *walked*) facilitated the subsequent recognition of the base form (e.g. the word stem *walk*), as efficiently as presentation of the base form itself, were interpreted in favor of the assumption that such complex word forms are parsed into their component morpheme parts (*walk*+*ed*) during language comprehension, and lexical access takes place via the stem. Accordingly, stems were found to dominate meaning analysis of inflected word forms, assumed to be processed through decomposition, during a semantic decision task (Laine, 1999). Findings for irregular items were much more inconsistent and often indicated limited facilitation for word stem recognition or complete absence of priming effects, which might suggest that these forms have separate representations in lexical memory (Sonnenstuhl et al., 1999). Furthermore, a series of electrophysiological studies reported different brain responses to regular versus irregular word forms, in line with the assumption that the underlying neural mechanisms might be different as well (Gross, Say, Kleingers, Clahsen, & Münte, 1998; Morris & Holcomb, 2005; Münte et al., 1999; Penke et al., 1997; Rodriguez-Fornells, Clahsen, Lleó, Zaake, & Münte, 2001; Weyerts, Penke, Dohrn, Clahsen, & Münte, 1997). Importantly, a left anterior negativity, a brain response pattern commonly associated with morphosyntactic processing, has been typically observed in connection with the presence of a regular inflection or stem formation pattern in the input (Gross et al. 1998; Morris & Holcomb, 2005; Penke et al., 1997; Rodriguez-Fornells et al., 2001; Weyerts et al., 1997).

Nevertheless, the situation seems rather more complex than a simple regular versus irregular distinction when data from a wider range of languages are considered, and further factors such as frequency of word forms in the input are taken into account. To begin with, it is reasonable to assume that frequent regular forms might get encoded in memory in full form in order to support rapid access to regularly encountered items (Pinker & Ullman, 2002). In this case, it has been argued that access to the stored representation versus decomposition might vary for the same word depending on, for instance, the nature of the task (Pinker & Ullman, 2002). Task requirements that draw attention to the formal features of the language input might then motivate decompositional analysis, whereas reading/listening for comprehension could be thought to favor whole-word access. At the same time, whole word storage of frequent regular forms might be less extensive in highly inflected languages due to long-term memory limitations related to the large number of inflected variants for the same stem (Gor & Cook, 2010). Also, in these languages even words belonging to non-default classes may show tendencies towards decomposition depending on the complexity and the degree of regularity of specific inflectional patterns. For instance, compositional processing of verbs might be preferred regardless of conjugational class if word forms can be easily analyzed into their stem and inflection parts, as it has been argued for Russian, a language with rich verbal morphology and several verb classes displaying different degrees of regularity in their inflectional paradigms (Gor & Jackson, 2013). In sum, it can be assumed that the modulation of the different processing routes might depend on a complex interplay with the morphological properties of the language as well as with various speaker- and context-specific factors. The core question, whether two different neural mechanisms are available during word form processing in native speakers, nevertheless still remains unanswered. This issue was investigated in the context of Swedish inflectional morphology processing in Study 1 and 2.

2.3 Brain networks of language

In this section, we will provide a brief overview of some of the core brain areas and major processing streams involved in language comprehension and production. Next, we will turn to some proposals concerning the neuroanatomical underpinnings of dual route mechanisms within this language network. According to current theoretical perspectives, cognitive functions, including language, are implemented in large-scale networks in the brain, encompassing several anatomically connected brain regions as specialized processing nodes (Saur et al., 2008). Within these systems, further functional specialization among anatomically distinct processing streams has been observed. For instance, the cortical organization of vision is characterized by two major streams of projections from primary sensory cortical areas: a ventral ("what") stream towards temporal regions, associated with visual object recognition; and a dorsal ("how") stream terminating in parietal areas, supporting visually guided actions involving such objects (Goodale & Milner, 1992; Ungerleider & Mishkin, 1982). Separate dorsal and ventral auditory processing streams have also been described in nonhuman primates, originating in non-primary auditory cortical regions (Rauschecker &

Tian, 2000; Romanski et al., 1999). On analogy with the visual and the auditory system, language processing has been proposed to involve two parallel, but potentially interacting, streams, which connect temporal and frontal language-relevant regions (e.g. Hickok & Poeppel, 2004, 2007; Saur et al., 2008). Functionally, the ventral stream has been related to aspects of semantic and conceptual processing (Bornkessel-Schlesewsky & Schlesewsky, 2013; Hagoort, 2013) or more generally to language comprehension (Hickok & Poeppel, 2007; Saur et al., 2008). Its anatomical substrate was reported to encompass regions of the temporal cortex and those of the ventrolateral prefrontal cortex (Brodmann areas (BA) 45/47), which are connected mainly via a ventral pathway running through the extreme capsule (Saur et al., 2008). As regards the dorsal stream, it has been attributed with various functions, including sensory-motor transformations underlying speech production (Hickok & Poeppel, 2004, 2007), hierarchical sentence structure processing (Friederici, 2009, 2012) and time-dependent aspects of combining and ordering linguistic elements in successively larger structures (Bornkessel-Schlesewsky & Schlesewsky, 2013). Brain regions activated for a prototypical task of dorsal language processing (pseudoword repetition) involved temporal lobe and premotor areas (BA 6/44) connected by a dorsal tract via the arcuate and the superior longitudinal fascicle (Saur et al., 2008). For higher level linguistic processing, a further functional subdivision of the dorsal pathway has been argued, where connections between the temporal cortex and the pars opercularis of the inferior frontal gyrus (BA 44) in Broca's area would support hierarchical syntactic analysis via the arcuate fasciculus (Friederici, 2012).

2.3.1 Neural substrates of dual route processing

Proposals that maintain a distinction between decompositional and full-form processing routes have associated these functions with separate subsystems within the language processing network, relating them to different processing streams as well (Bozic, Fonteneau, Su, & Marslen-Wilson, 2015; Marslen-Wilson & Tyler, 2007; Ullman 2001a, 2004). A detailed neurocognitive model has been formulated by Ullman (2001a, 2004) in the context of two general memory systems that have been extensively studied for non-linguistic functions in humans and non-human animals. According to this proposal, the mental lexicon, containing stored memory representations of word forms, is associated with the declarative memory system, whereas the mental grammar, underlying the combinatory processing of representations, is implemented in procedural memory (Ullman, 2001a, 2004). Declarative memory is largely subserved by temporal areas of the brain, representing knowledge about facts and events, including arbitrary word-related information (Ullman, 2004). Whole-word access is therefore associated with this system (Pinker & Ullman, 2002). Also, retrieval of stored auditory word form representations was related to the superior temporal cortex, in a meta-analysis of neuroimaging studies, which indicated that analysis of the incoming speech input in terms of increasingly more complex sound patterns appears to proceed along a ventral processing pathway in the temporal cortex (DeWitt & Rauschecker, 2012). Medial temporal lobe structures such as the hippocampus play an important role in the learning and consolidation of declarative knowledge. Long-term storage is mostly implemented in neocortical areas of the temporal lobe and the processing of this knowledge has been linked to the ventral stream (Ullman, 2004, 2016). Procedural memory is constituted by a highly interconnected brain network, encompassing the basal ganglia and frontal cortical regions, as well as potentially parts of parietal cortex, superior temporal cortex and cerebellum (Ullman, 2004). Procedural memory underlies the acquisition and performance of sensory-motor and cognitive skills, including the processing of complex linguistic representations with sequential and hierarchical structures (Ullman, 2004). Decompositional analysis of inflected word forms would consequently rely on this system (Pinker & Ullman, 2002). Whereas the basal ganglia appear to play a central role in the acquisition of procedural skills (Ullman, 2006a), performance of consolidated procedures might be largely tied to neocortical structures and the dorsal processing stream (Ullman, 2004, 2016). Broca's area (BA 44 and 45), and specifically the pars opercularis of the inferior frontal gyrus (BA 44), has been proposed to be important in the selection and maintenance of representations in working memory during the processing of sequential or hierarchical linguistic structures (Ullman, 2004).

Marslen-Wilson, Bozic and colleagues have also described different neural subsystems for whole-word access versus the processing of word forms with decomposable internal structure (Bozic et al., 2015; Bozic & Marslen-Wilson, 2010; Marslen-Wilson & Tyler, 2007). Their proposal differs from the dual route account by Clahsen (1999) and Pinker (1999) in several respects, importantly concerning assumptions about the input properties that trigger analysis along a decompositional route: regularly inflected word forms need to be decomposed in order to enable access to lexical representations, a process which takes place via the word stem and the affix, separately. All word forms that are potentially segmentable based on morphophonological cues are automatically parsed into component morphemes, and, therefore, this operation is not tied to the presence of a regular inflection and an associated morphological rule application (Marslen-Wilson & Tyler, 2007). Nevertheless, the distinction between two separate neurobiological subsystems is maintained. Empirical evidence suggests that structural decomposition of complex word forms crucially depends on the left inferior frontal cortex and on its connections with posterior temporal lobe areas, implicating a dorsal decompostional network (Bozic et al., 2015; Marslen-Wilson & Tyler, 2007). Among the frontal regions, Broca's area, in particular, the pars opercularis of the inferior frontal gyrus has been repeatedly observed to be involved in regularly inflected word form processing (Bozic et al., 2015; Fonteneau, Bozic, & Marslen-Wilson, 2015; Tyler, Stamatakis, Post, Randall, & Marslen-Wilson, 2005). Access to lexical-semantic content associated with the stem, as well as to stored representations related to the affix, have been reported to take place in regions of the superior and middle temporal cortex (Marslen-Wilson & Tyler, 2007). Whereas the proposed network for decompositional analysis is lateralized to the left hemisphere, whole-word access is assumed to rely on a bi-hemispheric subsystem (Bozic & Marslen-Wilson, 2010).

To sum up, regions of the temporal lobe can be assumed to play an important role for whole-word access during complex word form processing, which is also in line with views on the general neurological substrates of lexical, semantic and conceptual representations (e.g. Vigneau et al., 2006). The left inferior frontal gyrus, specifically pars opercularis, might be crucially involved in processes of decompositional analysis of inflected word forms. Study 2 examined this frontal versus temporal distinction in the context of Swedish tone processing in inflected nouns, scrutinizing specifically the role of cortical thickness in a frontal region, the pars opercularis of the inferior frontal gyrus, and in the planum temporale, which is a non-primary auditory region, constituting the core part of classical Wernicke's area (Hickok & Saberi, 2012) in the temporal lobe. Importantly, encoding of intonational pitch contours, irrespective of speaker-specific pitch variations, has been localized to higher-order auditory areas including the planum temporale (Tang, Hamilton, & Chang, 2017).

2.4 Swedish morphology

In this section, we will provide a brief descriptive introduction to some of the characteristic features of Swedish morphology, relevant to the language materials used in the investigations. In terms of its general morphological properties, Swedish shares several characteristics with analytic languages of the world. Such languages typically use separate words or word order to express grammatical and semantic relations, which might otherwise be marked by affixation. Thus, in Swedish syntactic relations (e.g. subject, object) are indicated by word order, and function words, e.g. prepositions are used in several contexts to mark a number of grammatical and semantic functions, for instance in adverbials of time and space (e.g. *till Lund* 'to Lund', *i affären* 'in the shop') (Teleman, Hellberg, & Andersson, 1999). Nevertheless, even if Swedish does not have a rich inflectional system comparable to languages characterized by free word order, it does express several grammatical and semantic relations through inflection, creating morphologically complex words. For example, Swedish uses affixation for the morphosyntactic categories of ‘number’ and ‘tense’. It even has some more unusual inflectional categories, which include marking definiteness on nouns as well as passive voice on verbs using suffixation. The inflectional system of Swedish is largely *agglutinating*: each suffix is associated with a specific meaning, and the boundaries between the morphemes as well as between the stem and the affixes tend to be clearly identifiable (e.g. *pojk+ar+na+s*: boy+PL+DEF+POSS, i.e. ‘the boys’’) (Teleman et al., 1999).

Each study in the present thesis focused on the processing of specific inflected word forms, which were either verbs or nouns, placed in sentence context. Relevant for the experimental manipulation used with nouns, Swedish morphology distinguishes between singular and plural forms, which largely corresponds to the semantic distinction ‘one versus many’ for count nouns (Teleman et al., 1999). As mentioned above, Swedish uses suffixation to mark definiteness on nouns, e.g. *bil* versus *bil-en* ‘car’ versus ‘the car’. When the noun is indefinite, only the plural form carries an overt suffix: e.g. *bil* versus *bil-ar*, ‘car’ versus ‘car-PL’. For definite forms, however, the suffix added varies with the number property, and even the singular noun gets an inflection: *bil-en* versus *bil-ar-na,* ‘bil-SG+DEF’ versus ‘bil-PL-DEF’. As a result, the morphological processing of the semantic distinction “one versus many” can be studied by contrasting comparable word forms, each made up of a word stem plus one inflectional suffix: *bil-en* versus *bil-ar*.

Finite Swedish verbs are inflected for tense, which is either a present or a preterite form. Verbs appearing as target words in the stimulus materials of the investigations constituted such morphologically complex forms. The present tense form is mainly used to indicate that an action takes place in the present or in the future, whereas the preterite denotes an action associated with a specific time point in the past. Further temporal aspects can be expressed with multi-word structures including an auxiliary verb, which will be not discussed here (Teleman et al., 1999).

Swedish verbs can be divided into several conjugational classes, largely based on the type of suffix they take in the preterite form. The main lexically specified distinction is between ‘weak’ and ‘strong’ verbs, where weak verbs are considered to be regular. The preterite of weak verbs is formed by attaching a *-de/-te/-dde* suffix to the stem. This group of words can be divided into three conjugational classes (1st, 2nd and 3rd conjugations) depending on the phonological form of the stem-final segment, which in turn specifies the suffix-variant to be used to build the present and the preterite form (Teleman et al., 1999). Thus, the subdivision within the weak verb class is based on a phonologically conditioned, and as such predictable, suffix-variation. Of the weak verb classes, 2nd conjugation verbs were used as target words in Study 1 and 3. These verb stems end in a consonant, and the suffix attached to the stem is *-de/-te* for the past tense (*-de* after voiced and *-te* after voiceless stem-final consonant), e.g. *häll-de* ‘pour-ed’, *tänk-te* ‘plann-ed’.

Strong verbs constitute the 4th conjugational class. Unlike in the case of weak verbs, the preterite of strong verbs is formed without attaching a tense suffix and it normally involves a vowel-change in the stem. These vowel alternations are typically not arbitrary but follow specific patterns, which can be often predicted from the vowel of the verb stem (the stem of the infinitive and present tense form). The vowel sequences associated with the most common inflectional subclasses are exemplified in Table 1, with present, preterite and supinum verb forms (supinum is used, for example, in constructions with auxiliary verbs) (Teleman et al., 1999). Therefore, members of the 4th conjugational class can be regarded as interesting intermediate instances between regularly and irregularly formed verbs. On the one hand, they are not completely regular to the same extent as the Swedish weak verbs or English regular verbs (e.g. *talk-ed*) are: the construction of the preterite cannot be described in one simple rule that automatically attaches a default past tense suffix to the stem, which is left largely unchanged by the operation. On the other hand, the 4th conjugational class preterite forms are not random either and, even if the underlying regularities are somewhat more complex, specific predictable patterns clearly exist. The way the morphological processing system in Swedish native speakers handles these verb forms, relative to the 2nd conjugational verb class, is investigated in Study 1.

Table 1
Regular vowel sequences associated with some of the most common inflectional subclasses in the 4th conjugational class.

	Present	Preterite	Supinum
i [i] – a – u	binder	band	bundit
i [i:]– e – i	skriver	skrev	skrivit
u/y – ö – u	bjuder; flyger	bjöd; flög	bjudit; flugit

The present tense of both weak and strong verbs is formed according to the same regularities, determined by the phonological form of the verb stem in the majority of cases. For example, stems ending with a vowel receive the suffix *-r* (*prata-r* ‘work-PRES’, whereas stems ending in a consonant (with the exception of long vowel + ‘r’ or ‘l’) get the suffix *-er* (e.g. *häll-er* ‘pour-PRES’, *skriv-er* ‘write-PRES’) (Teleman et al., 1999).

2.5 Swedish word accents

A characteristic feature of spoken Swedish is the presence of a word accent on each prosodic word. The two word accents of the language are called ‘accent 1’ and ‘accent 2’ (Bruce, 1977). In Central Swedish, which is the dialect that was used in the investigations, accent 1 appears as a low tone on the stressed syllable whereas accent 2 is realized as a high tone. Importantly, the word accent associated with the same stem may vary depending on the suffix attached. For example, the word stem *bil* ’car’ receives a low tone (accent 1) when it is followed by the singular definitive article *-en* and a high tone (accent 2) if it ends in the plural suffix *-ar*. According to one line of analysis, this apparently suffix-induced variation is related to the fact that the lexically specified tone, accent 2, is associated with a set of derivational and inflectional suffixes, including the plural suffix *-ar* (Bruce, 1977; Riad, 2015; Rischel, 1963). When these suffixes combine with other morphemes, they assign their associated accent 2 to the stressed syllable, which is most often the root syllable. In case there is no lexical tone present, or its realization is inhibited by well-formedness constraints on the structure, accent 1 is assigned as the default (Riad, 2015). From this perspective, accent 1 is intonation, whereas accent 2 is stored in the mental lexicon, as part of the information associated with the representation of specific suffixes. Accent 2 might nevertheless also be assigned postlexically, mainly in compound words, where the appearance of accent 2 is motivated by the presence of secondary stress (Riad, 2015).

In the present dissertation, the association between word accents and suffixes is investigated from a speech processing perspective. During actual speech comprehension, the tone realized on the word stem precedes the suffix and, therefore, could be assumed to function as a predictive cue to an upcoming word completion regardless of the lexical or postlexical status of the tone (Roll et al., 2015). Hearing the word *bil* with accent 2, the listener might expect a continuation with the plural suffix *-ar*, $bil_{accent2}$*-ar*, due to the association between the tone and the suffix. At the same time, pronouncing the same word stem with accent 1 makes a continuation with *-ar* highly unlikely, whereas the suffix *-en,* as in $bil_{accent1}$*-en,* is much more expected. In other words, if accent 2 might be assumed to cue its associated suffixes, accent 1 could be thought to similarly cue another set of suffixes, those that are not associated with accent 2. We therefore did not make an explicit distinction between accent 1 as the default, and accent 2 as the suffixed-induced tone in the investigations.

2.6 The processing of word accent-suffix associations in native speakers

There is substantial empirical evidence indicating that native speakers of Swedish rely on word accents to anticipate upcoming word endings during online language comprehension. Relevant results come from a range of behavioral, electrophysiological and brain imaging studies (Gosselke Berthelsen et al., 2018; Roll, 2015; Roll et al., 2010, 2013, 2015; Söderström, Horne, Mannfolk, van

Westen, & Roll, 2017; Söderström et al., 2012, 2016b). When listeners were asked to judge suffix meaning in morphologically complex words in a response-time experiment, they were observed to process faster suffixes that were preceded by their associated word accent on the word stem, relative to suffixes that were presented after a different stem tone than the one they are related to (Söderström et al., 2012). Thus, participants decided more rapidly between the present tense versus past tense meaning of words such as *lek*$_{accent2}$*-te* 'played', pronounced with the word accent associated with the past tense suffix *-te*, i.e. accent 2, as compared to verbs such as *lek*$_{accent1}$*-te*, presented incorrectly with accent 1 on the stem. The same pattern was observed for the present tense suffix *-er*, associated with accent 1. Since all the experimental items were grammatically correct and semantically plausible complex words, it was arguably the word accent that generated an expectation in listeners for a likely upcoming continuation. When the actually experienced suffix in the input disconfirmed this expectation, processing time increased as reflected in longer response latencies.

Next, consistent with the assumption that word accents function as predictive cues to their associated suffixes, Swedish tones were reported to generate an increased negativity in the electrophysiological brain response, referred to as PrAN, around 136 ms after tone onset on the word stem (Roll et al., 2015; Söderström, Horne, Frid, & Roll, 2016a). This negativity was greater for accent 1 than for accent 2, which seems to stem from a difference between the two word accents concerning their predictive significance. As mentioned above, compound words receive accent 2 in Central Swedish. Therefore, hearing a word stem with accent 2 opens up possibilities for an almost unlimited number of continuations as compound words (e.g. *bil-nyckel* 'car-key', *bil-dörr* 'car-door', *bil-bälte* 'car-belt' etc.). However, word endings that might follow accent 1 constitute a much smaller and well-defined set of suffixes (e.g. *bil-en*). Accent 1 is therefore associated with more predictive certainty and can be assumed to pre-activate related suffixes to a greater extent, hence the enhanced negativity (Roll et al., 2015). Further studies showed that the negativity indeed increases as the number of possible word completions decreases and the more frequent words those completions constitute, in line with its interpretation as an index of predictive activation of memory traces, modulated by the certainty with which a specific continuation might occur (Roll, Söderström, Frid, Mannfolk, & Horne, 2017; Söderström et al., 2016a). Observing a PrAN for word accents in native speakers thus clearly supports the idea that Swedish stem tones generate expectations for upcoming suffixes.

The PrAN effect was obtained even for processing tones on inflected pseudoword stems, i.e. on items that were phonotactically legal word forms, but not actually existing words in the Swedish language (Söderström et al., 2016b, 2017). Participants were also able to guess the identity of suffixes in cases when the actual pronunciation of the word ending on the pseudoword stem was replaced with a cough, and the only cue to the ending present was the word accent. The fact that native speakers seem to be able to make use of the predictive association between word accents and suffixes even in the absence of lexical content in the word stem suggests that a more abstract association exists between tones and suffixes, independently of stored lexical representations (Söderström et al., 2016b).

Neuroimaging studies have identified a left-lateralized brain network involved in the predictive use of word accents during speech comprehension (Roll et al., 2015; Söderström et al., 2017). Correlating functional brain activations with electrophysiological measures has provided insights into the time course of processing supported by different parts of this network (Roll et al., 2015). Based on these results, tones on inflected Swedish words are thought to be initially processed in temporal lobe areas, where discrimination of tone patterns in primary auditory cortex is followed by access to associated phonological representations of word accent categories in the superior temporal gyrus. Following word accent recognition, increased activation has been observed in frontal brain regions such as the inferior frontal gyrus (IFG), most likely related to some aspects of processing the suffix prediction generated by the tone (Roll et al., 2015). Specifically, left IFG activation associated with PrAN has been suggested to underlie lexical selection of likely word completions and inhibition of competing alternatives (Roll et al., 2017). Interestingly, when tones were realized on pseudowords, temporal areas have shown less prominent activations, and the pars opercularis in the left IFG has emerged as an important processing center instead (Söderström et al., 2017). This is different from the frontal activation pattern observed in Roll et al. (2015), where the area associated with the strongest activation in the IFG was BA 47, potentially indicating involvement of the ventral processing stream (e.g. Saur et al., 2008). It seems therefore that the involvement of frontal versus temporal nodes of this tone processing network might be modulated by the presence versus absence of lexical information in the word stem carrying the word accent. This hypothesis was further investigated in Study 2.

2.7 Investigating second language acquisition of Swedish tone-suffix associations

Swedish native speakers have been shown to rely on word accents to facilitate processing of upcoming word structure, but it is still unknown if adult second language (L2) learners of Swedish can acquire the morphological function of tones. This question was investigated in Study 3 and 4. Here we will discuss some of the basic assumptions and considerations related to L2 acquisition of tone-suffix associations that guided the focus of these investigations as well as some methodological choices in the studies.

2.7.1 Tone perception in L2 acquisition

It is reasonable to assume that learners' ability to effectively exploit the predictive significance of Swedish word accents depends on the accurate perception of accent 1 versus accent 2 tone distinctions. Research on the second language acquisition of tonal aspects has largely focused on the learning of tone languages such as Mandarin Chinese, where, unlike in Swedish, each syllable is associated with a distinctive tone. Despite significant differences concerning the status of tones in these languages, results from lexical tone studies are indicative of certain factors that are expected to play a role in Swedish word accent acquisition as well, most importantly previous language experience. Studies on cross-linguistic tone processing have repeatedly found that native speakers of tone versus non-tone languages differ in their ability to discriminate tonal contrasts in an L2 (Francis, Ciocca, Ma, & Fenn, 2008; Lee, Vakoch, & Wurm, 1996; Wang, 2013; Wayland & Guion, 2004). In this context, one theoretical model that is frequently referred to is Flege's (1995) speech learning model (SLM), applying its predictions originally formulated to involve segmental acquisition to the suprasegmental level. Importantly, the SLM argues against the existence of maturational constraints on L2 learners' ability to establish new phonetic categories. However, as the native language (L1) and the L2 categories are assumed to occupy the same representational space, the developmental state of the different subsystems and the relative similarity of the already established sound representations influence the way new L2 sounds are integrated. Therefore, learners are likely to create a new category for an L2 sound that is perceived to be markedly different from any L1 representation, whereas an L2 sound that is perceptually similar to a fully-developed L1 category tends to be processed through the already established long-term memory representation of the L1 sound. Even in these cases, learners might be able to recognize subtle auditory differences between the two sounds, and the shared memory representation will be gradually modified to incorporate the L2 sound features.

Applying this perspective to the acquisition of suprasegmental features, the existence of native tonal categories can either constrain or facilitate the accurate representation of L2 tonal contours, depending on the degree of similarity between specific tonal categories in the L1 and the L2. Also, speakers of non-tone languages should presumably be able to form representations for L2 tonal patterns, even in the absence of comparable phonetic categories in the L1. Still, it needs to be considered that pitch contours (fundamental frequency (f_0) patterns) are generally used to convey a variety of meanings in non-tone languages as well, for instance in sentence level intonation. Therefore, lexical tone processing might be influenced by learners' experience with native intonational categories (e.g. a rise in English yes-no questions), which, in contrast to lexical tones, lack associations with specific items at the syllable or morpheme level. Nevertheless, even if learners might not be able to make the sharp distinctions that are necessary for the native-like identification of tonal categories (Hallé, Chang, & Best, 2004) at the initial stages of learning, several studies have reported significant improvement in the perceptual identification of lexical tones as a result of focused training involving native speakers of non-tone languages such as English (Francis et al., 2008; Wang, Jongman, & Sereno, 2003; Wang, Spence, Jongman, & Sereno, 1999). Training has been argued to lead to the establishment of long-term memory representations for tonal categories in these learners (Wang et al., 1999) and to increased accuracy in production (Wang et al., 2003). Relevant findings on L2 perception of Swedish word accents indicated that, in the absence of training, beginner learners with a non-tone L1 processed Swedish tones non-linguistically, despite their presentation on words in sentence context (Gosselke Berthelsen et al., 2018). These results might indicate that learners have dissociated word accents from the L1 function of comparable tonal patterns (a pragmatic function in polite, soothing requests in German), which might be considered as a prerequisite for acquiring the morphological significance of Swedish tones. Also, a subset of relatively more proficient learners showed signs of developing greater sensitivity to pitch differences, which could be expected to support the creation of memory representations for tonal patterns (Gosselke Berthelsen et al., 2018).

The above considerations suggest that there do not seem to be absolute maturational constraints on learning to discriminate tones in an L2, which can be assumed to be a prerequisite to acquire the ability to rely on the predictive significance of word accents. Nevertheless, providing perceptual training might be beneficial for facilitating the acquisition process. Further, tone versus non-tone L1 background appears to be an important factor, and acquiring Swedish word accents is expected to constitute different kinds of challenges for these different learner groups. Native speakers of tone languages have extensive experience in the accurate detection of f_0 variation patterns at the word level, which they might be able to utilize for the discrimination of L2 tonal contrasts as well (Wayland & Guion, 2004). Relative to non-tone L1 speakers, these learners might process word accents as more salient and relevant linguistic features due to their predisposition to direct attention to f_0 at the word level, which could possibly provide an advantage in the acquisition of the tone-suffix associations. Even in these cases, however, learners would presumably need to overcome the tendency to interpret word accents in terms of native tone categories and learn to associate them with a morphological function instead of a lexical one. As for learners with a non-tone L1 background, they would need to establish tonal categories that are well-defined enough to underlie native-like discrimination of word accent patterns. Also, the development of effective perceptual strategies is necessary to be able to track the relevant features of the f_0 contour at the word level and to learn to form associations between these pitch contours and word accent categories. Considering these clear differences, studies in the present thesis focused exclusively on one of these groups, L2 learners with a non-tone background, who might also be expected to find learning to discriminate word accents relatively more challenging.

2.7.2 Implicit and explicit L2 learning

Swedish tone-suffix associations are normally largely neglected in formal L2 instruction, as can be judged from the general absence of this L2 feature in Swedish language course curriculums and course books. It is also an aspect of the language that native speakers are generally unaware of. Consequently, it can be assumed that the average L2 learner of Swedish has not received any instruction or explicit information about tones as cues to word structure, and a relevant question is if it is possible for late L2 learners to acquire this feature of the language without such explicit training. Generally, learning is considered implicit when “we acquire information without intending to do so, and in such a way that the resulting knowledge is difficult to express” (Cleeremans, Destrebecqz, & Boyer, 1998, p. 406). Explicit learning is an intentional process, which usually involves conscious hypothesis testing (Cleeremans et al., 1998).

Certain aspects of L2s have been previously found to be learned rapidly solely through exposure, including word boundaries (Saffran, Newport, & Aslin, 1996), lexical information (Gullberg, Roberts, & Dimroth, 2012), grammatical word categories (Mintz, 2002), lexical subcategories such as gender classes (Sandoval, Patterson, Dai, Vance, & Plante, 2017) and morphological regularities (De Diego Balaguer, Toro, Rodriguez-Fornells, & Bachoud-Lévi, 2007). Also, there is some indication that implicit learning conditions that engage distributional learning mechanisms might specifically promote the development of strong enough associations between representations of language features, which would then underlie predictive processing. For instance, Grüter, Lew-Williams and Fernald (2012) suggested that for L1 learners of Spanish, the only way to discover the gender class of specific nouns from the input is by focusing on co-occurrence relations between nouns and gender-marked determiners. This distributional learning mechanism naturally results in strong associations between nouns and determiners in the mental lexicon, which, even after the development of a more abstract representation of gender information, enable native speakers to rely on gender cues in articles to anticipate upcoming nouns. Adult L2 learners, however, tend to have access to a much wider range of information concerning the gender class of different nouns (e.g. metalinguistic information), and are unlikely to rely on distributional learning to any comparable extent in typical learning situations. Indeed, highly proficient L2 learners were found to display native-like predictive processing only with novel words that were acquired under learning conditions that specifically promoted reliance on co-occurrence information between determiners and nouns (Grüter et al., 2012).

Nevertheless, as for the Swedish word accent-suffix associations, the available evidence suggests that mere exposure to the language might not be sufficient for acquisition at earlier stages of language learning in speakers of non-tone L1s: beginner to early intermediate German learners of Swedish (A1 to B1 level of the Common European Framework of Reference) showed no signs of implicit acquisition of the morphological function of word accents in their electrophysiological brain responses (Gosselke Berthelsen et al., 2018). Certainly, some degree of implicit acquisition of the L2 feature might eventually take place after a longer period of exposure when learners have reached higher levels of proficiency. Since no previous study has explored word accent-suffix association processing in more advanced learners, this question was investigated in Study 3. Importantly, the ability to use prosodic cues to anticipate word endings in online speech processing seems to develop with increasing L2 proficiency: advanced L2 learners of Spanish were found to rely on lexical stress to predict an upcoming present tense versus past tense suffix in a visual-world eye-tracking experiment (Sagarra & Casillas, 2018). These learners had presumably acquired the relevant prosody-suffix connections as well as the native-like use of lexical stress for suffix anticipation implicitly, despite the fact that the same prosodic feature had a weaker functional load in their native language, English. Beginner L2 learners, however, did not make use of stress cues for predictive processing of likely word endings (Sagarra & Casillas, 2018). Furthermore, it might be also assumed that advanced L2 learners are in principle able to gain native-like tone-suffix processing mechanisms, even if the grammar of their native language is not characterized by any similar tone-morphology associations. For instance, Sagarra and Herschensohn (2010) investigated L2 acquisition of gender-number agreement between nouns and adjectives in Spanish, in adult native English speakers who did not have comparable grammatical features in their native language. Gender marking has been observed to facilitate processing of upcoming items with congruent gender features in native speakers of Spanish and other gendered languages (e.g. Wicha, Moreno, & Kutas, 2004). As for L2 acquisition, intermediate learners, but not beginners, were sensitive to gender and number agreement violations during an online language-processing task, displaying increased response latencies to sentences with mismatching items, in a similar manner to native speakers. Apparently, intermediate learners had started to develop mental representations for grammatical features absent in their native language, and were able to rely on this knowledge for the online computation of adjective agreement during language comprehension (Sagarra & Herschensohn, 2010, 2012).

As mentioned in the previous section, learners with non-tonal L1 background are unlikely to be characterized by an initial predisposition to pay attention to the functional significance of word accents, especially considering the fact that stem tones are not indispensible for recovering meaning from suffixes. Sagarra and Ellis

(2013), for instance, argued that “learned attention”, i.e. the kind of cues that the L2 learner is accustomed to direct attention to as a result of experience with the L1 is an important factor determining the success with which a certain aspect of the L2 is acquired. Failure to attend to word accents might thus partly explain the apparent lack of automatic acquisition of word accent-suffix associations at lower L2 proficiency levels (Gosselke Berthelsen et al., 2018). Also, attention has been argued to play a significant role in general co-variation learning (Hoffmann & Sebald, 2005) and more specifically in L2 acquisition: according to the ‘Noticing Hypothesis’ (Schmidt, 2001), the registration of some stimulus in focal attention is the initial step in the acquisition process. Once some language feature has been encoded in memory, it may undergo further unconscious processing and non-conscious activations during the emergence of a specific language skill. Indeed, following implicit training in a miniature language, those learners who reported to pay conscious attention to grammar during training performed better at the grammaticality judgment task than those participants who only focused on lexical aspects of the input (Batterink & Neville, 2013).

A further relevant observation is that significant variation in learning outcome has been reported in studies examining artificial language and grammar learning under implicit conditions (e.g. Franco, Cleeremans, & Destrebecqz, 2011; Misyak & Christiansen, 2012; Morgan-Short et al., 2015), indicating that there might be individual differences as regards the ability of adults to pick up linguistic regularities through mere exposure to the input. While some L2 learners might learn successfully and rapidly under purely implicit conditions, others would possibly perform poorly without some explicit information to aid the acquisition process. Importantly, it has been argued that native-like or near-native procedural language processing mechanisms might emerge from the initial explicit learning of relevant rules and meanings, as a result of gradual automatization of declarative knowledge through extensive practice (DeKeyser & Criado-Sánchez, 2012).

Based on the above considerations, L2 learners of Swedish might benefit from some form of structured training, which combines features of implicit and explicit learning conditions, to help the acquisition of the morphological function of tones. First, extensive exposure to word accent-suffix co-variations, in a context that makes these dependencies relevant for the objectives of the learner, might promote the development of strong associations between suffixes and specific tones as predictive cues. Second, a more explicit element, such as a task to be performed, might be necessary to direct learners’ attention to word accent variations and their significance in cuing morphological structure. Descriptions of rules for the successful performance of the task might be made available for learners who require more explicit information. Such a learning tool is described in Study 4 in detail, and its efficiency in promoting the acquisition of word accent-suffix associations is tested with low proficient L2 learners.

3. Methods

3.1. Response times

The idea that response-time (RT) experiments can provide an insight into mental processes dates back to the investigations of F. C. Donders in the middle of the 19th century. Inspired by Helmholtz's work on measuring the transmission speed of nerve impulses, Donders aimed at identifying the time required for the completion of different hypothesized processing stages of a mental task (Van Zandt & Townsend, 2012). With the advance of modern cognitive psychology and the development of increasingly precise time measurement techniques after the 1950s, RTs have become a crucial and extensively used dependent variable in psychology (Luce, 1991). In an RT experiment, the time it takes for participants to respond to a stimulus is measured, usually with an accuracy of a few milliseconds. RTs are generally assumed to reflect the duration of mental processes (Ratcliff, 2012), and in this sense their functional significance is quite clear: a specific increase in response latency for a stimulus presented in one experimental condition indicates how much longer the encoding, processing and acting on a stimulus takes in that condition relative to another (Luck, 2005). RTs are thus also often seen as a measure of processing ease or difficulty. Nevertheless, an important limitation of the method is that a single overt response might be an outcome of a multitude of underlying cognitive operations, and response latencies give little indication as to the nature of the specific mental processes involved (Luck, 2005). In order to gain insight into the "black box" of the mind, one might directly record the brain's response to a stimulus or event, using electroencephalography (EEG) and the event-related potential (ERP) technique.

3.2 EEG and ERPs

EEG measures the electrical activity of the brain, picked up by electrodes placed on the scalp. From the on-going EEG, brain responses related to specific sensory or cognitive events can be extracted, by averaging over many trials of stimulus presentation associated with a given experimental manipulation (Luck, 2005). The resulting ERP waveform constitutes a series of positive- and negative-going voltage deflections, as exemplified in Figure 1. Conventionally, negative voltages are plotted upwards. A voltage deflection associated with a given neural process occurring with a specific spatial distribution is referred to as an ERP component (Luck, 2012). Characteristic distribution of such ERP effects over the scalp are often illustrated with topographic maps, which show the voltage measured at specific electrode locations during the time window of the component on a color scale, interpolating values between the recording sites.

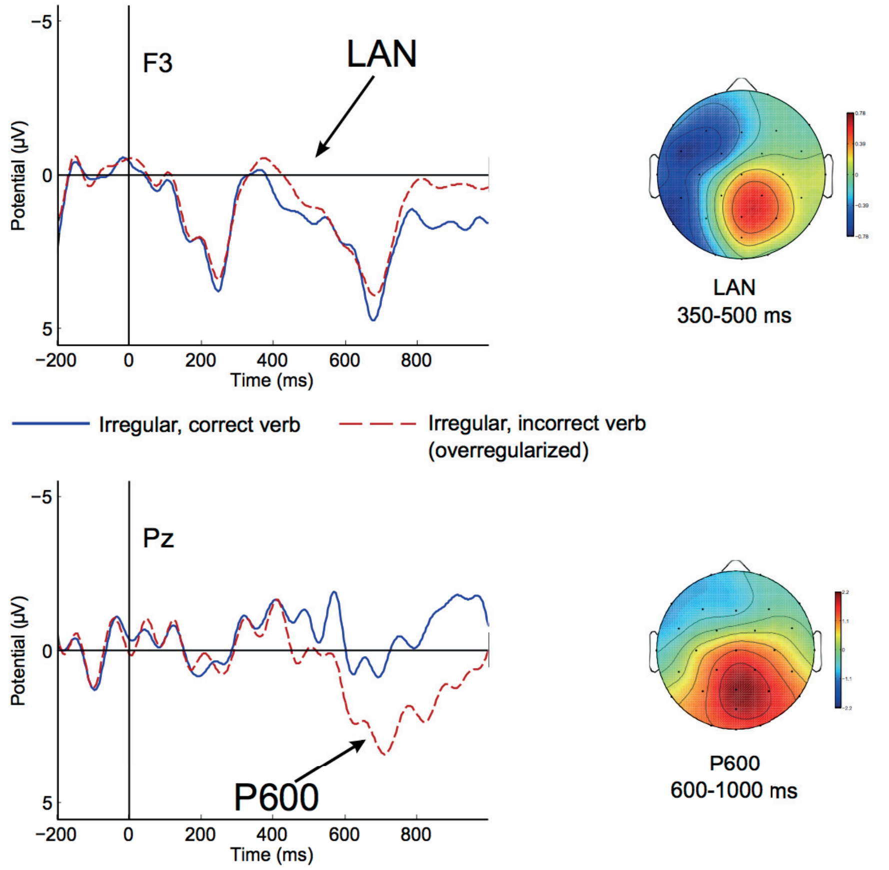

Figure 1
ERP waveforms (left) and topographic maps (right) from Study 1. Irregular incorrect verbs elicited a LAN effect 350-500 ms after verb presentation onset, shown at the left frontal electrode site F3 (top left). A P600 effect was also observed for irregular incorrect verbs at 600-1000 ms, exemplified at the posterior central site Pz (bottom left).

Whereas response times reflect the output of cognitive processes, ERPs can be used to track the modulation of neural activity as it happens, due to the excellent time resolution of the technique, and the observed ERP components can give information about the nature of cognitive processes underlying a specific behavioral response. Also, ERPs can be used to study neural processes that are not reflected in overt behavioral changes or responses (Luck, 2012). For instance, L2 learning effects might be detected in the electrical brain response even before any improvement in performing the L2 skill would occur and be observable in behavioral measures (e.g. van Hell & Tokowicz, 2010). Furthermore, knowing the exact onset of mental operations associated with a stimulus, down to a few milliseconds accuracy, can help establish whether a specific experimental manipulation modulates early sensory activity or later higher-level processes (Luck, 2012). In the context of language processing, the timing of observed ERP effects could be indicative of the involvement of rapid automatic processes versus late and controlled language comprehension mechanisms. Nevertheless, one important limitation of the ERP technique is its poor spatial resolution: as electricity in the brain is conducted through the tissue between the generating neural population and the surface, it spreads out and gets further diverted by the high resistance of the skull. This property makes it difficult to draw conclusions concerning the brain regions where neural operations take place. Based on solely the observation of a specific topographic distribution, it is not possible to localize the ERP generators, since the so-called *inverse problem* has no perfect solution: any given voltage distribution on the scalp might in principle correspond to an infinite number of different brain sources (Luck, 2005). Furthermore, it is important to be aware of the fact that voltages recorded on the scalp reflect only part of the electrical activity that occurs in the brain. The current that eventually reaches the surface originates as postsynaptic potentials generated during neurotransmission, which must occur simultaneously in large populations of spatially aligned neurons in order to produce a measurable signal on the scalp. Based on these considerations, EEG is most likely the reflection of synchronized activity of pyramidal cells in the cortex (Luck, 2005, 2012).

Typical EEG recording and ERP analysis procedures are described below to provide a background to the methods used in the electrophysiological study on Swedish word form processing, Study 1. During an EEG experiment, voltages from a participant's scalp are picked up by electrodes mounted on an elastic cap or net. These weak signals are then amplified and recorded in a digital format, as a series of voltage values corresponding to specific time points. The recorded EEG at this point is a mixture of brain activity as well as noise from various sources, including potentials generated by eye or muscle movements and external electrical appliances. Filtering during and after recording is often used to remove irrelevant parts of the signal that fall outside of the frequencies of interest associated with actual cognitive processes. Also, signal processing techniques have been developed to automatically remove common artefactual activities such as blinks. The averaging procedure typically used to extract ERP waveforms from the EEG relies on the following considerations: brain activity related to a stimulus is assumed to be more or less constant each time the given stimulus is presented, whereas unrelated noise is expected to vary from trial to trial in a random manner. Therefore, segments of EEG around the event of interest are extracted and aligned to the same time point relative to stimulus presentation. As many of these segments, also called epochs, are averaged together, randomly varying positive and negative values associated with noise will be reduced towards zero, and the stable stimulus-related brain activity emerges as an ERP waveform. These ERP amplitudes are quantified in some ways, typically by measuring mean voltage during a pre-defined time period, and the resulting values are submitted to statistical analysis (Luck, 2005, 2012).

3.2.1 ERPs in language processing

Three common language-related ERP effects are introduced in this section, which are also relevant for interpreting the results of the electrophysiological Study 1. These effects were originally observed and described as responses to various semantic or structural anomalies in language materials or to language input with increased complexity. By studying the brain's response as language processing fails or becomes effortful due to specific manipulations, one can even gain insight into the nature of neural mechanisms during normal language comprehension, associated with the processing of features affected by the given experimental manipulation.

3.2.1.1 LAN

Different types of violations related to inflectional morphology have been observed to elicit a left anterior negativity (LAN) in the electrophysiological brain response, typically between 300-500 milliseconds (ms) following presentation of the incorrect word or morpheme (see Figure 1 (top)). The name of the ERP effect reflects its characteristic distribution on the scalp, with maxima over anterior (frontal) electrode sites on the left side of the brain. In addition, LAN is referred to as a 'negativity' since it constitutes a negative voltage deflection in the ERP waveform, relative to some control condition. For instance, LAN has been regularly observed for errors in number agreement between sentence constituents (Molinaro, Barber, & Carreiras, 2011), including incorrect inflectional marking of subject-verb agreement with the suffix *-s* in English, e.g. *The elected officials *hopes to...* (Osterhout & Mobley, 1995). Also, word forms to which productive inflectional suffixes were incorrectly applied have been reported to elicit LANs, such as in **bring+ed* (Gross et al. 1998; Morris & Holcomb, 2005; Penke et al., 1997; Rodriguez-Fornells et al., 2001; Weyerts et al., 1997). Generally, LAN has been interpreted as a signal of morphosyntactic anomaly detection (Friederici, 2002), or more specifically as a response to violations of regularities related to morphosyntactic structure building (Penke et al., 1997). It has been associated with sentence structure analysis processes operating on morphologically expressed cues, such as the presence of decomposable inflectional morphemes in constituents (Molinaro et al., 2011).

3.2.1.2 N400

Words that are structurally well-formed but semantically anomalous in the given context tend to elicit a different ERP effect, a so-called N400, which is a negative deflection peaking around 400 ms after stimulus presentation, typically displaying a centro-parietal scalp distribution. The N400 was first described as a response to sentence-final words with meanings that mismatched the sentence context such as *He spread the warm bread with* <u>*socks*</u> (Kutas & Hillyard, 1980). Later it became clear that the processing of each word in a sentence might be associated with an N400, but the magnitude of the component is affected by various manipulations. For instance, words with low frequency of occurrence in the language elicit larger N400 effects than more frequent items (Münte, Urbach, Düzel, & Kutas, 2000). Even pseudowords (pronounceable nonwords) yield N400s, which tend to be large for non-repeated presentation of pseudoword items in lists or word pairs (Kutas, Van Petten, & Kluender, 2006).

A number of different views exist concerning the processes that the N400 component reflects. For instance, the N400 has been associated with semantic unification, involving the integration of the meaning of a lexical item into a larger semantic representation constructed on the basis of the preceding context (Hagoort, Baggio, & Willems, 2009). Greater difficulties with this integration process would be then expected to yield larger N400 amplitudes. Alternative perspectives relate the N400 to accessing information in long-term semantic memory (Kutas & Federmeier, 2000, 2011). From this perspective, modulation of N400 might be related to the activation state of the semantic memory system, where larger changes generate greater N400 responses. However, if features corresponding to the meaning representation of an item are already more or less activated in memory, due to, for instance, processing a related sentence context, lexical access does not induce a significant increase in activation state, moderating the observed N400 amplitude (Kutas & Federmeier, 2011).

3.2.1.3 P600

A later, positive-going ERP effect with a largely posterior scalp distribution has been observed for syntactic anomalies and complex sentence structures (see Figure 1 (bottom)). The P600 has an onset around 600 ms, and it might appear after earlier language-related ERP effects in certain cases, constituting a biphasic pattern. For instance, a P600 has been reported for incorrect use of inflectional marking on sentence constituents (e.g. the past tense suffix *-ed* on an irregular verb **bringed*), following a LAN (Morris & Holcomb, 2005). Presenting an intransitive verb (e.g. *departed*) that does not take an object argument (**departed the banker*) together with an object noun in German has been shown to result in an enhanced N400 as well as a P600 effect (**Anna weiß, dass der Kommissar (NOM) den Banker (ACC) abreiste (V)…* 'Anna knows that the inspector (NOM) the banker (ACC) departed (V)…') (Friederici & Frisch, 2000, p. 481). Completely well-formed sentences might produce a P600, if the reader/listener is forced to reanalyze an originally preferred structural interpretation at some point, such as at the auxiliary verb *was* in the garden path sentence *The lawyer charged the defendant was lying* (Osterhout, Holcomb, & Swinney, 1994). The P600 has thus been argued to reflect language comprehension processes associated with reanalysis and repair of syntactic structures (Friederici, 2002). Nevertheless, the P600 has even been reported for language materials where apparently no structural reanalysis is necessary: long distance dependencies, where related constituents – for instance the subject, object and the verb – are separated from each other by intervening words in the sentence, elicited P600 effects (Kaan, Harris, Gibson, & Holcomb, 2000). Based on these observations, the P600 has been proposed to reflect general syntactic integration difficulties associated with incorporating constituents into the emerging sentence structure (Kaan et al., 2000).

3.2.2 Neural oscillations

Already at the earliest observations of recordable electrical activity from the brain at the end of the 19th century, initially in animals, researchers noted the presence of rhythmic oscillations in the EEG (Bastiaansen, Mazaheri, & Jensen, 2012). For instance, high-amplitude 8-12 Hz oscillations, the *alpha waves*, are often easily detectable in the raw EEG, when subjects close their eyes (see Figure 2). Interest in neural oscillations, however, only started to grow in the 1980s and 1990s, when it became clear that ERPs constitute only one part of the event-related changes that take place in the EEG activity. Neural oscillations are ongoing phenomena, spontaneously present in the EEG even independently of a task; nevertheless, they might be modulated by experimental events. The related oscillatory changes are time-locked to the event of interest, but the phase of the oscillations (the position within the oscillatory cycle at a given moment) might vary from one presentation of the event to the next, due to the ongoing nature of rhythmic EEG activity. Consequently, non-phase-locked oscillatory event-related responses will be significantly reduced during the standard averaging procedure used to extract the ERP (Bastiaansen et al., 2012).

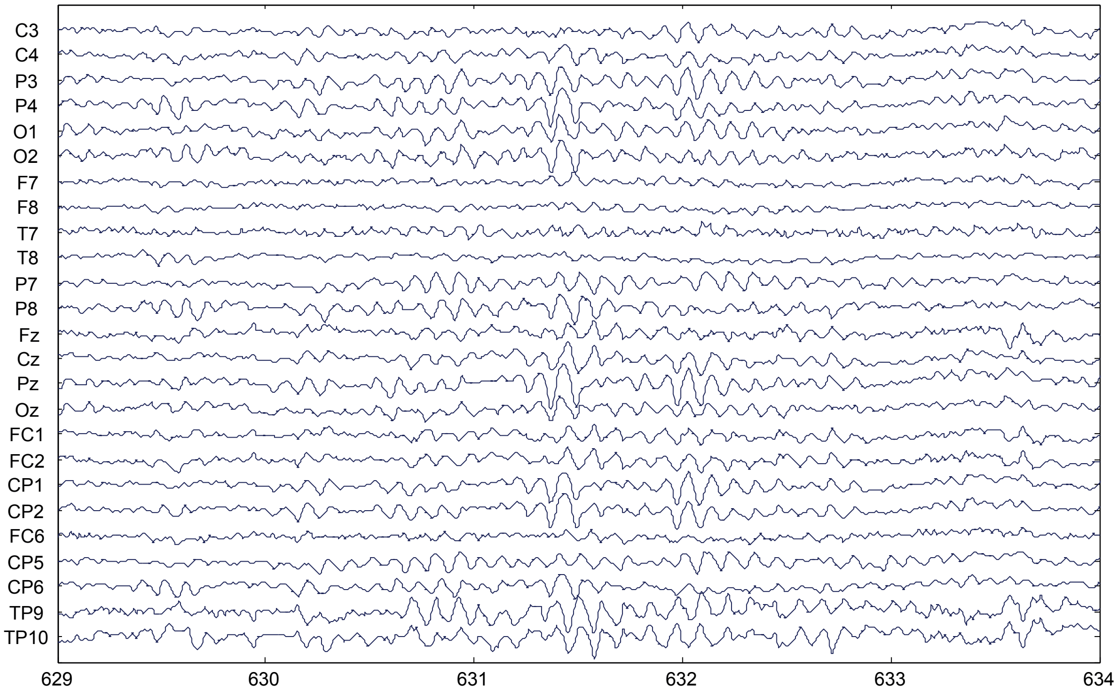

Figure 2
EEG represented in the time domain, between 629 and 634 seconds of a recording. Electrode names are shown along the vertical axis. Rhythmic alpha waves become especially prominent over parietal and occipital electrodes around 631 and 632 seconds.

The exact relationship between ERPs and neural oscillations is a matter of debate (e.g. Sauseng et al., 2007), and it is not clear whether these measures are the reflection of the same or independent phenomena. According to the *additive model*, ERPs are assumed to be produced by neural activity evoked by a stimulus that is additive to and independent of ongoing oscillations (e.g. Mazaheri & Jensen, 2006). The alternative *phase-resetting* view argues that ERPs are in fact the result of phase-related changes in ongoing oscillations: the onset of a stimulus in each trial causes a partial phase-resetting of the EEG, and the phase-locked rhythmic activity emerges as the ERP during averaging (e.g. Makeig et al., 2002). More recently it has also been suggested that both of these phenomena might contribute to ERP generation (Min et al., 2007).

Neural oscillations are often studied to gain insight into functional network formation in the brain (Bastiaansen et al., 2012). It has been argued that oscillatory synchronization among neuronal groups might constitute a mechanism for the dynamic coordination of distributed brain processes, underlying the emergence of unified concepts and experiences (e.g. Singer, 1999; Varela, Lachaux, Rodriguez, & Martinerie, 2001). For instance, visual objects are perceived as coherent entities, even though various attributes of an object are represented separately in different visual areas of the brain (Varela et al., 2001). Functional network formation can be assumed to rely on local neuronal synchrony within processing nodes of the network as well as on long-range synchronization between different nodes of the network (Bastiaansen et al., 2012). Elements constituting the same functional network will oscillate in synchrony at a specific frequency. Local synchrony will be reflected in power changes in a given frequency band: when a larger number of neurons within a population fire synchronously, the amplitude of field potentials recorded at a specific site increases (Bastiaansen et al., 2012). As for long-range synchronization, the phase relationship between oscillations picked up at different recording sites will be informative: with increased synchrony, the phase difference between the recorded rhythmic field potentials becomes more consistent (Bastiaansen et al., 2012). A number of methods exist for quantifying long-range neuronal synchrony (see e.g. Bastos & Schoffelen, 2016). In Study 1, Phase-Locking Value (PLV) analysis was conducted on the EEG data in order to gain insight into hypothesized modulation of the engagement of the language processing streams during the comprehension of different types of complex word forms. The PLV assesses the variance in the phase difference between two signals, e.g. oscillations recorded from two different electrodes, across trials of stimulus presentation. As input to the analysis, EEG data need to be represented in the time-frequency domain (Figure 2 shows EEG in the time domain), which involves estimating the magnitude and phase of oscillations at a given frequency for each time point in single-trial EEG epochs. Magnitude estimates are then unit-normalized (transformed to the same value) for the PLV analysis. Such magnitude normalized complex values are derived for signals obtained from both electrodes in question, and the two signals' difference in phase is calculated for each trial. Quantifying the consistency of trial-to-trial phase differences will then yield the PLV index, ranging from 0 to 1, where 1 stands for completely stable phase differences (Roach & Mathalon, 2008). Software tools are available for semi-automatized processing of EEG data. For example, the open source Matlab toolbox, Fieldtrip (Oostenveld, Fries, Maris, & Schoffelen, 2011), contains pre-defined methods for calculating time-frequency representations and deriving PLV values.

3.3 MRI and cortical thickness measurements

As was mentioned in the previous section, EEG data provide limited information as to the brain regions that underlie language-related functions. Nevertheless, with the development of the magnetic resonance imaging (MRI) technique during the last few decades, it became a standard procedure to create images of different parts of the body in vivo, including the brain. Various methods have been introduced for mapping cognitive functions to neural substrates in humans in a non-invasive manner. For instance, functional MRI (fMRI) can be used to localize patterns of brain activation, by measuring changes in blood oxygenation levels as blood flow to activated areas in the brain increases (Buxton, 2009). In addition, based on detailed anatomical images obtained with the MRI technique, one can examine the macrostructure of different brain areas and relate specific anatomical features to observed performance of cognitive functions. For instance, the thickness of the cerebral cortex has proved to be an especially informative measure in the study of various domains of human cognition. Pre-existing differences in the cortical thickness of higher-level association areas in the brain have been related to individual variation in the performance of associated cognitive abilities (Karama et al., 2009; Menary et al., 2013). Cortical thickness has been observed to change during an individual's lifetime as a result of a number of factors, including experience – for example L2 acquisition (e.g. Mårtensson et al., 2012) – aging (e.g. Salat et al., 2004) and disease (e.g. Meyer et al., 2016). Study 2 relies on this measure of cortical structure to investigate the neural substrates of Swedish tone-suffix association processing. As a methodological background to this study, a brief description of the MRI technique is provided below, followed by an introduction to an automatized method for measuring cortical thickness based on MR images.

3.3.1 The MRI technique

MRI most commonly relies on the signal from the hydrogen proton, the nucleus of hydrogen-1 atoms, to create images. Such nuclei are abundant in the human body, which contains large amounts of water. Hydrogen protons spin on their axis, like the planet earth. Spin is an intrinsic property of the proton, which always has the same magnitude, and only the axis of spin can change. In addition, the proton has magnetic moment, being a rotating mass that has an electrical charge. The proton is therefore affected by external magnetic fields, similarly to a compass needle, and the motion of its magnetic axis generates a signal. The MRI scanner applies a strong magnetic field to the body placed into it, which causes the magnetic moments of the protons to line up with the direction of the field. The magnetic fields of the protons sum up to form a net magnetization. The magnetization of the protons precesses around the direction of the static magnetic field with a frequency that depends on the strength of the static magnetic field and the chemical environment of the nucleus. Precession refers to the wobbling motion that occurs when an external force acts on a spinning object, gradually changing the orientation of its rotational axis. Additional energy is then added to the magnetic field in the form of a radio frequency wave, referred to as an RF pulse, in resonance with the precession of the magnetization, which tips over the net magnetization, producing a measurable signal. To encode spatial information, two additional magnetic fields are applied in two directions that manipulate the frequency of precession along one axis and the phase of the magnetizations along the other. The emitted signal is detected in the scanner using receiver coils, and its intensity is plotted on a grey scale to produce cross sectional images (Buxton, 2009; Weishaupt, Köchli, & Marincek, 2008). Importantly, protons in different tissues in the body relax back to their normal state at different rates, which creates the contrast in the resulting images. This relaxation time is measured in two ways: T1 refers to the recovery time of the net magnetization to reach equilibrium and T2 largely determines how much time it takes for the excited state to decay following excitation (Weishaupt et al., 2008). T1 and T2 times vary, for example, between white matter, grey matter and cerebrospinal fluid in the brain, and therefore such contrasts can be represented in the images (Buxton, 2009). For instance, as RF pulses are repeatedly applied to the imaged slice of the body with short intervals, the signal produced by a tissue with short T1 will be stronger, appearing bright in the images. Tissues with long T1 will produce relative weaker signals, appearing darker. The resulting digital MR image is a two-dimensional matrix of pixels, each standing for a value of signal intensity. Each pixel represents a corresponding three-dimensional tissue volume with a given slice thickness, referred to as a ‘voxel’ (Weishaupt et al., 2008).

The low energy of the radiation present in MRI experiments constitutes no biological hazards (Berger, 2002), but certain risks are involved largely related to the strong magnetic fields used, which can dislocate or heat up metal implants in the body. MR examinations are therefore preceded by rigorous screening and safety procedures. For clinical purposes, the magnetic field strength used is typically up to 3 Tesla, which is approximately 60 000 times the magnetic field of the Earth. For research applications, it is no longer uncommon to find 7 Tesla or even higher field systems (Duyn, 2012).

3.3.2 Measuring cortical thickness

The human cerebral cortex is a highly convoluted sheet of neurons, constituting two-thirds of the neuronal mass of the brain (Rakic, 1988). The thickness of the cortex varies between 1 and 4.5 mm, with an average of 2.5 mm over the whole brain (Fischl & Dale, 2000). Until the introduction of automatized methods around 2000, the measurement of cortical thickness from anatomical MR images was an extensively complex and labor-intensive task even for trained anatomists. One important difficulty is related to precisely identifying the three-dimensional folding of the cortex from a series of two-dimensional images. Therefore, studies on larger populations used to be rare, and cortical thickness was most commonly examined in post-mortem investigations (Fischl & Dale, 2000). Nowadays, however, open source software tools are freely available for the accurate and automated generation of cortical thickness measurements over the whole brain. In

Study 2, cortical thickness was measured using a surface-based automated method offered as part of the Freesurfer software package (Dale, Fischl, & Sereno, 1999). The input data constitutes MR images with sufficiently high spatial resolution and T1 contrast. The image processing method then involves the generation of accurate models of the grey and white matter surfaces as well as the pial surface, which is the boundary between the grey matter and the cerebrospinal fluid (see Figure 3). Cortical thickness is subsequently calculated as the shortest distance between the white matter and the pial surface (Fischl & Dale, 2000). To support identification of specific regions of interest in the brain, e.g. the pars opercularis of the inferior frontal gyrus, automated systems have been developed for labeling cortical (and subcortical) structures (e.g. Desikan et al., 2006). Mean cortical thickness values can be extracted for delimited brain regions and submitted to statistical analysis.

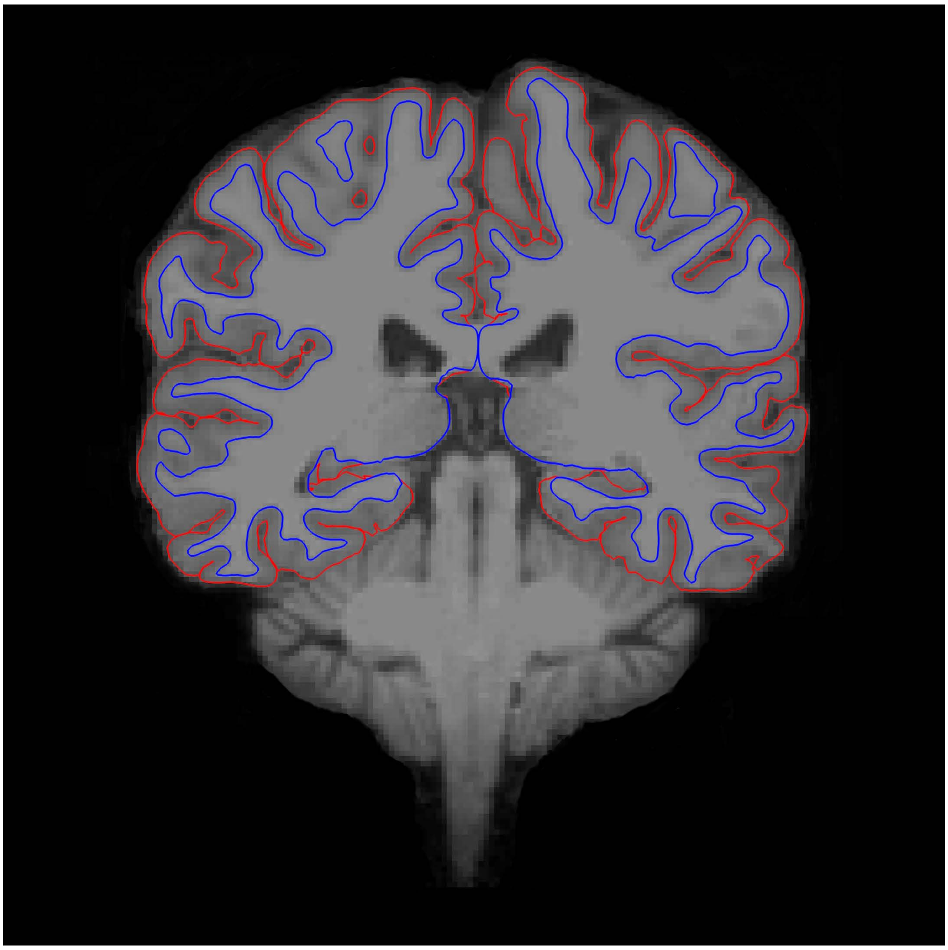

Figure 3
Illustration of the pial surface (red) and the white/grey matter boundary (blue). Cortical thickness can be measured as the distance between the white matter and the pial surface.

4. The investigations

4.1 Study 1 – Brain responses to morphologically complex verbs

Study 1 (Schremm, Novén, Horne, & Roll, submitted) focused on the question as to whether regularly inflected versus irregular verbs are processed by different neural mechanisms in Swedish during reading, as reflected in electrophysiological brain responses (ERPs). Previous studies have reported different ERP effects for regularly inflected words versus irregular forms in a range of other languages (Gross et al., 1998; Morris & Holcomb, 2005; Münte et al., 1999; Penke et al., 1997; Rodriguez-Fornells et al., 2001; Weyerts et al., 1997), which have typically been interpreted to indicate the involvement of separate processing mechanisms, largely in line with dual route models (Clahsen, 1999; Pinker, 1999). Specifically, misapplication of the regular inflection to an irregular stem has been observed to elicit a left anterior negativity (LAN), which is commonly interpreted as an index of morphosyntactic anomaly detection. Therefore, it has been suggested that the regular inflection is apparently associated with a decompositional rule-based operation, underlying its segmentation from the stem, explaining the brain response associated with violations of morphosyntactic structure (e.g. Penke et al., 1997; Rodriguez-Fornells et al., 2001). Furthermore, the operation of this decompositional mechanism is apparently tied to the presence of the regular inflection, as irregularized regular words have yielded no or different effects relative to the correct variant, implicating full-form access for correct irregular words in the mental lexicon.

Due to the absence of any relevant electrophysiological results on regular/irregular verb processing in Swedish, it was unclear whether the incorrect application of the regular inflection, such as the past tense suffix *-er/-te*, would elicit a LAN in Swedish, similarly to findings in other languages. A further question was whether the observed response to the regular inflection would be any different from the effect for the misapplication of the irregular pattern. In the regular/irregular word processing research paradigm, the default, i.e. regular, word class is typically considered to be the one where a regular and productive inflection is applied, inducing no changes to the stem (e.g. Sonnenstuhl et al., 1999; Weyerts et al., 1997). From this perspective, the 4th conjugation class of strong verbs in Swedish can be considered as the non-default, irregular class. Nevertheless, these types of verbs are still characterized by largely predictable vowel changes in the verb stem, which raises the possibility that such word forms might in fact be processed based on morphological regularities, similar to regular verbs, instead of retrieving a stored whole-word representation from memory.

EEG was recorded from Swedish native speakers while they read sentences with overregularized irregular (e.g. **bär+de* 'bear + past tense') and irregularized regular (e.g. **löft* 'lifted') verbs, as well as corresponding correct irregular (e.g. *bar* 'bore') and regular (e.g. *lyft+(t)e* 'lift+ed') forms. Overregularized items were constructed by attaching the regular past tense (preterite) suffix to an irregular (4th conjugation class) verb, and irregularized words were formed by applying the predictable vowel change patterns of irregular past tense forms to regular (2nd conjugation class) verbs. The task was to judge the correctness of sentence form after each trial. In line with previous findings, overregularized verbs elicited a left-lateralized negativity between 350 and 500 ms following verb onset, interpreted as a LAN. Assuming that the source of this effect was the incorrect application of the default past tense rule to the stem, these results implicated rule-based decomposition for correct regular verbs in Swedish. Also, no difference was found between irregularized verbs and correct regular forms in the LAN time window, suggesting that the stem vowel alternations of the irregular class might not be perceived as productive morphological regularities with a comparable status to the regular past tense suffix, and correct irregular verbs might be retrieved in full form from the mental lexicon. Both incorrect conditions elicited a P600 as expected, potentially due to difficulties related to sentence structure processing with an incorrect verb form.

In addition, inspection of the ERP waveforms superimposed for all four conditions, instead of considering regular and irregular conditions separately, suggested the presence of a negativity in the LAN time window for not only overregularized verbs, but also for both regular conditions (regular correct and irregularized verbs) relative to correct irregular verbs. Indeed, increased morphological processing could have conceivably taken place in the conditions showing a negativity, which might be reflected in LANs, under a more general view of this ERP effect as an index of morphological analysis (Krott & Lebib, 2013). Thus, even irregularized verbs could have been processed based on morphological regularities of the vowel alternation pattern, since participants might have reanalyzed the stem during reading the sentences in order to recover the original correct regular form. This interpretation would implicate relatively more reliance on semantic information in processing the familiar irregular correct verbs, due to whole-word access, thus suggesting involvement of the semantic ventral stream (e.g. Hagoort, 2013). At the same time, relatively greater reliance on the dorsal stream might be assumed for the other conditions, where morphological processing for the verb is engaged as well (Bozic et al., 2015;

Marslen-Wilson & Tyler, 2007; Rolheiser, Stamatakis, & Tyler, 2011). In order to test these hypotheses, we conducted a follow-up analysis on the EEG data, comparing oscillatory phase synchrony between frontal and posterior electrodes across the experimental conditions. The rationale behind the analysis was that modulation of oscillatory phase synchrony between distant sites could indicate transient long-range functional network formation in the brain (von Stein & Sarnthein, 2000), and therefore might tap into patterns of engagement of the dorsal versus ventral processing streams for comprehension of the different verb forms. Results indicated increased synchrony for the irregular correct verb condition relative to overregularized verbs in the theta frequency range (4-7 Hz), which was confined to the left side of the brain during the time period of the LAN effect but later spread to both hemispheres in the P600 time window. This observation was tentatively interpreted to indicate a relative difference in the processing streams engaged, with greater reliance on the ventral, more semantic, route for irregular correct items. As expected, no difference was found between regular correct versus irregularized verb conditions, which might suggest similar involvement of the dorsal stream, assumed to be the decompositional route, for processing both of these word form types.

In sum, the proposed interpretations for both the ERP and the oscillatory phase synchrony results were consistent with the assumption that two separate processing routes might be engaged during the comprehension of visually presented complex word forms in Swedish. Processes associated with decompositional analysis versus whole-word access of inflected verb forms might potentially differ in their reliance on the ventral versus dorsal language processing streams. Furthermore, it seems that even regularities applying in the stem of the non-default class might be associated with morphological processing under specific conditions; nevertheless, the correct Swedish irregular verbs tested were apparently retrieved as whole words during reading.

4.2 Study 2 – Cortical thickness in native language tone processing

The results of Study 1 indicated two separate processing routes underlying the comprehension of different types of inflected word forms in Swedish. Nevertheless, as these findings were obtained with visually presented sentences, it was still unclear how Swedish native speakers process complex word forms when word accents on the stem cue upcoming inflections in speech stimuli. This question was investigated in Study 2 (Schremm et al., 2018), where the focus was on the way the cortical structure of brain regions implicated in Swedish tone processing could support integration of the word accent cue into the morphological processing system.

Tones on word stems in Swedish elicit a pre-activation negativity (PrAN) in the brain response, suggesting anticipatory activation of memory representations of likely upcoming word endings, modulated by the certainty and frequency of a given continuation (Roll et al., 2017; Söderström et al., 2016a). Considering the gradual nature of this process, individual differences among Swedish native speakers might be observed as regards the degree to which they rely on word accents during suffix processing. Such differences could be reflected in response-time (RT) patterns to cued inflections: the more listeners rely on the word accent, the more their suffix processing is disrupted by word forms with invalid tone-suffix associations, resulting in longer decision latency as regards the meaning of the inflection, relative to the case when a valid tonal cue facilitates processing of upcoming word structure. Furthermore, reliance on word accents might be associated with macrostructural variation in core brain areas implicated in Swedish tone processing. Specifically, cortical thickness has been associated with individual differences in cognitive abilities, implemented in those brain regions that displayed variation in the measure (Karama et al., 2009).

Based on previous neuroimaging studies on functional brain activation during speech comprehension, the planum temporale (PT) and the pars opercularis of the inferior frontal gyrus (IFGpo) in the left hemisphere were identified as crucial areas for word accent processing in inflected Swedish words (Roll et al., 2015) and in pseudowords carrying regular Swedish suffixes (Söderström et al., 2017), respectively. Pseudowords clearly do not have any memory representations in the mental lexicon that would enable processing through stored full forms, and comprehension would therefore presumably involve segmenting the only familiar and grammatically meaningful element, the suffix, from the stem. Previous studies indeed reported left IFGpo involvement in decompositional processing of regularly inflected words (Bozic et al., 2015; Tyler et al., 2005). At the same time, speakers might potentially store more frequent (real) Swedish words in lexical memory (Lehtonen, Niska, Wande, Niemi, & Laine, 2006), in which case the stem tone could be thought to be incorporated into the stored whole-word representation. Study 2 investigated whether cortical thickness could support these two hypothesized tone-suffix processing mechanisms, by examining the relationship between listeners' reliance on word accent cues, quantified by their RTs, and the cortical thickness of the PT as well as the IFGpo. Magnetic resonance imaging and RT data were analyzed from two previous experiments, testing real words (Roll et al., 2015) and pseudowords (Söderström et al., 2017). Participants listened to sentences with words (real or pseudoword stems) inflected with the singular or plural suffix, and made a decision to the question as to whether the target words referred to "one" or "many" things. RTs were measured from suffix onset. In the Valid condition, the tone on the word stem (accent 1 or accent 2) was followed by its associated singular or plural suffix (e.g. *hatt*$_{accent1}$*+en* 'hat+sg', *kvut*$_{accent1}$*+en* 'kvut+sg'), and in the Invalid condition an incorrect stem tone-suffix sequence was presented (e.g. **hatt*$_{accent1}$*+ar*, **kvut*$_{accent1}$*+ar*). The analysis in Study 2 involved extracting mean cortical thickness of bilateral PT and IFGpo using Freesurfer. Subsequently, Invalid minus Valid RT differences, quantifying the relative processing advantage for correctly cued suffixes, were correlated with the obtained cortical thickness measurements for each participant.

For real word processing, results showed that reliance on the tonal cue correlated positively with cortical thickness in left PT, but not in right PT or bilateral IFGpo. For pseudowords, RT advantage for validly cued suffixes correlated positively with cortical thickness in left IFGpo instead. These results suggest that the way cortical thickness of left PT supports tone processing seems to be specific to real words. Importantly, the tested pseudowords consisted of Swedish phonemes, but larger chunks such as syllables of the pseudowords did not occur in actual words. Based on these considerations, the following possible mechanism was proposed underlying tone pre-activation, when inflected words are accessed in full form in the mental lexicon: native speakers could be assumed to process the speech input in terms of stored memory representations for frequent speech sound patterns, e.g. syllables, which could even incorporate tone patterns in Swedish. Given the previously observed role of left PT in linguistic tone processing (Xu et al., 2006), greater cortical thickness of PT might enable more efficient analysis of tone information and in turn rapid activation of the stored sound patterns incorporating tone, which would facilitate pre-activation of the whole word form with the tone-associated ending. For pseudowords, however, the pre-activation process cannot rely on stored syllable chunks incorporating tones and might take place via a morphological rule instead, as indicated by the correlation found with left IFGpo. Thus, thicker cortex in left IFGpo might enable more efficient use of an abstracted association between the tone itself and the inflectional suffix, and could potentially support the segmentation process as well, separating the meaningful suffix from the stem.

In general, it seems that two mechanisms are available for processing inflected Swedish word forms in speech, and cortical structure of specific areas in the left hemisphere might modulate the efficiency of these processes. Cortical thickness in the left PT might play an important role in the processing of tonal cues when stored whole-word representations with the associated suffix are retrieved, and cortical thickness in left IFGpo could facilitate rule application specifying the relevant tone-suffix association during decompositional analysis.

4.3 Study 3 – Implicit acquisition of tone-suffix connections in L2 learners of Swedish

Study 3 (Schremm, Söderström, Horne, & Roll, 2016) examined L2 acquisition of the morphological function of word accents by adult learners of Swedish. The main question was whether learners with a non-tone native language background would implicitly acquire the predictive use of tone-suffix associations during L2 speech processing after relatively long exposure to Swedish and when they have reached higher levels of proficiency. It was assumed that any learning effects found would be the outcome of implicit acquisition, since Swedish tone-suffix associations are not normally taught at language courses and they are unlikely to be pointed out by native speakers who are typically unaware of the regularity.

In order to test whether relatively advanced L2 learners use word accents predictively, we analyzed response-time patterns to regular verbal inflections, validly or invalidly cued by the preceding tone on the word stem. The experimental conditions were similar to the ones used in Study 2, but the target words presented in sentences were inflected verbs instead of nouns, and exclusively real Swedish words. In the Valid condition, accent 1 or accent 2 was followed by its related present tense *-er* or past tense (preterite) *-de/-te* suffix in regular 2nd conjugation class verbs, e.g. *lek*$_{accent1}$*+er* ‘play+s’, *lek*$_{accent2}$*+te* ‘play+ed’. In the invalid condition, the suffix was preceded by an incorrect stem tone, e.g. **lek*$_{accent1}$*+te*, **lek*$_{accent2}$*+er*. The task was to decide on the present tense versus past tense reference of the sentence after each verb presentation, as quickly as possible. The participants were L2 learners of Swedish with a non-tone, non-Scandinavian native language background, who were all at an intermediate to upper intermediate proficiency level in the L2 and had spent on average 1.9 years in Sweden. Their response-time patterns were compared to data collected with native speakers in Swedish in a previous study (Söderström et al., 2012).

Results showed that, similarly to native speakers, L2 learners responded significantly faster to suffixes validly cued by the stem tone, relative to invalidly cued suffixes. This finding suggests that the learners had acquired the tested tone-suffix associations and they relied on tones to anticipate likely upcoming inflections. Encountering a suffix that mismatched the tone-based expectation in the Invalid condition generated greater processing difficulty, reflected in increased response times. It seems therefore that it is possible to acquire the predictive use of tones as cues to morphological structure without instruction. Presumably, L2 learners acquired this feature via implicit learning mechanisms that operate on statistical regularities, such as the transitional probability of the suffix to follow a specific word accent on the stem. Such regularities are abundant in the input given the pervasiveness of Swedish word accents, and the co-varying features (tone-suffix) are often realized locally, e.g. on adjacent syllables in disyllabic words.

Nevertheless, L2 learners displayed a smaller processing advantage for validly cued suffixes than the control group, suggesting that they still did not rely on the predictive significance of word accents to the same extent as native speakers do, possibly due to weaker tone-suffix associations in their mental representations. However, a marginal positive correlation obtained between time spent in Sweden and the response-time advantage for validly cued suffixes suggested that processing might become more native-like with increased exposure to the L2.

Interestingly, L2 learners responded faster and more accurately to the suffixes than native speakers did, which was tentatively attributed to the fact the learners were on average younger, which might have constituted a slight general cognitive processing advantage. Furthermore, suffix-processing patterns were also modulated by group: native speakers responded faster to present tense than to past tense suffixes, while no such difference became significant for L2 leaners. As a possible explanation, it was suggested that learners' L2 tense system might be still somewhat less complex than that of native speakers, perceiving both the tested present tense and preterite suffixes as default ways of expressing the given tense reference, whereas native speakers might have been more influenced by the fact that a larger number of complex tense constructions can be used to grammatically refer to the past than to the present in Swedish.

4.4 Study 4 – Training predictive L2 processing with a digital game

The results of Study 3 indicated that it is possible for adult L2 learners to implicitly acquire the Swedish tone-suffix associations, through exposure to the language. Nevertheless, even relatively advanced learners displayed more limited predictive use of word accents as compared to native speakers, suggesting that implicit acquisition of this L2 feature is a gradual and slow process. Therefore, in Study 4 (Schremm, Hed, Horne, & Roll, 2017) we explored the possibility of training low proficient L2 learners of Swedish in the anticipatory use of tones as cues to upcoming suffixes. Based on previous findings of L2 acquisition studies, we formulated a number of hypotheses as regards the learning conditions that could facilitate acquisition of the targeted L2 skill. For instance, extensive exposure to the tone-suffix associations in naturalistic native speech input was assumed to be beneficial for promoting the development of predictive associations between tones and suffixes in the learners' L2 system. Also, introduction of a more explicit task requiring the actual performance of a tone-based prediction was considered necessary, in order to direct attention to the stem tone as an anticipatory cue. Finally, a task encouraging fast performance of the tone-based suffix prediction was assumed to facilitate the emergence of an L2 predictive processing skill that can underlie the rapid generation of suffix predictions under the time-constraints of online speech processing.

Motivated by the above considerations, a prototype of a digital L2 learning game was developed and tested. Game play consisted of presentations of sentence contexts (both auditory and visual), up until a predictive tonal cue on the target word stem is heard. For each sentence item, the player was required to decide how the target word stem would continue by selecting one of two alternative inflectional suffixes, as quickly as possible. Both suffixes constituted grammatically correct continuations, but only one of them was cued by the preceding word accent. The player then received immediate feedback on the accuracy and speed of the choice, and the correct continuation was always pronounced and displayed, in order to foster the development of correct associations between word accents and suffixes. Target words included nouns with singular versus plural inflections (e.g. *bil-en* 'car-the' versus *bil-ar* 'car-s') as well as regular verbs with present versus past tense (preterite) inflections (e.g. *lek-er* 'play-s' versus *lek-te* 'play-ed'), similar to the word forms tested in Study 2 and 3. Only valid tone suffix associations were presented, in the context of real and relatively frequent Swedish words. The language material was organized into levels of increasing difficulty, and an accuracy of 80% for a whole round (18-20 sentence items) was required for progression to the next level. In order to test the proposed L2 training method, L2 learners of Swedish with non-tone native language background played the prototype of the game for 10 days, 15 to 60 minutes each day, while response-time and accuracy data were continuously logged. Learners were at low to intermediate proficiency levels and had lived in Sweden for an average of 5.8 months. A sentence production test was conducted before and after training, to see if there would be any improvements in learners' pronunciation of tone patterns, correctly preceding the trained noun and verb inflections.

Analysis of game performance data indicated clear learning effects by the end of the training period: L2 learners' accuracy in selecting the correct suffix continuation cued by the tone showed a general increase throughout the levels of the game, at the same time as they became gradually faster at making the correct choice. Thus, the game seems to have promoted the acquisition of the tone-suffix associations as well as the development of the anticipatory use of tones. More time spent on the final level of the game, practicing the complete language material, was associated with greater accuracy gains, further indicating that performance improvement was actually due to training. Interestingly, response-time reduction was not straightforwardly related to practice time, as suggested by an absence of correlation between the measures. This observation might be indicative of the role of qualitative changes, such as automatization, in significantly speeding up the performance of the predictive L2 skill, possibly explaining the lack of a simple gradual learning curve. In addition, a transient increase in response times was associated with the introduction of mixed target word types in the game, i.e. when sentences with either inflected noun or verb targets were first presented within the same sequence. This apparent increase in processing difficulty was possibly related to the fact that acquisition of the predictive use of word accents is not limited to the development of suffix pre-activations, but one should also learn to generate predictions that are contextually relevant. For instance, a word accent on a verb stem preferentially pre-activates only a subset of its associated suffixes. These would include word endings that constitute grammatical continuations, excluding therefore noun inflections. Also, pre-activation of associated suffixes might be modulated by further contextual (such as semantic or pragmatic) constraints. The L2 acquisition of this mechanism, i.e. inhibition of possible continuations according to dynamically changing contextual constraints, might temporarily increase processing difficulty. Finally, accuracy in pronouncing tone patterns improved significantly from pre- to post-training, indicating that L2 perceptual training focusing on tonal cues might beneficially affect production. Lack of any significant correlations with game performance gains pointed to a complex relationship between perception and production improvements.

In conclusion, only after ten days of playing the game prototype, L2 learners' performance indicated significantly improved anticipatory suffix processing based on word accent cues. These results indicate that even low proficient L2 learners might begin to integrate Swedish tones as predictive cues into their L2 inflectional morphology processing system, if they receive focused training.

5. Conclusions

Inflectional morphology processing in Swedish was investigated in four studies. Studies 1 and 2 focused on native speakers and examined core processing mechanisms involved in the comprehension of complex word forms, in reading as well as in speech, when tones on word stems function as predictive cues to upcoming suffixes. Studies 3 and 4 addressed issues related to the L2 acquisition of a unique aspect of Swedish inflectional morphology processing: the word accent-suffix associations and reliance on this feature to anticipate word structure in online speech comprehension, at higher as well as lower L2 proficiency levels.

The results of Study 1 suggest that two separate processing routes are available for the comprehension of complex Swedish verb forms: rule-based decompositional analysis and whole-word access in lexical memory, in line with dual route models (Clahsen, 1999; Pinker, 1999). Generally, decomposition was associated with the presence of the regular past tense inflection, indicating that verbs such as *lekte* 'played' might be processed by analyzing the verb form into stem and suffix parts (i.e. *lek+te*). Thus, similar to results in a number of previously investigated languages, incorrect application of the regular past tense inflection in Swedish elicited a LAN in the electrophysiological brain response, commonly interpreted as an index of morphological anomaly detection. Interestingly, LAN-like negativities were apparently also present for the incorrect use of the irregular verb formation pattern and for correct regularly inflected verbs in Study 1. This observation would be consistent with a more general interpretation of the LAN effect, signaling morphological processing as such (Krott & Lebib, 2013). Therefore, when no corresponding stored whole-word representations exist, it seems that decompositional mechanisms might be engaged even for processing regular patterns associated with non-default word classes, i.e. the predictable vowel alternations in Swedish irregular verb stems. Participants reading irregularized verbs such as **löft* might have made an attempt to recover the correct word form, potentially based on changing the stem vowel (**löft* > *lyft-* > *lyfte* 'lifted'). The only experimental condition that showed no signs of morphological processing of target words in Study 1 constituted of correct irregular verbs, suggesting that native speakers reading an irregular verb such as *bar* 'bore' might directly access a corresponding stored inflected word form in lexical memory. Facilitated semantic processing associated with whole-word access to irregular word forms was proposed to be reflected in the increased posterior-frontal oscillatory synchrony obtained for that experimental condition. Increase in synchronization between these distant regions of the brain might indicate engagement of a functional network along the ventral language processing stream, potentially in relation to direct lexical access to complex word forms.

Based on the findings of Study 2, Swedish stem tones can be assumed to be used predictively to anticipate upcoming inflectional suffixes during both whole-word access and decomposition of complex word forms. Predictive reliance on tones might be implemented via incorporation of the tone pattern into stored representations of whole inflected word forms. When such stored items are unavailable, e.g. for pseudowords, the application of a regularity specifying the relevant abstracted tone-suffix association could facilitate decompositional processing of the cued word ending. These proposals were formulated considering the functional significance of the investigated brain regions where cortical thickness showed an association with anticipatory tone processing performance in Study 2. Thus, left planum temporale (PT) seems to play an important role when stored full form representations are accessed, as reflected in a positive correlation between response-time advantage for cued suffixes in real words and cortical thickness in this region. Thicker left PT cortex might in general enable more efficient left-hemispheric tone processing due to greater prevalence of cortical organization tuned for the accurate representation of slower changing acoustic cues (e.g. Harasty, Seldon, Chan, Halliday, & Harding, 2003; Poeppel, 2003). Assuming that Swedish native speakers have stored phonological representations for certain inflected word forms specifying stem tones as well, processing a stem tone would automatically generate greater pre-activation of those complex word forms that are inflected with the suffix the specific tone pattern is associated with.

A significant positive correlation obtained between cortical thickness and response times to inflected pseudowords suggests that the pars opercularis of the left inferior frontal gyrus (IFGpo) might be involved when predictive suffix processing relies on abstract stem tone-suffix associations. Thicker cortex in this area could conceivably support effective morphological rule application, given that left IFGpo was previously seen to be implicated in decompositional processing of inflected word forms (Bozic et al., 2015; Tyler et al., 2005). It seems therefore that the abstracted association between Swedish tones and suffixes might be captured in terms of a morphological regularity, operating independently of specific lexical items, as has also been proposed by Söderström et al. (2016b). Even though these results were obtained for pseudowords, similar tone-suffix processing mechanisms and neural substrates might be assumed for the comprehension of less frequent regularly inflected real words that are not stored in lexical memory in their various inflected forms.

The findings of Study 2 that the presence or absence of stored whole-word representations might modulate the role of specific brain regions in inflectional morphology processing are in line with the apparent differential engagement of language processing streams observed in Study 1, for full-form access versus morphological analysis of inflected verbs. Moreover, the involvement of frontal (IFGpo) versus temporal (PT) areas is consistent with proposed dual-route brain systems, associating decomposition with a fronto-striatal network and full-form access largely with temporal regions (Pinker & Ullman, 2002; Ullman, 2004).

Turning to Swedish inflectional morphology processing in adult L2 acquisition, Study 3 showed that tone-suffix associations are acquired implicitly by more proficient learners as a result of extensive exposure to the L2. In a manner similar to that of native speakers, the learners tested in this study responded relatively faster to those suffixes that were cued by the preceding word accent. At the same time, incorrect tone-suffix associations increased processing time, potentially due to the need to re-evaluate a disconfirmed suffix prediction. Nevertheless, the predictive use of tones appeared to be less extensive in learners as compared to native speakers, even at relatively advanced L2 proficiency level: it can be assumed that the emergence of strong tone-suffix associations in mental representations and/or the acquisition of relevant predictive processing skills in adult L2 learners take a long time to develop under implicit learning conditions.

However, L2 training combining features of implicit and explicit learning conditions can effectively promote the acquisition of the anticipatory use of tone-suffix associations even at lower proficiency levels in Swedish, as shown by Study 4. During a two-week-period of training using a game prototype, learners displayed a gradual reduction in their response times to suffixes cued by preceding tones. Together with the observed increase in accuracy in selecting the cued endings, these findings suggest that learners acquired the relevant tone-suffix associations and started to use these to predict upcoming suffixes. Moreover, speakers of non-tone native languages could apparently learn to discriminate Swedish tone patterns well enough to begin to anticipate suffixes accurately, and the provided perceptual training even led to improved production of word accents.

A number of features of the tested game mechanics could be assumed to have contributed to the observed learning effects in Study 4. First, ample exposure to the tone-suffix associations in native speech input was assumed to engage learning mechanisms operating on the transitional probabilities between the predictive tonal cue and the target, the suffix. Such learning mechanisms could be thought to have promoted the development of strong mental associations between tones and suffixes in learners, supporting predictive processing. Second, it was considered important to direct attention to the stem tone as an anticipatory cue, in the form of a task that requires the performance of an actual prediction as regards the upcoming inflection. Finally, repeated and extensive performance of the suffix-prediction, under circumstances that motivated rapid responses, could have contributed to speeding up, and potentially automatizing, learners' emerging predictive L2 processing skill.

To sum up, Swedish native speakers seem to process inflected word forms either by morphological processes of decomposition or by direct access to stored full form representations in the mental lexicon. Swedish stem tones appear to be integrated into this system so that that they can effectively cue upcoming suffixes via both processing routes. Cortical thickness of specific brain regions might facilitate this process, in the left PT during whole-word access and in the left IFGpo during decompositional analysis, respectively. Furthermore, results of the L2 studies generally indicate that adult learners of Swedish can learn to rely on tonal cues to upcoming suffixes during L2 morphological processing, even in the absence of comparable tonal features in their native language. The use of tones to facilitate suffix processing seems to emerge implicitly after a longer exposure to the L2 and when higher levels of proficiency have been reached, whereas learners at lower proficiency levels might need focused training in the predictive L2 skill.

6. Outstanding issues and future directions

6.1 Factors modulating inflectional morphology processing mechanisms in native speakers

The results of Studies 1 and 2 raise questions as to the factors that might modulate the morphological processing route in native speakers for regularly inflected items in different contexts. In Study 1, correct regular verb forms were apparently processed through decomposition (yielding a LAN-like negativity in the brain response). In Study 2, inflected real nouns (items in the real word experiment) were associated with full-form access. As Pinker and Ullman (2002) argued, even certain regular word forms might be stored in declarative memory, and the processing route chosen in a given context might then depend on item-, task- or speaker-specific factors. In the present case, the most relevant differences between the real-word stimuli of Study 1 and Study 2 seem to concern the task (grammaticality judgement versus identifying singular/plural meaning), the presentation modality (visual versus auditory) and the word class of the target items (verbs versus nouns). First, in Study 1, the task ("Correct or Incorrect"), as well as the presentation of incorrectly inflected items could have motivated a general focus on word form and in turn decompositional processing. In addition, word-by-word visual presentation, which makes it possible to start processing the word stem and the inflection almost simultaneously, could have also favoured decompositional analysis. In Study 2, the task was more semantic in nature ("One or Many") and the target words were presented as spoken stimuli, which further raises the question whether the presence of tonal cues to suffixes might have specifically promoted whole-word access, if such tonal patterns could be assumed to be incorporated into stored full-form representations. Finally, it is possible that the nominal suffixes involved in Study 2 did not have the same status in participants' grammatical system as the regular past tense inflection tested in Study 1. In fact, Roll et al. (2010) noted that Swedish has no default plural formation rule, comparable to the *-s* plural suffix in English or German, and nouns can be classified into several declension classes. Nevertheless, a specific plural suffix is associated with each of the seven declension classes (Teleman et al., 1999), and it could be assumed that the inflected form might be processed decompositionally following identification of the declensional class of a given noun stem. Still, Roll et al. (2010) observed an increased N400, as well as a P600, for plural suffixes that were incorrectly applied to noun stems of a different declension class (e.g. **mink+or* instead of correct *mink+ar* ‘mink+s’). The obtained N400 effect indicates that the incorrectly inflected nouns were treated as unfamiliar lexical items, suggesting the absence of morphological decomposition related to the plural suffix. This is in contrast to the LAN effect obtained for the incorrect application of the regular past tense inflection in Study 1, indicating morphological analysis. Roll et al. (2010) employed auditory presentation, just like Study 2, whereas the task involved relatively greater focus on form (acceptability judgements: “OK or Wrong”), similarly to Study 1. In general, it seems that all the discussed factors could have potentially modulated the processing route for the inflected word forms in Studies 1 and 2, possibly in a complex interaction with each other. An EEG experiment, similar to that in Study 1, systematically manipulating factors such as presentation modality, task requirement, target word class and the presence versus absence of tones as task-relevant cues to suffixes could further clarify the nature of neural mechanisms involved in native inflectional morphology processing.

6.2 Issues related to L2 processing and acquisition of tone-suffix associations

More research is necessary to identify the neural mechanisms and brain structures that subserve L2 processing of complex Swedish word forms and the predictive use of word accents. Advanced L2 learners display native-like tonal cue processing tendencies in their behavioural responses as shown in Study 3, but it is not clear whether the underlying representations and mechanisms are native-like as well and how these might develop with increasing L2 proficiency. First of all, it is still unknown whether two separate processing routes are available to adult L2 learners for the comprehension of complex word forms in Swedish and whether they function like they do in native speaker processing. In fact, late L2 learners have been argued to tend to rely on lexically stored whole-word representations, even for regularly inflected words, until high levels of proficiency have been reached (Clahsen, Felser, Neubauer, Sato, & Silva, 2010; Ullman, 2001b). From this perspective, the procedural memory system is characterized by reduced availability during adult L2 acquisition due to, for instance, hormonal changes in adolescence and the development of the declarative system (Ullman, 2006b). One might speculate whether the fact that different response-time patterns were observed for present tense versus past tense suffixes in native speakers as compared to L2 learners in Study 3 could possibly reflect an associated difference in the morphological processing route between these participant groups. Native speakers processed present tense suffixes faster than past tense ones, while there was no significant difference in L2 learners. One highly tentative explanation could be that learners used whole-word access for the comprehension of the inflected verbs, whereas native speakers relied on decompositional processing of the regular present and past tense suffixes, in a manner similar to the processing strategies observed in Study 1, potentially motivated by the task requirements (decision on grammatical tense). Direct retrieval of stored full forms could partially explain the generally faster response times and the limited influence of suffix type in L2 learners. Certainly, native speakers could have showed a relative processing advantage for the present tense inflection solely due to its association with accent 1, which is the more predictive word accent (Roll et al., 2015). In that case, however, it is not clear why the learners tested in Study 3, who implicitly acquired tone-suffix associations through exposure to the L2, did not show a similarly facilitated processing of the accent 1-associated suffix. The available data do not enable us to draw any conclusions as to the questions whether results obtained in Study 3 could actually reflect whole-word access in L2 learners and whether this strategy would be due to the limited availability of the procedural memory system for L2 processing.

Nevertheless, previous neuroimaging studies have reported activations in brain areas related to native grammatical computations in adult L2 learners, even at low proficiency levels, a finding which challenges the assumption that the procedural system might generally be unavailable at earlier stages of L2 acquisition (Abutalebi, 2008). Also, ERP responses have been obtained in low proficient L2 learners of Swedish that were indicative of decompositional analysis of inflected word forms: following training with the game prototype presented in Study 4, L2 learners showed a left anterior negativity (LAN) for singular/plural suffixes invalidly cued by the preceding word accent (e.g. *$hatt_{accent2}$+*en*, 'hat+sg') (Hed, Schremm, Horne, & Roll, submitted). A similar ERP effect has been observed in Swedish native speakers for invalidly cued suffixes in pseudowords (Söderström et al., 2016b). It seems that L2 learners might not have been familiar with the tested lexical items, and therefore processed these in a manner similar to inflected pseudowords, but they detected the incorrect tone-suffix associations as they decomposed the word forms (Hed et al., submitted). The earliness of the LAN effect, 225-300 ms following suffix onset, might indicate the involvement of automatic processes, which would be consistent with the assumption that decomposition observable after L2 training could actually be implemented in the procedural brain system, instead of reflecting conscious rule-application. Nevertheless, further neuroimaging studies are necessary to identify the exact brain regions underlying L2 processing of complex Swedish word forms.

A left-lateralized brain network has been identified in Swedish native speakers for the predictive use of word accents (Roll et al., 2015) and the brain regions where cortical structure was associated with tonal cue processing were also localized to the left hemisphere in Study 2. However, non-lexical tonal information in general is preferentially processed in the right hemisphere (Zatorre & Gandour, 2008), and native speakers of English with no experience in tonal languages have been found to differ from Chinese listeners in that they do not show left dominant processing of Chinese lexical tones (Wang, Jongman, & Sereno, 2001). It could therefore be assumed that at the earliest stages of L2 acquisition of Swedish, word accents are processed largely in the right hemisphere in learners with non-tone native language background. Indeed, low proficient L2 learners of Swedish displayed a centrally distributed late negativity in their brain responses to accent 1, which became more prominent at right-hemispheric electrode sites with increasing L2 proficiency, as learners presumably started to develop greater sensitivity to pitch differences (Gosselke Berthelsen et al., 2018). The development pattern of functional brain activation as a result of L2 training in Swedish tone-suffix associations could be tracked using fMRI in order to establish if and when a shift to left-hemispheric tone processing might take place in learners. Examining the timeline of this change relative to the emergence of signs of predictive use of word accents in response-time patterns as well as the ERP (PrAN) could also help answer the question whether left-lateralization of tone processing is a prerequisite or a consequence of integrating word accent cues into the L2 morphological system. In addition, it could be examined whether L2 training of the tone-suffix associations would lead to increased cortical thickness in brain regions such as the left PT and IFGpo or, alternatively, if pre-existing differences in the macrostructure of these areas would predict learning success. The results would contribute to our understanding of the plasticity of the adult brain and potentially shed light on the question whether experience with a tonal language could result in an increase in the cortical thickness of specific brain areas. Also, observing training-related changes in the left IFGpo would be suggestive of the involvement of the procedural memory system in adult L2 acquisition.

6.3 Neural oscillatory synchrony and the language processing streams

Investigating neural oscillatory synchrony in order to gain insight into dynamic functional language network formation constitutes a promising research direction. In Study 1, increased theta (4-7 Hz) synchrony between posterior and frontal sites was tentatively suggested to reflect engagement of the ventral language processing stream for whole-word access. Recording magnetoencephalographic (MEG) activity during an experimental task similar to that in Study 1 would enable localization of the brain areas that participate in the oscillatory synchrony in order to ascertain increased engagement of the ventral stream during the processing of familiar irregular verbs. Furthermore, it would be possible to examine whether the comprehension of regularly inflected items is associated with increased synchrony among nodes of the dorsal route. Interestingly, long-range synchrony in the gamma (and higher beta) frequency band (20-60 Hz) along the dorsal stream – between left posterior superior temporal gyrus and left IFGpo (BA 44) – has been reported to specifically underlie the processing of regularly inflected English verbs in spoken stimuli (Fonteneau et al., 2015). The observation of both synchronized slower theta as well as faster gamma oscillations in relation to complex word form processing raises intriguing possibilities as regards the mechanisms by which distant nodes of the language network might dynamically integrate their activity. In general, the phase of theta oscillations has been observed to modulate power in the gamma band in the human neocortex, and interactions between theta and gamma frequency oscillations have been proposed to facilitate communication within distributed brain systems during cognitive tasks (Canolty et al., 2006). One hypothesis, specifically formulated in the context of memory processes, is that nesting several gamma cycles within slower theta activity could provide a neural code for transmitting multi-item messages, where the theta phase encodes the onset of the message and the gamma band signifies separate items in an ordered sequence (Lisman & Jensen, 2013). Modulation of gamma band synchronization by theta phase has been reported in relation to expressive language processing (covert verb generation) (Doesburg, Vinette, Cheung, & Pang, 2012), and it would be interesting to investigate the potential role of theta-gamma interaction in dynamically coordinating engagement of the dorsal and ventral processing streams during the comprehension of complex word forms.

References

Abutalebi, J. (2008). Neural aspects of second language representation and language control. *Acta Psychologica, 128,* 466-478.

Aronoff, M., & Anshen, F. (2001). Morphology and the lexicon: Lexicalization and productivity. In A. Spencer & A. M. Zwicky (Eds.), *The handbook of morphology* (pp. 237-247). Oxford, UK: Blackwell.

Bastiaansen, M., Mazaheri, A., & Jensen, O. (2012). Beyond ERPs: Oscillatory neuronal dynamics. In S. J. Luck & E. S. Kappenman (Eds.), *The Oxford handbook of event-related potential components* (pp. 31-49). New York, NY: Oxford University Press.

Bastos, A. M., & Schoffelen, J.-M. (2016). A tutorial review of functional connectivity analysis methods and their interpretational pitfalls. *Frontiers in Systems Neuroscience, 9*, 175.

Batterink, L., & Neville, H. (2013). Implicit and explicit second language training recruit common neural mechanisms for syntactic processing. *Journal of Cognitive Neuroscience, 25,* 936-951.

Berger, A. (2002). How does it work? Magnetic resonance imaging. *BMJ, 324*(7328), 35.

Booij, G. (2007). *The grammar of words: An introduction to linguistic morphology*. Oxford: Oxford University Press.

Bornkessel-Schlesewsky, I., & Schlesewsky, M. (2013). Reconciling time, space and function: A new dorsal–ventral stream model of sentence comprehension. *Brain and Language, 125*(1), 60-76.

Bozic, M., Fonteneau, E., Su, L., & Marslen-Wilson, W. D. (2015). Grammatical analysis as a distributed neurobiological function. *Human Brain Mapping, 36,* 1190-1201.

Bozic, M., & Marslen-Wilson, W. (2010). Neurocognitive contexts for morphological complexity: Dissociating inflection and derivation. *Language and Linguistics Compass, 4*(11), 1063-1073.

Bruce, G. (1977). *Swedish word accents in sentence perspective*. Lund: Gleerup.

Buxton, R. B. (2009). *Introduction to functional magnetic resonance imaging: Principles and techniques*. Cambridge: Cambridge University Press.

Canolty, R. T., Edwards, E., Dalal, S. S., Soltani, M., Nagarajan, S. S., Kirsch, H. E., … Knight, R. T. (2006). High gamma power is phase-locked to theta oscillations in human neocortex. *Science, 313*(5793), 1626-1628.

Chomsky, N. (1965). *Aspects of the theory of syntax*. Cambridge, MA: MIT Press.

Clahsen, H. (1999). Lexical entries and rules of language: A multidisciplinary study of German inflection. *Behavioral and Brain Sciences, 22,* 991-1060.

Clahsen, H. (2016). Contributions of linguistic typology to psycholinguistics. *Linguistic Typology, 20*(3), 599-614.

Clahsen, H., Felser, C., Neubauer, K., Sato, M., & Silva, R. (2010). Morphological structure in native and nonnative language processing. *Language Learning, 60*(1), 21-43.

Cleeremans, A., Destrebecqz, A., & Boyer, M. (1998). Implicit learning: News from the front. *Trends in Cognitive Sciences, 2,* 406-416.

Dale, A. M., Fischl, B., & Sereno, M. I. (1999). Cortical surface-based analysis: I. Segmentation and surface reconstruction. *NeuroImage, 9*(2), 179-194.

De Diego Balaguer, R., Toro, J. M., Rodriguez-Fornells, A., & Bachoud-Lévi, A.-C. (2007). Different neurophysiological mechanisms underlying word and rule extraction from speech. *PLoS ONE, 2*(11), e1175.

DeKeyser, R., & Criado-Sánchez, R. (2012). Automatization, skill acquisition, and practice in second language acquisition. In C. A. Chapelle (Ed.), *The encyclopedia of applied linguistics* (pp. 323-331). Oxford, UK: Wiley-Blackwell.

Desikan, R. S., Ségonne, F., Fischl, B., Quinn, B. T., Dickerson, B. C., Blacker, D., … Killiany, R. J. (2006). An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *NeuroImage, 31*, 968-980.

DeWitt, I., & Rauschecker, J. P. (2012). Phoneme and word recognition in the auditory ventral stream. *Proceedings of the National Academy of Sciences, 109*(8), E505-E514.

Doesburg, S. M., Vinette, S. A., Cheung, M. J., & Pang, E. W. (2012). Theta-modulated gamma-band synchronization among activated regions during a verb generation task. *Frontiers in Psychology, 3,* 195.

Duyn, J. H. (2012). The future of ultra-high field MRI and fMRI for study of the human brain. *NeuroImage, 62*(2), 1241-1248.

Fischl, B., & Dale, A. M. (2000). Measuring the thickness of the human cerebral cortex from magnetic resonance images. *Proceedings of the National Academy of Sciences, 97*(20), 11050-11055.

Flege, J. E. (1995). Second language speech learning: theory, findings and problems. In W. Strange (Ed.), *Speech perception and linguistic experience: Issues in cross-language speech research* (pp. 233-277). Timonium, MD: York Press.

Fonteneau, E., Bozic, M., & Marslen-Wilson, W. D. (2015). Brain network connectivity during language comprehension: Interacting linguistic and perceptual subsystems. *Cerebral Cortex, 25*(10), 3962-3976.

Francis, A. L., Ciocca, V., Ma, L., & Fenn, K. (2008). Perceptual learning of Cantonese lexical tones by tone and non-tone language speakers. *Journal of Phonetics, 36,* 268-294.

Franco, A., Cleeremans, A., & Destrebecqz, A. (2011). Statistical learning of two artificial languages presented successively: How conscious?. *Frontiers in Psychology, 2*, 229.

Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences, 6,* 78-84.

Friederici, A. D. (2009). Pathways to language: Fiber tracts in the human brain. *Trends in Cognitive Sciences, 13*, 175-181.

Friederici, A. D. (2012). The cortical language circuit: From auditory perception to sentence comprehension. *Trends in Cognitive Sciences, 16*(5), 262-268.

Friederici, A. D., & Frisch, S. (2000). Verb argument structure processing: The role of verb-specific and argument-specific information. *Journal of Memory and Language, 43*(3), 476-507.

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences, 15*(1), 20-25.

Gor, K., & Cook, S. (2010). Non-native processing of verbal morphology: In search of regularity. *Language Learning, 60*(1)*,* 88-126.

Gor, K., & Jackson, S. (2013). Morphological decomposition and lexical access in a native and second language: A nesting doll effect. *Language and Cognitive Processes, 28*(7), 1065-1091.

Gosselke Berthelsen, S., Horne, M., Brännström, K. J., Shtyrov, Y., & Roll, M. (2018). Neural processing of morphosyntactic tonal cues in second-language learners. *Journal of Neurolinguistics, 45,* 60-78.

Gross, M., Say, T., Kleingers, M., Clahsen, H., & Münte, T. F. (1998). Human brain potentials to violations in morphologically complex Italian words. *Neuroscience Letters, 241,* 83-86.

Grüter, T., Lew-Williams, C., & Fernald, A. (2012). Grammatical gender in L2: A production or a real-time processing problem?. *Second Language Research, 28*(2), 191-215.

Gullberg, M., Roberts, L., & Dimroth, C. (2012). What word-level knowledge can adult learners acquire after minimal exposure to a new language?. *International Review of Applied Linguistics in Language Teaching, 50*(4), 239-276.

Hagoort, P. (2013). MUC (Memory, Unification, Control) and beyond. *Frontiers in Psychology, 4,* 416.

Hagoort, P., Baggio, G., & Willems, R. M. (2009). Semantic unification. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (4th ed., pp. 819-836). Cambridge, MA: MIT Press.

Hallé, P. A., Chang, Y.-C., & Best, C. T. (2004). Identification and discrimination of Mandarin Chinese tones by Mandarin Chinese vs. French listeners. *Journal of Phonetics, 32,* 395-421.

Harasty, J., Seldon, H. L., Chan, P., Halliday, G., & Harding, A. (2003). The left human speech-processing cortex is thinner but longer than the right. *Laterality, 8*(3), 247-260.

Hed, A., Schremm, A., Horne, M., & Roll, M. (submitted). Neural correlates of second language acquisition of tone-grammar associations.

Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition, 92*, 67-99.

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience, 8*(5), 393-402.

Hickok, G., & Saberi, K. (2012). Redefining the functional organization of the planum temporale region: Space, objects, and sensory-motor integration. In D. Poeppel, T. Overath, A. N. Popper & R. R. Fay. (Eds.), *The human auditory cortex* (pp. 333-350). New York, NY: Springer.

Hoffmann, J., & Sebald, A. (2005). When obvious covariations are not even learned implicitly. *European Journal of Cognitive Psychology, 17*, 449-480.

Jackendoff, R. (2003). *Foundations of language*. Oxford: Oxford University Press.

Joanisse, M. F., & Seidenberg, M. S. (1999). Impairments in verb morphology after brain injury: A connectionist model. *Proceedings of the National Academy of Sciences, 96,* 7592-7597.

Kaan, E., Harris, A., Gibson, E., & Holcomb, P. (2000). The P600 as an index of syntactic integration difficulty. *Language and Cognitive Processes, 15,* 159-201.

Karama, S., Ad-Dab'bagh, Y., Haier, R. J., Deary, I. J., Lyttelton, O. C., Lepage, C., & Evans, A. C. (2009). Positive association between cognitive ability and cortical thickness in a representative US sample of healthy 6 to 18 year-olds. *Intelligence, 37*(2), 145-155.

Krott, A., & Lebib, R. (2013). Electrophysiological evidence for a neural substrate of morphological rule application in correct wordforms. *Brain Research, 1496,* 70-83.

Kutas, M., & Federmeier, K. D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Sciences, 4,* 463-470.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: Finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology, 62*, 621-647.

Kutas, M., & Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science, 207*(4427), 203-205.

Kutas, M., Van Petten, C. K., & Kluender, R. (2006). Psycholinguistics electrified II (1994-2005). In M. J. Traxler & M. A. Gernsbacher (Eds.), *Handbook of psycholinguistics* (2nd ed., pp. 659-724). Amsterdam: Elsevier.

Laine, M. (1999). Meaning analysis of inflected words. *The Quarterly Journal of Experimental Psychology: Section A, 52*(1), 253-259.

Lee, Y.-S., Vakoch, D. A., & Wurm, L. H. (1996). Tone perception in Cantonese and Mandarin: A cross-linguistic comparison. *Journal of Psycholinguistic Research, 25,* 527-542.

Lehtonen, M., Niska, H., Wande, E., Niemi, J., & Laine, M. (2006). Recognition of inflected words in a morphologically limited language: Frequency effects in monolinguals and bilinguals. *Journal of Psycholinguistic Research, 35*(2), 121-146.

Lisman, J. E., & Jensen, O. (2013). The theta-gamma neural code. *Neuron, 77*(6), 1002-1016.

Luce, R. D. (1991). *Response times: Their role in inferring elementary mental organization.* New York: Oxford University Press.

Luck, S. J. (2005). *An introduction to the event-related potential technique*. Cambridge, MA: MIT Press.

Luck, S. J. (2012). Event-related potentials. In H. Cooper, P. M. Camic, D. L. Long, A. T. Panter, D. Rindskopf & K. J. Sher (Eds.), *APA handbook of research methods in psychology, Vol. 1: Foundations, planning, measures, and psychometrics* (pp. 523-546). Washington, DC: American Psychological Association.

Makeig, S., Westerfield, M., Jung, T.-P., Enghoff, S., Townsend, J., Courchesne, E., & Sejnowski, T. J. (2002). Dynamic brain sources of visual evoked responses. *Science, 295*(5555), 690-694.

Marslen-Wilson, W. D., & Tyler, L. K. (2007). Morphology, language and the brain: The decompositional substrate for language comprehension. *Philosophical Transactions of the Royal Society B: Biological Sciences, 362*, 823-836.

Mazaheri, A., & Jensen, O. (2006). Posterior alpha activity is not phase-reset by visual stimuli. *Proceedings of the National Academy of Sciences, 103*(8), 2948-2952.

Menary, K., Collins, P. F., Porter, J. N., Muetzel, R., Olson, E. A., & Kumar, V., … Luciana, M. (2013). Associations between cortical thickness and general intelligence in children, adolescents and young adults. *Intelligence, 41*(5), 597-606.

Meyer, M., Neff, P., Liem, F., Kleinjung, T., Weidt, S., Langguth, B., & Schecklmann, M. (2016). Differential tinnitus-related neuroplastic alterations of cortical thickness and surface area. *Hearing Research, 342*, 1-12.

Min, B.-K., Busch, N. A., Debener, S., Kranczioch, C., Hanslmayr, S., Engel, A. K., & Herrmann, C. S. (2007). The best of both worlds: Phase-reset of human EEG alpha activity and additive power contribute to ERP generation. *International Journal of Psychophysiology, 65*(1), 58-68.

Mintz, T. H. (2002). Category induction from distributional cues in an artificial language. *Memory & Cognition, 30*(5), 678-686.

Misyak, J. B., & Christiansen, M. H. (2012). Statistical learning and language: An individual differences study. *Language Learning, 62*(1), 302-331.

Molinaro, N., Barber, H. A., & Carreiras, M. (2011). Grammatical agreement processing in reading: ERP findings and future directions. *Cortex, 47*(8), 908-930.

Morgan-Short, K., Deng, Z., Brill-Schuetz, K. A., Faretta-Stutenberg, M., Wong, P. C. M., & Wong, F. C. K. (2015). A view of the neural representation of second language syntax through artificial language learning under implicit contexts of exposure. *Studies in Second Language Acquisition, 37*(2), 383-419.

Morris, J., & Holcomb, P. J. (2005). Event-related potentials to violations of inflectional verb morphology in English. *Cognitive Brain Research, 25,* 963-981.

Mårtensson, J., Eriksson, J., Bodammer, N. C., Lindgren, M., Johansson, M., Nyberg, L., & Lövdén, M. (2012). Growth of language-related brain areas after foreign language learning. *NeuroImage, 63*(1), 240-244.

Münte, T. F., Say, T., Clahsen, H., Schiltz, K., & Kutas, M. (1999). Decomposition of morphologically complex words in English: Evidence from event-related brain potentials. *Cognitive Brain Research, 7,* 241-253.

Münte, T. F., Urbach, T. P., Düzel, E., & Kutas, M. (2000). Event-related brain potentials in the study of human cognition and neuropsychology. In F. Boller, J. Grafman & G. Rizzolatti (Eds.), *Handbook of neuropsychology* (2nd ed., vol. 1, pp. 139-235). Amsterdam: Elsevier.

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.-M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience, Vol 2011 (2011),* 1-9.

Osterhout, L., Holcomb, P. J., & Swinney, D. A. (1994). Brain potentials elicited by garden-path sentences: Evidence of the application of verb information during parsing. *Journal of Experimental Psychology: Learning, Memory and Cognition, 20,* 786- 803.

Osterhout, L., & Mobley, L. A. (1995). Event-related brain potentials elicited by failure to agree. *Journal of Memory & Language, 34*(6), 739-773.

Penke, M., Weyerts, H., Gross, M., Zander, E., Münte, T. F., & Clahsen, H. (1997). How the brain processes complex words: An event-related potential study of German verb inflections. *Cognitive Brain Research, 6,* 37-52.

Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: One phenomenon, two approaches. *Trends in Cognitive Sciences, 10,* 233-238.

Pinker, S. (1999). *Words and rules: The ingredients of language*. London: Weidenfeld & Nicolson.

Pinker, S., & Ullman, M. T. (2002). The past and future of the past tense. *Trends in Cognitive Sciences, 6,* 456-463.

Poeppel, D. (2003). The analysis of speech in different temporal integration windows: Cerebral lateralization as 'asymmetric sampling in time'. *Speech Communication, 41*(1), 245-255.

Rakic, P. (1988). Specification of cerebral cortical areas. *Science, 241*(4862), 170-176.

Ratcliff, R. (2012). Response time distributions. In H. Cooper, P. M. Camic, D. L. Long, A. T. Panter, D. Rindskopf & K. J. Sher (Eds.), *APA handbook of research methods in psychology: Vol. 1: Foundations, planning, measures, and psychometrics* (pp. 429-443). Washington, DC: American Psychological Association.

Rauschecker, J. P., & Tian, B. (2000). Mechanisms and streams for processing of "what" and "where" in auditory cortex. *Proceedings of the National Academy of Sciences, 97*(22), 11800-11806.

Regel, S., Opitz, A., Müller, G., & Friederici, A. D. (2015). The past tense debate revisited: Electrophysiological evidence for subregularities of irregular verb inflection. *Journal of Cognitive Neuroscience, 27(9),* 1870-1885.

Riad, T. (2014). *The phonology of Swedish*. Oxford: Oxford University Press.

Riad, T. (2015). *Prosodin i svenskans morfologi*. Stockholm: Morfem.

Rischel, J. (1963). Morphemic tone and word tone in Eastern Norwegian. *Phonetica, 10*, 154-164.

Roach, B. J., & Mathalon, D. H. (2008). Event-related EEG time-frequency analysis: An overview of measures and an analysis of early gamma band phase locking in schizophrenia. *Schizophrenia Bulletin, 34*(5), 907-926.

Rodriguez-Fornells, A., Clahsen, H., Lleó, C., Zaake, W., & Münte, T. F. (2001). Event-related brain responses to morphological violations in Catalan. *Cognitive Brain Research, 11,* 47-58.

Rolheiser, T., Stamatakis, E. A., & Tyler, L. K. (2011). Dynamic processing in the human language system: Synergy between the arcuate fascicle and extreme capsule. *The Journal of Neuroscience*, *31*(47), 16949-16957.

Roll, M. (2015). A neurolinguistic study of South Swedish word accents: Electrical brain potentials in nouns and verbs. *Nordic Journal of Linguistics, 38,*149-162.

Roll, M., Horne, M., & Lindgren, M. (2010). Word accents and morphology - ERPs of Swedish word processing. *Brain Research, 1330,* 114-123.

Roll, M., Söderström, P., Frid, J., Mannfolk, P., & Horne, M. (2017). Forehearing words: Pre-activation of word endings at word onset. *Neuroscience Letters, 658*, 57-61.

Roll, M., Söderström, P., & Horne, M. (2013). Word-stem tones cue suffixes in the brain. *Brain Research, 1520,* 116-120.

Roll, M., Söderström, P., Mannfolk, P., Shtyrov, Y., Johansson, M., van Westen, D., & Horne, M. (2015). Word tones cueing morphosyntactic structure: Neuroanatomical substrates and activation time-course assessed by EEG and fMRI. *Brain and Language, 150,* 14-21.

Romanski, L. M., Tian, B., Fritz, J., Mishkin, M., Goldman-Rakic, P. S., & Rauschecker, J. P. (1999). Dual streams of auditory afferents target multiple domains in the primate prefrontal cortex. *Nature Neuroscience, 2*(12), 1131-1136.

Rumelhart, D. E., & McClelland, J. L. (1985). On learning the past tenses of English verbs. In D. E. Rumelhart, J. L. McClelland & the PDP Research Group (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition, Vol. 2* (pp. 216-271). Cambridge, MA: MIT Press.

Saffran, J. R., Newport, E. L., & Aslin, R. N. (1996). Word segmentation: The role of distributional cues. *Journal of Memory and Language, 35*(4), 606-621.

Sagarra, N., & Casillas, J. V. (2018). Suprasegmental information cues morphological anticipation during L1/L2 lexical access. *Journal of Second Language Studies, 1*(1), 31-59.

Sagarra, N., & Ellis, N. C. (2013). From seeing adverbs to seeing verbal morphology. Language experience and adult acquisition of L2 tense. *Studies in Second Language Acquisition, 35,* 261-290.

Sagarra, N., & Herschensohn, J. (2010). The role of proficiency and working memory in gender and number agreement processing in L1 and L2 Spanish. *Lingua, 120*(8), 2022-2039.

Sagarra, N., & Herschensohn, J. (2012). Processing of gender and number agreement in late Spanish bilinguals. *International Journal of Bilingualism, 17*(5), 607-627.

Salat, D. H., Buckner, R. L., Snyder, A. Z., Greve, D. N., Desikan, R. S. R., Busa, E., … Fischl, B. (2004). Thinning of the cerebral cortex in aging. *Cerebral Cortex, 14*, 721-730.

Sandoval, M., Patterson, D., Dai, H., Vance, C. J., & Plante, E. (2017). Neural correlates of morphology acquisition through a statistical learning paradigm. *Frontiers in Psychology, 8*, 1234.

Saur, D., Kreher, B. W., Schnell, S., Kümmerer, D., Kellmeyer, P., Vry, M.-S., …Weiller, C. (2008). Ventral and dorsal pathways for language. *Proceedings of the National Academy of Sciences, 105,* 18035-18040.

Sauseng, P., Klimesch, W., Gruber, W. R., Hanslmayr, S., Freunberger, R., & Doppelmayr, M. (2007). Are event-related potential components generated by phase resetting of brain oscillations? A critical discussion. *Neuroscience, 146*(4), 1435-1444.

Schmidt, R. (2001). Attention. In P. Robinson (Ed.), *Cognition and second language instruction* (pp. 3-32). Cambridge: Cambridge University Press.

Schremm, A., Hed, A., Horne, M., & Roll, M. (2017). Training predictive L2 processing with a digital game: Prototype promotes acquisition of anticipatory use of tone-suffix associations. *Computers & Education, 114,* 206-221.

Schremm, A., Novén, M., Horne, M., & Roll, M. (submitted). Brain responses to morphologically complex verbs: An electrophysiological study of Swedish regular and irregular past tense forms.

Schremm, A., Novén, M., Horne, M., Söderström, P., van Westen, D., & Roll, M. (2018). Cortical thickness of planum temporale and pars opercularis in native language tone processing. *Brain and Language, 176,* 42-47.

Schremm, A., Söderström, P., Horne, M., & Roll, M. (2016). Implicit acquisition of tone-suffix connections in L2 learners of Swedish. *The Mental Lexicon 11*(1), 55-75.

Singer, W. (1999). Neuronal synchrony: A versatile code for the definition of relations?. *Neuron, 24*(1), 49-65.

Sonnenstuhl, I., Eisenbeiss, S., & Clahsen, H. (1999). Morphological priming in the German mental lexicon. *Cognition, 72,* 203-236.

Stanners, R. F., Neiser, J. J., Hernon, W. P., & Hall, R. (1979). Memory representation for morphologically related words. *Journal of Verbal Learning and Verbal Behavior, 18*(4), 399-412.

Stump, G. T. (2001). Inflection. In A. Spencer & A. M. Zwicky (Eds.), *The handbook of morphology* (pp. 13-43). Oxford, UK: Blackwell.

Söderström, P., Horne, M., Frid, J., & Roll, M. (2016a). Pre-activation negativity (PrAN) in brain potentials to unfolding words. *Frontiers in Human Neuroscience, 10,* 512.

Söderström, P., Horne, M., Mannfolk, P., van Westen, D., & Roll, M. (2017). Tone-grammar association within words: Concurrent ERP and fMRI show rapid neural pre-activation and involvement of left inferior frontal gyrus in pseudoword processing. *Brain and Language, 174,* 119-126.

Söderström, P., Horne, M., & Roll, M. (2016b). Stem tones pre-activate suffixes in the brain. *Journal of Psycholinguistic Research, 46*(2), 271-280.

Söderström, P., Roll, M., & Horne, M. (2012). Processing morphologically conditioned word accents. *The Mental Lexicon, 7*(1), 77-89.

Tang, C., Hamilton, L. S., & Chang, E. F. (2017). Intonational speech prosody encoding in the human auditory cortex. *Science, 357*(6353), 797-801.

Teleman, U., Hellberg, S., & Andersson, E. (1999). *Svenska Akademiens grammatik.* Stockholm: Svenska Akademien.

Tyler, L. K., Stamatakis, E. A., Post, B., Randall, B., & Marslen-Wilson, W. D. (2005). Temporal and frontal systems in speech comprehension: An fMRI study of past tense processing. *Neuropsychologia, 43,* 1963-1974.

Ullman, M. T. (2001a). A neurocognitive perspective on language: The declarative/procedural model. *Nature Reviews Neuroscience, 2,* 717-726.

Ullman, M. T. (2001b). The neural basis of lexicon and grammar in first and second language: The declarative/procedural model. *Bilingualism: Language and Cognition, 4,* 105-122.

Ullman, M. T. (2004). Contributions of memory circuits to language: The declarative/procedural model. *Cognition, 92,* 231-270.

Ullman, M. T. (2006a). Is Broca's area part of a basal ganglia thalamocortical circuit?. *Cortex, 42*(4), 480-485.

Ullman, M. T. (2006b). The declarative/procedural model and the shallow structure hypothesis. *Applied Psycholinguistics, 27,* 97-105.

Ullman, M. T. (2016). The declarative/procedural model: A neurobiological model of language learning, knowledge and use. In G. Hickok & S. A. Small (Eds.), *Neurobiology of language* (pp. 953-968). Amsterdam: Elsevier.

Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale & R. J. W. Mansfield (Eds.), *Analysis of visual behaviour* (pp. 549 -586). Cambridge, MA: MIT Press.

van Hell, J. G., & Tokowicz, N. (2010). Event-related brain potentials and second language learning: Syntactic processing in late L2 learners at different L2 proficiency levels. *Second Language Research, 26*(1), 43-74.

Van Zandt, T., & Townsend, J. T. (2012). Designs for and analyses of response time experiments. In T. D. Little (ed.), *The Oxford handbook of quantitative methods, Vol. 1* (pp. 260-285). New York: Oxford University Press.

Varela, F., Lachaux, J.-P., Rodriguez, E., & Martinerie, J. (2001). The brainweb: Phase synchronization and large-scale integration. *Nature Reviews Neuroscience, 2*, 229-239.

Vigneau, M., Beaucousin, V., Hervé, P. Y., Duffau, H., Crivello, F., Houdé, O., … Tzourio-Mazoyer, N. (2006). Meta-analyzing left hemisphere language areas: Phonology, semantics, and sentence processing. *NeuroImage, 30*(4), 1414-1432.

von Humboldt, W. (1836). *Über die Verschiedenheit des menschlichen Sprachbaues und ihren Einfluss auf die geistige Entwickelung des Menschengeschlechts*. Berlin: Druckerei der Königlichen Akademie der Wissenschaften.

von Stein, A., & Sarnthein, J. (2000). Different frequencies for different scales of cortical integration: From local gamma to long range alpha/theta synchronization. *International Journal of Psychophysiology, 38,* 301-313.

Wang, X. (2013). Perception of Mandarin tones: The effect of L1 background and training. *The Modern Language Journal, 97,* 144-160.

Wang, Y., Jongman, A., & Sereno, J. A. (2001). Dichotic perception of Mandarin tones by Chinese and American listeners. *Brain and Language, 78*(3), 332-348.

Wang, Y., Jongman, A., & Sereno, J. A. (2003). Acoustic and perceptual evaluation of Mandarin tone productions before and after training. *Journal of the Acoustical Society of America, 113,* 1033-1043.

Wang, Y., Spence, M. M., Jongman, A., & Sereno, J. A. (1999). Training American listeners to perceive Mandarin tones. *Journal of the Acoustical Society of America, 106,* 3649-3658.

Wayland, R. P., & Guion, S. G. (2004). Training English and Chinese listeners to perceive Thai tones: A preliminary report. *Language Learning, 54,* 681-712.

Weishaupt, D., Köchli, V. D., & Marincek, B. (2008). *How does MRI work? An introduction to the physics and function of magnetic resonance imaging* (2nd ed.). Berlin: Springer.

Weyerts, H., Penke, M., Dohrn, U., Clahsen, H., & Münte, T. F. (1997). Brain potentials indicate differences between regular and irregular German plurals. *NeuroReport, 8,* 957-962.

Wicha, N. Y. Y., Moreno, E. M., & Kutas, M. (2004). Anticipating words and their gender: An event-related brain potential study of semantic integration, gender expectancy, and gender agreement in Spanish sentence reading. *Journal of Cognitive Neuroscience, 16*(7), 1272-1288.

Xu, Y., Gandour, J., Talavage, T., Wong, D., Dzemidzic, M., Tong, Y., … Lowe, M. (2006). Activation of the left planum temporale in pitch processing is shaped by language experience. *Human Brain Mapping, 27*, 173-183.

Zatorre, R. J., & Gandour, J. T. (2008). Neural specializations for speech and pitch: Moving beyond the dichotomies. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*(1493), 1087-1104.