Research paper

Prosodically controlled derivations in the mental lexicon

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ABSTRACT

Swedish morphemes are classified as prosodically specified or prosodically unspecified, depending on lexical or phonological stress, respectively. Here, we investigate the allomorphy of the suffix -(i)sk, which indicates the distinction between lexical and phonological stress; if attached to a lexically stressed morpheme, it takes a non-syllabic form (-sk), whereas if attached to a phonologically stressed morpheme, an epenthetic vowel is inserted (-isk). Using mismatch negativity (MMN), we explored the neural processing of this allomorphy across lexically stressed and phonologically stressed morphemes. In an oddball paradigm, participants were occasionally presented with congruent and incongruent derivations, created by the suffix -(i)sk, within the repetitive presentation of their monomorphemic stems. The results indicated that the congruent derivation of the lexically stressed stem elicited a larger MMN than the incongruent sequences of the same stem and the derivational suffix, whereas after the phonologically stressed stem a non-significant tendency towards an opposite pattern was observed. We argue that the significant MMN response to the congruent derivation in the lexical stress condition is in line with lexical MMN, indicating a holistic processing of the sequence of lexically stressed stem and derivational suffix. The enhanced MMN response to the incongruent derivation in the phonological stress condition, on the other hand, is suggested to reflect combinatorial processing of the sequence of phonologically stressed stem and derivational suffix. These findings bring a new aspect to the dual-system approach to neural processing of morphologically complex words, namely the specification of word stress.

1. Introduction

In many languages, word stress is distributed according to phonological generalizations, e.g., on heavy syllables, or at edges of words. In some languages there may also be morphological generalizations for the distribution of stress, e.g., stress on root morphemes, or prefixes and suffixes requiring or assigning stress on adjacent syllables. In these latter cases, stresses are to some extent lexically specified. Lexical stress refers to prominence that is memorized together with other information of particular morphemes, whereas phonological stress refers to prominence that is assigned by a grammatical generalization (a rule). The particular issue that the present article investigates is the potential neural distinction between lexically represented stresses and phonologically assigned stresses in Swedish. Within the framework of the dual-system approach to morphologically complex word processing, the present study for the first time tests a new constraint to derivational morphology, i.e., the specification of word stress assignment, and

hypothesizes that in Swedish, derivations are processed either holistically or combinatorially based on the source of word stress, namely, lexically represented stress and phonologically assigned stress, respectively.

1.1. Prosodic specification of word stress in Swedish

The general trend in phonological analyses of stress systems has been to try to account for as much of the stress distribution as possible by a phonological so-called stress algorithm, as dictated by economy and Ockham's razor (van der Hulst, 1984; Kager, 1989; Hayes, 1995; Kristoffersen, 2000). Exceptional stress placement has usually been taken to be lexically determined, typically by extrametricality of final segments, syllables or suffixes,[1] by lexical quantity, or, as a last resort, by direct lexical specification of stress. This reliance on grammar/ phonology for the assignment of *all* stress naturally predicts that all stresses are of essentially the same kind, namely phonological. In Swedish there is, however, a contrast between lexically represented stress – roughly (but not completely) corresponding to the Germanic vocabulary – and phonologically assigned stress – roughly (but not completely) corresponding to the Romance and Greek vocabulary (Riad, 1999, 2012, 2014, 2015). Therefore, morphemes are classified as 1) prosodically unspecified, obtaining stress through a phonological rule (if at all), or 2) prosodically specified in three different ways, including morphemes that are lexically stressed (tonic) or appear either before (pretonic) or after (posttonic) a stressed syllable. In compounding, derivation and inflection, morphemes with different prosodic specification may come together. The combinations are predicted to be prosodically harmonic or disharmonic (i.e., conflicting), giving us some insight into the prosodic influence in the morphology of Swedish (Riad, 2015).

The surface patterns that motivate this contrast are of two kinds: variable vowel effects in destressed syllables, and allomorphy in a particular suffix. The first effect shows up when a lexical stress in a root gets overridden by a phonological stress in the suffix, in a form that can only carry a single stress (a minimal prosodic word, Ito & Mester, 2007). Forms like this are given to the left in Table 1. An etymologically Germanic root like *gjuta* [ˈjʉːta] 'to mould' has lexical stress on the root syllable. When an etymologically Romance derivational suffix *-eri* is added to it, that suffix triggers the phonological stress rule, which puts primary stress on the last syllable, yielding *gjuteri* [jʉˑtɛˈriː] 'foundry'. In both forms, a single prosodic word is formed and, as per the phonology of Swedish, only one stress is admitted. The initial syllable of *gjuta* [ˈjʉːta] thus gets destressed in the derived form, which is stressed on the final syllable *gjuteri* [jʉˑtɛˈriː]. However, some properties associated with stress linger in the destressed syllable, namely some vowel quantity and the vowel quality (hence [jʉˑ] rather than [jʉ] or [jø]). This is a sort of faithfulness effect that is found with lexical stress but not with phonological stress, exemplified to the right in Table 1. With phonological stress, all vestiges of former phonological stress are lost when the stress shifts, e.g., *drama* [ˈdrɑːma] 'drama', *dramatisk* [drɑˈmɑːtɪsk] 'dramatic'.[2]

This basic phonological pattern was investigated in Zora, Riad, Schwarz, and Heldner (2016b), by comparing neural responses to vowel quantity (duration) and vowel quality (formant frequency) changes in the stems *banal* [baˈnɑːl] 'id.' and *banan* [baˈnɑːn] 'banana' that are (by hypothesis) phonologically stressed and lexically stressed, respectively. Prosodic specification was attested by combining these stems with prosodically unspecified suffixes *-itet* and *-eri*, as in *banalitet* [banaliˈteːt] 'banality' and *bananeri* [banɑˑnɛˈriː].[3] In line with the phonological pattern presented above, when the stress shifted, the vowel quality and, to some degree, the vowel quantity remained the same in *bananeri*, whereas both parameters changed radically in *banalitet*. Once the prosodic specification of *banal* and *banan* was confirmed, neural responses to stems [banal] and [banan] were scrutinized with regard to their potential lexical derivations. The results indicated that duration and formant frequency changes cue the upcoming derivation in a phonologically stressed stem [banal] but not in a lexically stressed stem [banan]. Specifically, larger neural responses for the former were due to the association between stress shift and changes in vowel quantity and vowel quality, whereas the latter lacks such variable vowel effects on destressed syllables. The results thus provide support for the hypothesis that stress in Swedish is partly lexically specified and partly phonologically assigned (Riad, 2012).

The second surface pattern, suffix allomorphy, also appears to indicate the distinction between lexical and phonological stress in Swedish phonology. The suffix *-(i)sk* exhibits two phonologically conditioned allomorphs, non-syllabic *-sk* and syllabic *-isk*, which occur in complementary distribution (Riad, 1999). Some of the variation is due to factors like the lexical quantity of the segments in the root rhyme (*sam-isk* [ˈsɑːmɪsk] 'Sámi' vs. *glöm-sk* [ˈɡlømːsk] 'forgetful')[4] and phonotactics (*tjeck-isk* [ˈɕɛkːɪsk] 'Czech' vs. *skot-sk* [ˈskɔtːsk] 'Scottish'). The main control of the patterning, however, appears to emanate from the status of the stress in the root as lexical or as phonologically assigned, as seen in forms that do not exhibit a quantitative or phonotactic contrast in the relevant place: lexical in *kuban-sk* [kʉˈbɑːnsk] 'Cuban' and *syn-sk* [ˈsyːnsk] 'psychic' vs. phonological in *mekan-isk* [mɛˈkɑːnɪsk] 'mechanical' and *cyn-isk* [ˈsyːnɪsk] 'cynical'. Lexical stress thus conditions the *-sk* allomorph, while phonologically assigned stress, along with quantitative and phonotactic factors, occasions the *-isk* allomorph, which we take to represent the elsewhere case. The suffix *-(i)sk* shares the property of being posttonic, that is, requiring the presence of a stress in the preceding syllable, with many suffixes in Swedish that are predominantly of Germanic origin. Both allomorphs *-sk* and *-isk* fulfill the posttonic criterion in forms like the ones given above, but with stresses from different sources. Examples of this pattern are given in Table 2.

If attached to a tonic morpheme, i.e., a morpheme containing lexical stress, the suffix takes its basic form /-sk/. On the other hand, if the suffix attaches to a phonologically stressed morpheme, it surfaces with the epenthetic vowel [ɪ]. This allomorphic pattern can be

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[1] Ignoring a final segment, syllable or suffix for the purposes of stress placement.

[2] In Table 1, only the relevant vowels are marked with IPA transcription.

[3] Although not being a lexical entry in Swedish, *bananeri* seems to be related to the concept of *orangeri* 'orangery' (Zora et al., 2016b).

[4] Stressed syllables are always heavy in Swedish, either by virtue of a long vowel or a long consonant following a short vowel. Whether it is vowels or consonants (or both) that should be considered to carry the lexical distinction is subject to a longstanding discussion, which does not affect the observation here (for a summary and references, see Riad, 2014).

Table 1

Lexically stressed morphemes: traces of vowel quantity and vowel quality; Phonologically stressed morphemes: no trace of vowel quantity and change in vowel quality.

	Lexical stress			Phonological stress	
/i/	sl[ˈiː]pa 'to grind'	sl[iˑ]peˈri 'grindery'	iˑ ~ ɪ	pol[ˈiː]tiker 'politician'	pol[ɪ]tiˈsera 'to politicize'
/y/	pr[ˈyː]d 'prudish'	pr[yˑ]deˈrier 'pruderies'	yˑ ~ ʏ	f[ˈyː]siker 'physicist'	f[ʏ]siˈkalisk 'physical'
/e/	l[ˈeː]k 'game'	l[eˑ]koˈtek 'play place'	eˑ ~ ɛ	prof[ˈeː]t 'prophet'	prof[ɛ]ˈtera 'to prophesy'
/ø/	s[ˈøː]ka 'to seek'	(fel)s[øˑ]keˈri 'trouble shooting'	øˑ ~ ø	milj[ˈøː] 'environment'	"milj[ø]ˈdi" 'environmental melody'
/ɛ/	kl[ˈɛː]der 'clothes'	kl[ɛˑ]deˈri '(constant) dressing'	ɛˑ ~ ɛ	ess[ˈɛː] 'essay'	ess[ɛ]isˈtik 'essay writing'
/ɑ/	b[ˈɑː]gare 'baker'	b[ɑˑ]geˈri 'bakery'	ɑˑ ~ a	dr[ˈɑː]ma 'drama'	dr[a]ˈmatisk 'dramatic', dr [a]maˈtik 'drama'
/o/	sk[ˈoː]da 'to behold'	(navel)sk[oˑ]deˈri 'navel-gazing'	oˑ ~ ɔ	elektr[ˈoː]n 'electron'	elektr[ɔ]ˈnik 'electronics'
/u/	k[ˈuː]ka 'to boil'	k[ʊˑ]keˈri, '(place for) boiling'	ʊˑ ~ ʊ	positi[ˈuː]n 'position'	positi[ʊ]ˈnera 'to position'
/ʉ/	gj[ˈʉː]ta 'to mould'	gj[ʉˑ]teˈri 'foundry'	ʉˑ ~ ʉ	komm[ˈʉː]n 'municipality'	komm[ʉ]naliˈsera 'municipalize'

Table 2

Epenthesis/no epenthesis in the –(i)sk suffix.

Lexical stress		Phonological stress	
sparˈtan, sparˈtan-sk	'spartan'	mekaˈn-ik, meˈkan-isk	'mechanics, mechanical'
ˈsyn, ˈsyn-sk	'vision, psychic'	cyˈn-ism, ˈcyn-isk	'cynicism, cynical'
ˈglömma, ˈglöm-sk	'forget, forgetful'	teoˈri, teoˈret-iker, teoretiˈse-ra	'theory, theoretician, to theorize'
ˈbonde, ˈbond-sk	'farmer, rural'	eleˈg-i, eˈleg-isk	'elegy, elegiac'
veˈgan, veˈgan-sk	'vegan'	vulˈkan, vulˈkan-isk	'volcano, volcanic'

accounted for within the framework of Optimality Theory (OT), a grammatical model, which models the observed (surface) forms of language as the results of the interaction of ranked preferences, so-called constraints. The differences between individual grammars amount to the different rankings of these constraints (Kager, 1999; Prince & Smolensky, 1993). Constraints are universal and come in two types: *markedness constraints*, which require that surface forms fulfill some criterion of structural well-formedness, and therefore allow changes from the underlying form, and *faithfulness constraints*, which require that the surface form does not differ unnecessarily from the underlying form (Kager, 1999; van Oostendorp, 2004). Accordingly, the basic form of /-sk/ when attached to a lexically stressed morpheme is interpreted as a faithfulness effect, bringing the suffix closer to the stem. If the suffix attaches to a phonologically stressed morpheme, the overall prosodic word shape is optimized by epenthesis in the suffix (Riad, 2014). The prosodic well-formedness here resides in the creation of a disyllabic domain with stress on the first syllable of that domain (a trochee). The optimality of this domain in Swedish is evident in nickname formation (Riad, 2002).

It is worth pointing out that there are general differences in word shape between Germanic and Romance words in the vocabulary. In Germanic forms, stems strongly tend to be monosyllabic and predominantly have lexical stress. Further derivation and inflection with Germanic suffixes will not affect such stresses. Romance forms tend to be polysyllabic, with phonological stress occurring at the right edge of the word.[5] The rule by which phonological stress is assigned looks for the rightmost, stressable syllable. This will either be the final syllable (*position* [pʊsɪˈʂuːn] 'position', *kontroversiell* [kɔntrʊvæʂɪˈɛlː] 'controversial') or the syllable before a posttonic suffix (*positioner-a* [pʊsɪʂʊˈneːra] 'to place', *banalitet-er* [banalɪˈteːtɛr] 'banalities').

1.2. The dual-system approach to morphologically complex word processing

Several models have been suggested to explain the neurocognitive basis of morphologically complex word processing, arguing either for obligatory morphemic decomposition (Rastle & Davis, 2008; Stockall & Marantz, 2006; Taft, 2004) or for a dual-system approach, in which complex words are either decomposed into their constituent morphemes or are accessed as whole units depending on linguistic regularity and markedness (Clahsen, 1999; Clahsen, Sonnenstuhl, & Blevins, 2003; Pinker, 1991; Ullman, 2001). According to the dual-system models, regular forms are processed combinatorially by grammatical rules, whereas irregular forms are stored in lexical memory and accessed holistically. This distinction between regular and irregular forms has often been argued for inflectional morphology (e.g., *walk-walked* vs. *go-went*), and separate neural mechanisms have been indicated for regular and irregular inflections (Beretta et al., 2003; Jaeger et al., 1996; Pinker, 1999; Ullman, 2001; Ullman et al., 1997). Previous behavioral, electrophysiological and neuroimaging research on Swedish inflectional morphology have indicated different results, extending from full form storage of inflected forms (Lehtonen et al., 2009) to the dual-system approach depending on frequency (Lehtonen, Niska, Wande, Niemi, & Laine, 2006a), regularity, and the presence of stored memory representations (Schremm et al., 2018; 2019).

Most previous research on derivational morphology, which mostly investigated visual processing, has suggested obligatory morphemic decomposition (Rastle, Davis, & New, 2004; Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007; Lavric, Clapp, & Rastle, 2007; for a review, see; Hanna & Pulvermüller, 2014). Some research has, however, suggested a dual-system approach under certain circumstances such

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[5] The actual stems of Romance forms are not regularly stressed, and without suffixes they often look like cranberry morphemes (*nat-*, *nation* 'nation', *bagat-*, *bagatell* 'trifle', etc.). In this sense, the Romance vocabulary is nearly always made up of at least two morphemes.

as suffix productivity, frequency and semantic transparency (Bertram, Schreuder, & Baayen, 2000; Bozic, Tyler, Su, Wingfield, & Marslen-Wilson, 2013; Clahsen et al., 2003; Leminen et al., 2011, 2010; Lewis, Solomyak, & Marantz, 2011; Vannest & Boland, 1999; Vannest, Polk, & Lewis, 2005; Whiting, Marslen-Wilson, & Shtyrov, 2013). For instance, Whiting et al. (2013), investigating semantically transparent and semantically opaque derived forms (e.g., *baker* vs. *beaker*), have suggested that all forms containing a stem and a potential suffix would initially undergo morphemic decomposition. At a later stage, words would be reassessed and accessed as whole forms, depending on the acceptability of the decomposed form. A broader and bilateral topographical distribution of derivational word processing in comparison to inflected words has been suggested as evidence for holistic processing of derived words, with the possibility of parallel access through decomposition in some cases (Bozic et al., 2013; Leminen et al., 2011).

The difference between combinatorial and holistic processing has been explained by the nature of neural circuits, which emanate when words and constructions are established (see Hanna & Pulvermüller, 2014; Pulvermüller et al., 2014). Different words in the mental lexicon have distinct neural circuits, which are characterized by short- and long-distance connections, and whole forms are stored lexical items represented by these neural circuits (Garagnani, Wennekers, & Pulvermüller, 2008; Pulvermüller & Fadiga, 2010). In holistic processing, enhanced brain activation is therefore expected for stored items compared to unstored items (e.g., pseudowords), which lack such representations. By contrast, combinatorial processing involves two or more sets of neural circuits of whole forms, which prime the activation of each other (Pulvermüller, 2010), and reduced brain activation is therefore expected for forms that are regularly connected by a combinatorial mechanism compared to unconnected (ill-combined) forms, which will lead to a full ignition of different sets of neural circuits (Pulvermüller & Shtyrov, 2003; Hanna & Pulvermüller, 2014).

1.3. Mismatch negativity (MMN) as an index of the dual-system model

The distinct neurophysiological patterns of combinatorial and holistic processing have often been indicated with the mismatch negativity (MMN) component of event-related potentials (ERPs). MMN is a negative ERP component, which typically peaks at 100–250 ms after change onset, and shows a frontocentral scalp distribution (Näätänen et al., 1978, 2007; Näätänen & Winkler, 1999). Besides indexing the brain's automatic response to any acoustic change, MMN reflects higher-level cognitive processes in the auditory system (for reviews, see Pulvermüller & Shtyrov, 2006; Näätänen et al., 2007). The MMN evidence for language-specific stress patterns (Honbolygó, Csépe, & Ragó, 2004; Weber, Hahne, Friedrich, & Friederici, 2004; Friederici, Friedrich, & Christophe, 2007; Ylinen, Strelnikov, Huotilainen, & Näätänen, 2009; Zora, Schwarz, & Heldner, 2015, Zora, Heldner, & Schwarz, 2016a) and language-specific phonemes (Dehaene-Lambertz, 1997; Eulitz & Lahiri, 2004; Näätänen et al., 1997; Winkler et al., 1999; Ylinen et al., 2010) has been shown by a number of studies. Several studies have also established long-term memory traces associated with spoken words (Pulvermüller et al., 2001; Shtyrov & Pulvermüller, 2002b). Pulvermüller et al. (2001) indicated for instance larger MMN response to the same syllable when completing a word than when completing a pseudoword. This enhanced MMN activation, also called *lexical MMN* (lMMN), has been explained by the above-mentioned neural circuits of stored, familiar items and features, which elicit larger activation in comparison to unstored, unfamiliar items and features that do not have such representations (Pulvermüller, Shtyrov, & Hauk, 2009; Alexandrov, Boricheva, Pulvermüller, & Shtyrov, 2011; Bakker, Macgregor, Pulvermüller, & Shtyrov, 2013; Hanna & Pulvermüller, 2014).

Using lMMN, Hanna and Pulvermüller (2014) investigated whether morphologically complex words are processed combinatorially according to morphological rules or processed holistically as single lexical items. To this end, the authors examined MMN responses elicited by congruent and incongruent derivations, formed by the congruent and incongruent sequences of the same stems and derivational suffixes, in German. The authors argued that German is optimal for investigating whether complex words are processed as whole lexical units or not because there are no straightforward morphophonological criteria describing the relationship between stems and suffixes. The results indicated stronger lMMN activation for congruent derivations than incongruent derivations, presumably due to the stored long-term memory representations of derivational constructions, which is argued to support the holistic processing of derivations.

Leminen, Leminen, Kujala, and Shtyrov (2013) examined neural correlates of inflectional and derivational processes using Finnish words and their pseudoword equivalents. Overall, derived words evoked larger activation than inflected words. The results further indicated that real derived words elicited larger activation than derived pseudowords, whereas inflected pseudowords elicited a greater response than real inflected words. The larger activation for derived words is considered to be lMMN response, reflecting the long-term memory representations and holistic processing of derivations in the brain. The larger response to inflected pseudowords is argued to reflect combinatorial processing, consistent with earlier MMN research, which indicated a larger MMN response to ungrammatical morpheme strings than grammatical ones (hereafter called combinatorial MMN; also called syntactic MMN, *sMMN*; Hanna & Pulvermüller, 2014). Bakker et al. (2013), for instance, investigated congruent and incongruent past tense inflections in English, and found larger MMN activation to incongruent inflections, indicating combinatorial processing for regular past tense, rather than holistic processing. Reduced MMN activation to grammatically congruent combinations is argued to result from priming from a corresponding sequence. It has been asserted that in the case of combinatorial sequences, MMN does not only indicate the activation of single representations of morphemes that form the sequence, but also the interaction between them. Frequently co-activated morphemes are connected through two or more sets of neuronal assemblies, which ensure the activation of each other. Since no such connection exists between the morphemes of the incongruent combinations, no such priming effect is seen. An unprimed suffix would therefore lead to a full ignition, which in turn elicits a larger MMN response in comparison to the primed suffix (Pulvermüller, 2002; Shtyrov, Pulvermüller, Näätänen, & Ilmoniemi, 2003; Pulvermüller & Knoblauch, 2009; Bakker et al., 2013; Leminen et al., 2013).

Scharinger, Lahiri, and Eulitz (2010) investigated the vowel alternations in morphologically complex word forms in German (*stock-stöcke* 'stick-sticks' vs. *stoff-stoffe* 'cloth-cloths'), and examined the relevance of these alternations for lexical representations.

They looked into the MMN responses to [ɔ] in *stock*, which changes phonological shape with inflection, and in *stoff*, which stays the same even after inflection, when presented in the context of the front vowel [œ] and in the context of the back vowel [ɔ]. The results indicated that the MMN response was modulated by the representations of phonological stem variants; they showed higher MMN amplitude for *stoff* than *stock* in the front vowel context. This has been explained by priming; in the context of front vowel [œ], *stoff* was a novel stem and not primed by the standard, whereas due to its plural version *stöcke*, *stock* was facilitated. These findings are in line with previous research, which indicated that word beginnings activate their corresponding whole words (Cooper, Cutler, & Wales, 2002; Friedrich, Kotz, Friederici, & Gunter, 2004) and with Zora et al. (2016b), which indicated that depending on the specification of morphological features, vowel quantity and vowel quality changes in the stems activate memory traces associated with their potential derivations in Swedish.

1.4. The present study

An interaction between prosody and morphology has previously been suggested for lexical tones as well in Swedish (Riad, 1999, 2012, 2014, 2015). Tones have been considered to be part of the lexical specification of suffixes, and it has been argued that the word stem receives a lexical tone (accent 2) or not (accent 1) based on the upcoming suffix (Riad, 1999, 2012, 2014). The plural suffix, for instance, would induce a high lexical tone early in the stem (in Central Swedish), whereas the singular suffix would assign no such tone yielding instead a low tone early in the stem. This tone and suffix interaction has been investigated in a number of behavioral, electrophysiological and neuroimaging studies, and tones on the stems have been shown to pre-activate upcoming suffixes, and hence facilitate word processing (Roll, Horne, & Lindgren, 2010, 2013, 2015; Söderström, Roll, & Horne, 2012, 2017). Low tones, with fewer possible continuations, have been argued to be more predictive than high tones, and provide therefore a more direct access to suffixes (Roll et al., 2015; Söderström et al., 2012). The predictive processing of tones has been shown to depend on the presence of stored memory representations of tone-morpheme associations, and inflected words are argued to be processed either holistically or combinatorially based on the incorporation of tones into word representation (Schremm et al., 2019).

Given this interplay between tones and morphology, Zora et al. (2016b) investigated whether stress, too, is a lexical property of some morphemes in Swedish by examining the neural responses to variable effects in destressed syllables. The present study expands upon the findings of Zora et al. (2016b) and the previous literature on the prosody-morphology interaction, and investigates the relevance of stress specification to the derivational processes by examining suffix allomorphy. Given there is no surface difference between syllables that are stressed either way, we scrutinize the relevance of the specification of word stress on the stems (i.e., lexical stress vs. phonologically assigned stress) for the processing of the posttonic derivational suffix *-(i)sk* in the brain. To our knowledge, the role of word stress specification in stems in the neural processing of derivations has not been addressed before, beyond the case with variable effects in destressed syllable (Zora et al., 2016b). We explored how prosodically conditioned suffix alternations are coded in the mental lexicon, and studied MMN responses to suffix allomorphy in Swedish words *vegan* 'vegan' and *vulkan* 'volcano' that are lexically or phonologically stressed, respectively.

The neural responses were recorded in relation to the posttonic suffix *-(i)sk*, which is realized as non-syllabic (*-sk*) in combination with the lexically stressed (tonic) stem *vegan*, and syllabic (*-isk*) in combination with the phonologically stressed stem *vulkan*, namely, *vegansk* and *vulkanisk*, respectively. In line with previous MMN studies focusing on derivations (Hanna & Pulvermüller, 2014; Leminen et al., 2013), we used an auditory oddball paradigm, where stems were always presented as standards, and their congruent (*vegan-sk* and *vulkan-isk*) and incongruent (*vegan-isk* and *vulkan-sk*) derived versions as deviants. As reviewed above, with regard to derivational morphology, the dual-system model argues for whole word storage under certain circumstances relating to the productivity of the affix and the semantic transparency. In the present study, given that the distribution of allomorphs emanates from the specification of word stress, we investigate whether the source of word stress constitutes a new constraint to the derivational morphology. Since lexically specified stress is memorized together with other information of particular morphemes and the faithfulness effect minimizes the distance between the stem and the suffix, it was hypothesized that lexically stressed stems and derivational suffixes are processed holistically as single lexical units, in accordance with previous research on derivational processes and as argued for stored derived words (Hanna & Pulvermüller, 2014; Leminen et al., 2013). By contrast, since phonological stress refers to prominence that is assigned by a grammatical generalization (a rule) and the overall prosodic shape is optimized by epenthesis in the suffix, it was predicted that a phonologically stressed stem and a derivational suffix are processed combinatorially as in inflectional processes (Bakker et al., 2013; Leminen et al., 2013). Accordingly, based on the previous MMN findings, the congruent deviant is expected to elicit a lMMN response in the context of a lexically stressed stem, whereas the incongruent deviant is expected to elicit a *combinatorial MMN* response (cf. syntactic MMN) in the context of a phonologically stressed stem.

2. Method

2.1. Participants

Fourteen[6] native speakers of Swedish (7 males, 7 females; age range 16–46 years, *M* = 28.2, *SD* = 9.2) were recruited and tested in Stockholm. All participants were right-handed, as evaluated by the Edinburgh Handedness Inventory (Oldfield, 1971), and

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[6] Initially 19 participants were recruited; however 5 participants were excluded from data analysis: (i) 1 participant due to excessive artifacts, (ii) 2 participants due to left-handedness; (iii) 2 participants due to incomplete recording.

reported no history of hearing and neurological disorders. Informed consent was signed before testing, and two movie tickets were awarded to all participants. The study was approved by the Stockholm Regional Ethics Committee (2015/63–31).

2.2. Stimuli

The experimental stimuli consisted of a lexically stressed stem, *vegan* 'vegan' and a phonologically stressed stem *vulkan* 'volcano'[7] and their congruent and incongruent derivations created by the posttonic suffix -(i)sk, which takes either a syllabic form (-*isk*) or a non-syllabic form (-*sk*) depending on the nature of stress assignment in the stem (*vegan-sk* 'vegan', *vulkan-isk* 'volcanic', **vegan-isk*, and **vulkan-sk*). In addition to the word stimuli, the study contained pseudoword stimuli. Pseudowords were composed of meaningless stems *began** and *bulkan**, which differ from the real words only in the initial segment, and the same suffixes (*began-sk**, *began-isk**, *bulkan-sk**, and *bulkan-isk**). The pseudoword contrast was used to differentiate lexical processing from non-lexical processing, and to control for the effects of inevitable differences in the acoustic features and the syllable structure of the suffixes. A female native Swedish speaker with phonetic training (from Stockholm, 52 years old) was recorded pronouncing all stimuli in isolation in an anechoic chamber. The recordings were conducted using REAPER digital audio workstation (version 5.93), and were sampled at a rate of 44.1 kHz with 16 bits/per sample.

The recordings were analyzed and manipulated in Praat (Boersma & Weenink, 2014). Exemplars with similar pitch contour and peak sound energy were selected among several repetitions of each stimulus in order to eliminate the possible effect of these acoustic features on neural responses. Stems always served as standards and their congruent and incongruent derived versions as congruent and incongruent deviants. To minimize the acoustic differences between the standards and the deviants as well as between the word and pseudoword stimuli, the stems *vegan* and *vulkan* were taken as bases, and the deviants and the pseudoword stimuli were created out of these bases. The pseudoword stimuli were created by simply replacing the initial segment of the base stems, /v/ with /b/.[8] Suffixes, which were cut from the recorded suffixed versions, were then spliced to the base stems to create both congruent and incongruent derivations in both the word and pseudoword stimuli. All stimuli were matched for duration (standards: 400 ms; deviants with the suffix -*sk*: 630 ms; deviants with the suffix -*isk*: 660 ms), and 2 ms ramps were added to both ends of the stimuli to eliminate possible clicks. The word and pseudoword stimuli differed only in the initial segment, and there was no difference between the standard and deviant stimuli before the suffix onset (Lexical stress block, overall intensity, ~74 dB, fundamental frequency (*f0*), ~165 Hz; Phonological stress block, overall intensity, ~73 dB, fundamental frequency (*f0*), ~170 Hz; Suffix -*sk*, overall intensity, ~51 dB; Suffix -*isk*, overall intensity, ~54 dB). Fig. 1 illustrates waveforms, spectrograms, and pitch and intensity contours of all stimuli in each block.

It was crucial to keep the deviants and standards identical up to the suffix onset to control exactly the point in time when the acoustic contrast occurred. The same stem recording was therefore used in both conditions, which means that no phonetic cue of syllabification would be traceable in the forms as such before the suffix. To exclude the possibility that either form sounded less natural than the other due to different syllabification of [n] in *ve.gansk* and *vul.ka.nisk,* a Naturalness Rating Task was run in online research platform, FindingFive (version 1.0)[9]. Sixteen native speakers of Swedish (8 males, 8 females; age range 21–61 years, $M = 38.1$, $SD = 12.1$) with linguistics background judged the acoustic quality and naturalness of the stimuli using a 1–5 Likert Scale (1 = highly natural to 5 = highly unnatural). Mean naturalness ratings for *vegansk* ($M = 1.5$, $SD = 0.7$) and *vulkanisk* ($M = 1.8$, $SD = 0.6$) were comparable, and therefore gave no basis for a syllabification effect either way. Note that the syllabifications do not affect the quantity constraint on stressed syllables. The [n] is extrametrical in *vega* < *n* > [vɛˈɡɑːn] and the derivation does not affect quantity: *vegansk* [vɛɡɑːnsk]. In *vulkanisk* [vɵlˈkɑːnɪsk], the [n] becomes the onset of the following syllable, but in practice the syllabification does not become evident before the suffix -*isk*.

2.3. Procedure

The experiment was built and run in E-Prime (version 2.0.1.06; Psychology Software Tools, Pittsburgh, Pennsylvania, USA). In a passive auditory oddball paradigm, two deviant stimuli (p = 2/10) were randomly presented within the frequently repeated standard stimulus (p = 8/10) with a stimulus onset asynchrony (SOA) of 1200 ms. The stimuli were presented via loudspeakers at a convenient listening level (60–65 dB SPL at the source). The experiment consisted of four blocks: 1) the lexical stress block with *vegan* and its derivations, 2) the phonological stress block with *vulkan* and its derivations, and the corresponding pseudowords 3) *began** and its derivations and 4) *bulkan** and its derivations (see Table 3).

Each block contained 1200 stimuli: 960 standards and 240 deviants (120 for each). The order of four blocks was counterbalanced across participants. In order to eliminate the elicitation of attention-dependent ERP components such as N2b (Näätänen, 1992; Näätänen et al., 2007), participants' attention was directed away from the auditory stimuli using a silent documentary (without subtitles). Each block took 24 min, making an experimental time of 1 h 36 min.

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[7] According to Swedish Blog Sentences (Östling & Wirén, 2013), database, consisting of 6,160,682,397 tokens, *vegan* and *vulkan* have lemma frequencies of 15,083 and 14,658 respectively, indicating that they are equally frequent.

[8] The segment /b/ was taken from both [bɛ] and [bɵ] contexts.
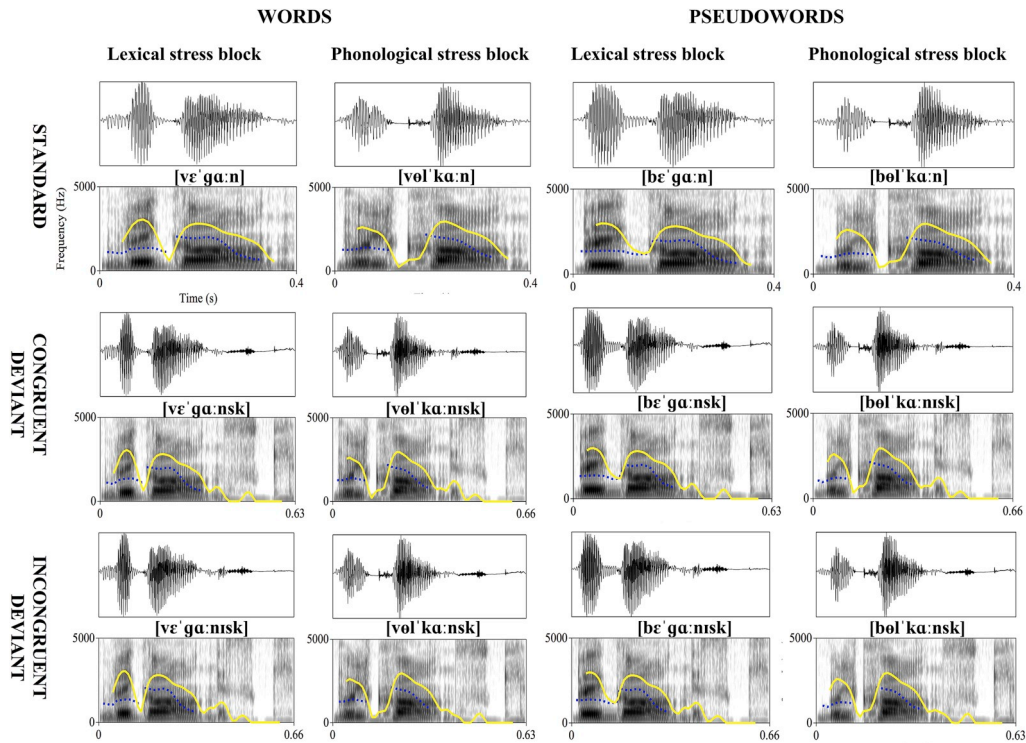
[9] https://www.findingfive.com

Fig. 1. Waveforms, spectrograms, and pitch and intensity contours of all stimuli in the lexical stress block and the phonological stress block. Phonetic transcriptions are given between the waveforms and spectrograms. Blue dotted line, pitch; Yellow solid line, intensity. Duration of stimuli is given in seconds (s) and frequency in hertz (Hz).

Table 3
Excerpts from the word and pseudoword blocks; S, Standard; D, Deviant; CD, Congruent deviant; ID, Incongruent deviant.

				Word block				
	S	S	CD	S	S	S	ID	S
Lexical stress block	vegan	vegan	vegansk	vegan	vegan	vegan	veganisk	vegan
Phonological stress block	vulkan	vulkan	vulkanisk	vulkan	vulkan	vulkan	vulkansk	vulkan
				Pseudoword block				
	S	S	D	S	S	S	D	S
	began	began	begansk	began	began	began	beganisk	began
	bulkan	bulkan	bulkanisk	bulkan	bulkan	bulkan	bulkansk	bulkan

2.4. Electroencephalography recordings and data analysis

The electroencephalography (EEG) recordings were performed using the BioSemi ActiveTwo system and ActiView acquisition software (BioSemi, Netherlands). Data collection was made at a sampling rate of 2048 Hz from 16 cap-mounted electrodes (Fp1, Fp2, F3, Fz, F4, T7, C3, Cz, C4, T8, P3, Pz, P4, O1, Oz, O2) arranged in accordance with the International 10–20 system. Seven external electrodes were used for electrooculogram (4), mastoid (2) and nose (1) recordings. Offline data analysis was performed using MATLAB (The Math Works Inc., Natick, Massachusetts, USA) and the EEGLAB toolbox (Delorme & Makeig, 2004). The EEG data were first resampled to 256 Hz and then filtered using a band-pass of 0.5–30 Hz. All channels were referenced offline to the nose channel. Eye artifacts were detected and removed using independent component analysis (ICA; Jung et al., 2000). Components with a strong far-frontal projection, mostly in the leading position in the component array, were removed. The component time course and EEG spectrum were also taken into consideration during the artifact rejection. On average, two components were removed. The EEG data were epoched into segments of 1000 ms, with 200 ms interval before the divergence point (i.e., suffix onset) used for baseline correction (Luck, 2014). Activation exceeding ± 100 μV at any channel was rejected. Percentage of excluded trials in Lexical stress block is as follows: Word-Standard: 5.8%; Word-Deviant I: 5.5%; Word-Deviant II: 4.9%; Pseudoword-Standard: 5.4%; Pseudoword-Deviant I: 5.2%; Pseudoword-Deviant II: 5.8%. Percentage of excluded trials in Phonological stress block is as follows: Word-

Standard: 6.2%; Word-Deviant I: 6.1%; Word-Deviant II: 5.5%; Pseudoword-Standard: 5.6%; Pseudoword-Deviant I: 5.4%; Pseudoword-Deviant II: 4.3%. Neural responses to the standard stimuli following a deviant stimulus were excluded from data analysis. The grand average ERP for each stimulus type was computed, and deviant-minus-standard subtraction signals were calculated for each block.

The electrodes were grouped together in three regions of interest (ROI): Frontal, F3, Fz, and F4; Central, C3, Cz, and C4; and Parietal, P3, Pz, and P4. The amplitude measurement window for MMN data was based on the typical peak latency of MMN and the visual analysis of grand averages. It is noteworthy that the MMN was quantified beyond N1 latency to eliminate the differences in the obligatory ERP responses to the standard and deviant stimuli (see Näätänen et al., 2007). Amplitudes were measured as a mean voltage over a 50-ms-window around the peak. Based on the grand average ERP waveforms, three time windows were defined: first time window, 100–150; second time window, 200–250; third time window, 300–350.

2.5. Statistical analysis

Statistical analysis was performed in SPSS (International Business Machines Corp., Armonk, New York, USA). Two types of statistical methods are used for the analysis of the ERP data: repeated measures of ANOVAs in each ROI and time window to test the pattern across stress assignment type (lexical stress vs. phonological stress) and congruency (congruent vs. incongruent), and paired samples *t*-tests to examine the overall difference between the word and pseudoword stimuli. Amplitude data extracted by subtracting the MMN elicited in the pseudoword context from the MMN elicited in the word context (i.e., word-minus-pseudoword subtraction) were used for repeated-measures ANOVAs. The subtraction was performed to cancel out the effect of different degrees of acoustical change and different syllable structure in *-isk/-sk* derivations (*-isk* deviated acoustically more from the standard than *-sk*), and the effect of differences in the refractoriness of the neural populations activated by the standard and deviant stimuli. Two-way repeated-measures ANOVA with factors of *Specification* (two levels: lexical stress and phonological stress) and *Congruency* (two levels: congruent and incongruent suffix) was carried out in each ROI and time window. To interpret significant interactions, follow-up ANOVAs and pairwise comparisons with Bonferroni adjustment were performed. Effect sizes are given in partial η2 measures, and mean values are reported with standard deviations. In addition to the ANOVAs, separate paired samples *t*-tests were conducted to evaluate the distinction between the word (e.g., *vegan-sk*) and pseudoword (e.g., *began-sk*) stimuli as well as between congruent (e.g., *vegan-sk*) and incongruent (e.g., *vulkan-sk*) realization of the suffix *-(i)sk* in the word condition. Amplitude data extracted by typical deviant-minus-standard subtractions were used for *t*-tests.

3. Results

Fig. 2A, B, and C present the grand average ERP waveforms elicited by deviant-minus-standard subtractions in the frontal (F3, Fz, and F4), central (C3, Cz, and C4), and parietal (P3, Pz, and P4) ROIs, respectively, in each block. Topographic difference maps are displayed for all the stimuli in each time window (first time window, 100–150 ms; second time window, 200–250 ms; third time window, 300–350 ms) in Fig. 3. It seems that in both the lexically stressed block and the phonologically stressed block, deviants elicited larger ERP responses especially in the first (100–150 ms) and second (200–150 ms) time windows in the frontal and central ROI compared to the parietal ROI. In the first time window, the congruent derivation seems to elicit a larger negativity in the word condition compared to the pseudowords condition (Fig. 2A and B). As predicted, the amplitude of acoustically more deviant *-isk* is larger in comparison to less deviant *-sk* in both lexically stressed and phonologically stressed blocks regardless of the congruency in both the first (100–150 ms) and the third (300–350 ms) time windows (Fig. 2A and B). This response appears to be larger to the pseudoword stimuli in comparison to the word stimuli especially in the third time window (300–350 ms).

The statistical analysis in the first time window indicates that in the frontal ROI, there are no main effects of Specification (F (1,13) = 0.295, p = 0.596, η^2 = 0.022) and Congruency (F (1,13) = 1.040, p = 0.326, η^2 = 0.074), however, there is a significant interaction between the two factors (F (1,13) = 5.592, p = 0.034, η^2 = 0.301; Table 4). Similarly, in the central ROI, the analysis yields no main effects of Specification (F (1,13) = 0.333, p = 0.573, η^2 = 0.025) and Congruency (F (1,13) = 2.685, p = 0.125, η^2 = 0.171) but a significant interaction between them (F (1,13) = 4.966, p = 0.044, η^2 = 0.276; Table 5). In the parietal ROI, neither main effects of Specification (F (1,13) = 0.217, p = 0.649, η^2 = 0.016) and Congruency (F (1,13) = 0.533, p = 0.487, η^2 = 0.039), nor interaction between the two factors (F (1,13) = 3.647, p = 0.078, η^2 = 0.219; Supplementary Table 1) reach significance. Enhanced activations leading to these significant interactions are further visible in the topographic maps (Fig. 3; color map min −2, max 2). Follow-up analysis in the frontal ROI reveals that there is a significant main effect of Congruency in the Lexical stress block (F (1,13) = 12.224, p = 0.004, η^2 = 0.485; Table 4), indicating that there is a statistically significant difference between MMN responses elicited by congruent and incongruent deviants. Pairwise comparisons show that the congruent deviant (M = −0.504 μV, SD = 1.271) elicited larger MMN than the incongruent deviant (M = 0.445 μV, SD = 1.732). There is no significant main effect of Congruency in the Phonological stress block (F (1,13) = 1.382, p = 0.261, η^2 = 0.096; Table 4), which indicates that there is no statistically significant difference between MMN responses elicited by congruent (M = 0.484 μV, SD = 1.462) and incongruent deviants (M = −0.049 μV, SD = 0.859). According to follow-up analysis in the central ROI, there is a significant main effect of Congruency in the Lexical stress block (F (1,13) = 9.485, p = 0.009, η^2 = 0.422; Table 5), showing a significant difference between MMN responses elicited by congruent and incongruent deviants. Pairwise comparisons show that the congruent deviant (M = −0.709 μV, SD = 1.223) elicited larger MMN than the incongruent deviant (M = 0.528 μV, SD = 2.153). There is no significant main effect of Congruency in the Phonological stress block (F (1,13) = 1.842, p = 0.198, η^2 = 0.124; Table 5), indicating the lack of a statistically significant difference between MMN responses elicited by congruent (M = 0.579 μV, SD = 1.427) and
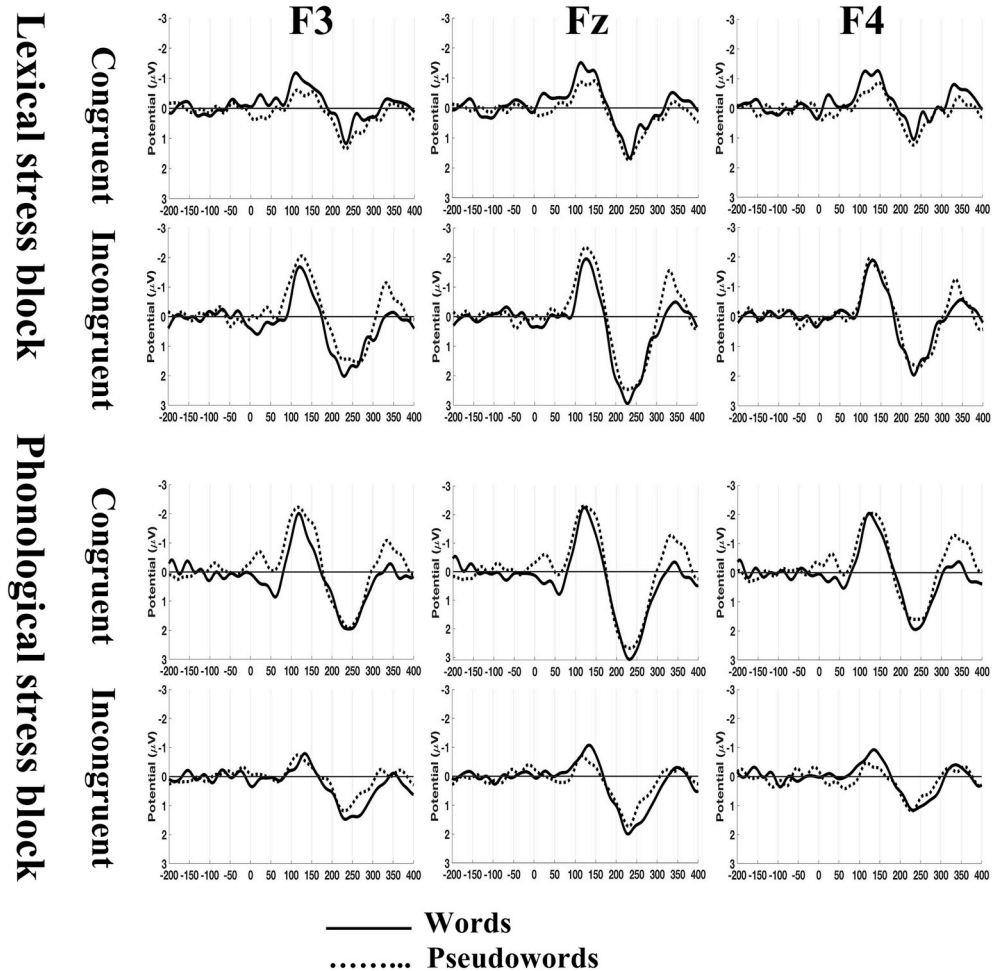
Fig. 2. Grand average ERPs. The grand average of difference (deviant-minus-standard) waveforms recorded from each region of interest (ROI): Fig. 2A, frontal ROI, F3, Fz, F4; Fig. 2B, central ROI, C3, Cz, C4; Fig. 2C, parietal ROI, P3, Pz, P4. Negativity is plotted upward. Amplitude is given in microvolts (μV) and latency in milliseconds (ms).

incongruent deviants ($M = -0.128\,\mu V$, $SD = 1.245$). Paired samples t-tests yield no significant difference between the word and pseudoword stimuli in the frontal ROI (Table 4, t-test – I), whereas t-tests in the central ROI reveal that there is a statistically significant difference ($t(13) = -2.170$, p = 0.049) between the MMN responses elicited by the word ($M = -1.026\,\mu V$, $SD = 2.092$) and pseudoword ($M = -0.317\,\mu V$, $SD = 1.345$) stimuli in the lexical stress block for the congruent derivation (Table 5, t-test – I).

The results of ANOVA in the second time window (Supplementary Tables 2–4) do not show any significant interaction between Specification and Congruency in any of the ROIs. In the third window, there are no main effects of Specification ($F(1,13) = 0.257$, $p = 0.621$, $\eta^2 = 0.019$) and Congruency ($F(1,13) = 6.573$, $p = 0.024$, $\eta^2 = 0.336$, but a significant interaction between them in the frontal ROI ($F(1,13) = 4.838$, $p = 0.047$, $\eta^2 = 0.271$; Supplementary Tables 5–7). Follow-up analysis indicates that there is a significant main effect of Congruency in the Lexical stress block ($F(1,13) = 6.573$, $p = 0.024$, $\eta^2 = 0.336$; Supplementary Table 5), revealing a statistically significant difference between MMN responses elicited by congruent and incongruent deviants. Pairwise comparisons showed that the congruent deviant ($M = -0.354\,\mu V$, $SD = 2.128$) elicited larger MMN than the incongruent deviant ($M = 0.706\,\mu V$, $SD = 1.842$). There is no significant main effect of Congruency in the Phonological stress block ($F(1,13) = 1.821$, $p = 0.200$, $\eta^2 = 0.123$; Supplementary Table 5), indicating that there is no statistically significant difference between MMN responses elicited by congruent ($M = 0.829\,\mu V$, $SD = 1.677$) and incongruent deviants ($M = 0.181\,\mu V$, $SD = 1.500$). Paired samples t-tests show no significant difference between the word and pseudoword stimuli in these time windows (Supplementary Tables 2–7, t-test – I). Paired samples t-tests for the distinction between congruent and incongruent realization of the suffix -(i)sk in the word condition verify that in the second time window, in both the central ($t(13) = -2.405$, p = 0.032) and the parietal ($t(13) = -2.371$, p = 0.034) ROI, -sk elicited a larger MMN response as congruent deviant in the lexical stress block compared to as incongruent deviant in the phonological stress block (Supplementary Tables 3–4, t-test – II). A similar pattern is seen in the third time window, in

B

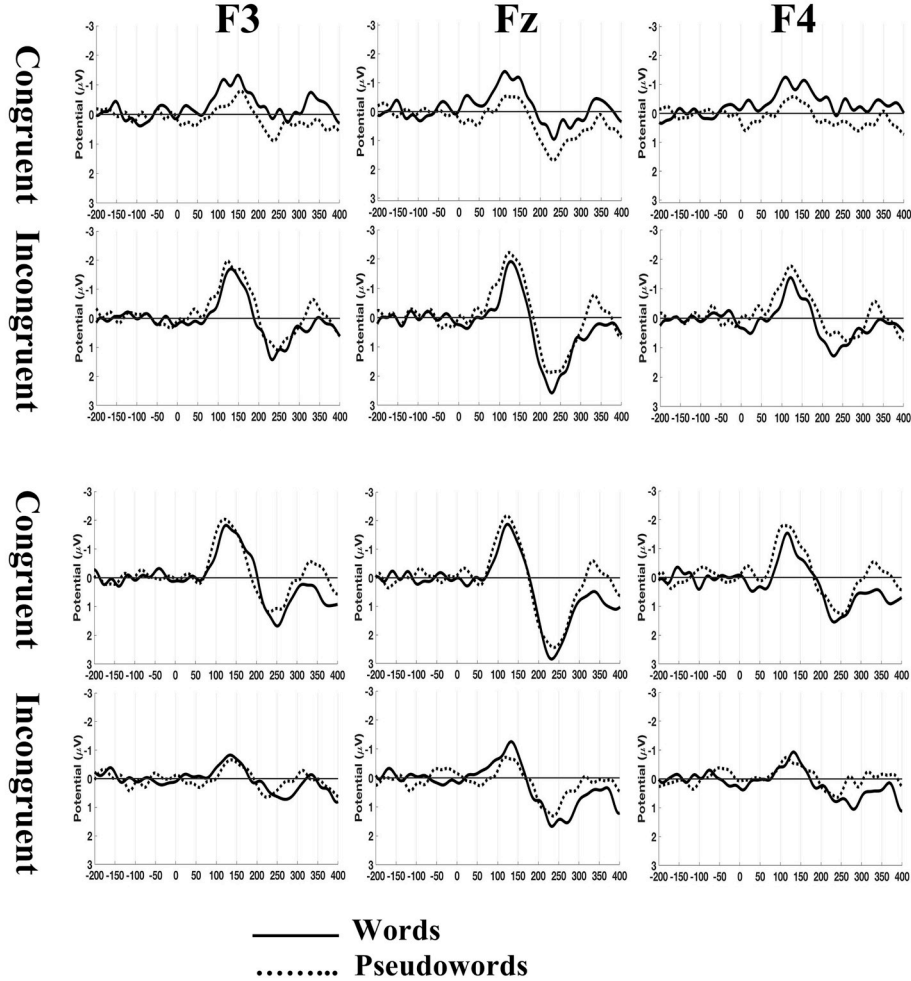
——— **Words**
········ **Pseudowords**

Fig. 2. (*continued*)

the parietal ROI (*t* (13) = −2.766, p = 0.016; Supplementary Table 7, *t*-test – II).

4. Discussion

The present study investigated for the first time the relevance of word stress specification in early morphological processing. We explored whether and how the specification of word stress as lexically marked or phonologically assigned influences the processing of derivations in Swedish. To this end, MMN responses were recorded to congruent and incongruent derivations, formed by the post-tonic derivational suffix -(*i*)*sk*, which takes either a syllabic form (-*isk*) or a non-syllabic form (-*sk*) depending on the specification of word stress in the stem. Since the MMN response is sensitive to stimulus variance and the physical characteristics of stimuli, we used single words rather than a large group of stimuli in order to study the early effects of derivational processing (see Pulvermüller & Shtyrov, 2006). The results indicated that, in line with previous MMN research on processing of morphologically complex words (Hanna & Pulvermüller, 2014; Leminen et al., 2013; Shtyrov & Pulvermüller, 2002a), derivations elicited MMN responses as early as 100–150 ms after the onset of critical information (i.e., suffix onset), and the MMN responses were maximal over frontal and central scalp locations, which is the typical topographical distribution of MMN (Näätänen and Winkler, 1999; Näätänen et al., 2007). However, supporting the hypothesis of the present study, MMN amplitudes to the congruent and incongruent derivations revealed differences in the processing of lexically stressed and phonologically stressed stems as well as differences in the processing of derived words and derived pseudowords. The congruent derivation of the lexically stressed stem elicited a larger MMN than the incongruent sequences of the same stem and the derivational suffix, whereas after the phonologically stressed stem this was not the case.

It is worth noting that we controlled for psycholinguistic and acoustic factors that could potentially affect these neural responses. Considering the frequency sensitivity of MMN, stems were matched for frequency. Moreover, the difference waveforms were calculated from the ERPs and MMNs in two manners: (i) by subtracting the neural response elicited by standard from the neural response

C
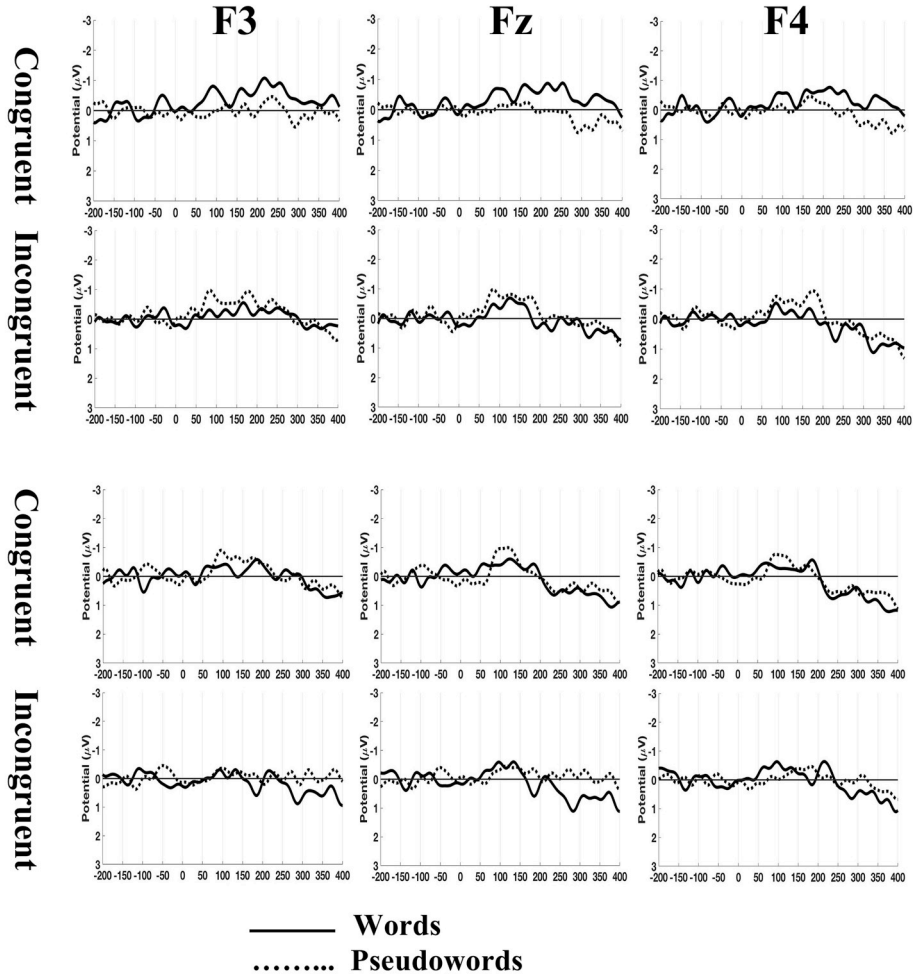
Fig. 2. (*continued*)

elicited by deviant, and (ii) by subtracting the MMNs elicited by pseudowords from the MMNs elicited by words. Subtractions were performed to cancel out the effect of physical differences between the deviant stimuli (-*sk/-isk*) on the MMN, and differential states of refractoriness of deviants and standards. It is crucial to distinguish the MMN response elicited by cognitive pre-attentive memory-based comparison of sound stimuli from the ERP responses elicited by differential states of neural refractoriness or pure stimulus features (Näätänen & Alho, 1997; Jacobsen & Schröger, 2001; 2003). In addition to the traditional deviant-minus-standard subtractions, we therefore carried out word-minus-pseudoword subtractions to eliminate acoustic and refractoriness effects on the MMN to suffix (see also the approach used in Jacobsen & Schröger, 2003). These subtractions thus enabled us to differentiate the word-type-related effects from the possible acoustic-change effects on the neural responses. Without word-minus-pseudoword subtractions, MMNs were clearly influenced by acoustic processing, as the amplitude of acoustically more deviant -*isk* was larger in comparison to less deviant -*sk* in both lexically stressed and phonologically stressed blocks regardless of the congruency (Fig. 2A and B). However, when the acoustic effects were cancelled out by word-minus-pseudoword subtractions, the results indicated that -*sk* elicited larger MMN in lexically stressed condition as congruent deviant. Since we are interested in the pattern across word type (lexical stress vs. phonological stress) and congruency (congruent vs. incongruent), our ANOVA statistics are based on the difference between the word (e.g., *vegan-sk*) and pseudoword (e.g., *began-sk*) stimuli to cancel out the effects of different acoustic features and syllable structure. Paired samples *t*-test were also carried out separately to evaluate the distinction between the word and pseudoword stimuli as well as between congruent (e.g., *vegan-sk*) and incongruent (e.g., *vulkan-sk**) realization of the suffix -(*i*)*sk* in the word condition.

Neural processing of derivations has previously been studied using MMN (e.g., Hanna & Pulvermüller, 2014; Leminen et al., 2013), yet the role of word stress specification in this process has never been addressed. Previous research indicated that derivations as linguistic forms that are frequently recombined with each other are stored as whole forms. Similar to enhanced MMN activation to words over acoustically matched pseudowords, enhanced MMN activation has been shown for existing derived words relative to incongruent combinations (e.g., Hanna & Pulvermüller, 2014). This enhanced MMN response to derivations has been argued to be
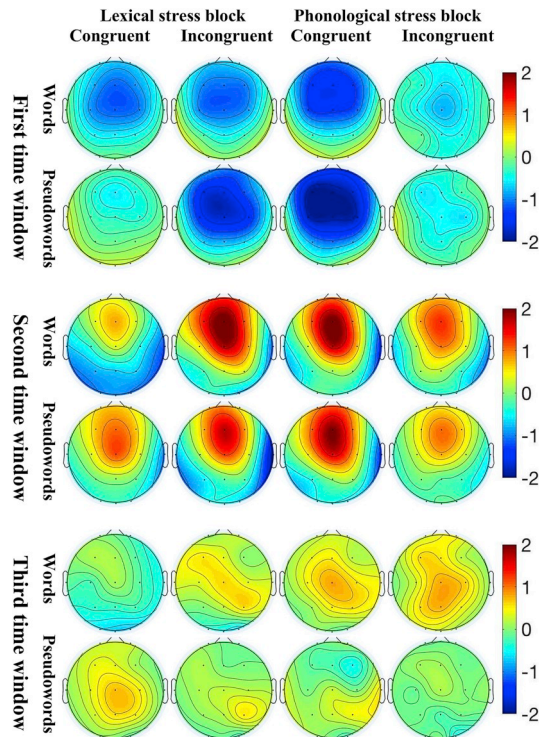
Fig. 3. Topographic difference maps (deviant-minus-standard) of all stimuli in the lexical stress block and the phonological stress block in each time window: First time window, 100–150 ms; Second time window, 200–250 ms; Third time window, 300–350 ms.

lMMN activation, and therefore a holistic processing has been suggested for derivational processes. The dual-system approach to the derivational morphology argued for holistic processing of derived words, with the possibility of parallel access through decomposition in some cases depending on the suffix productivity, frequency and semantic transparency (Bertram et al., 2000; Bozic et al., 2013; Clahsen et al., 2003; Leminen et al., 2010, 2011; Lewis et al., 2011; Vannest & Boland, 1999; Vannest et al., 2005; Whiting et al., 2013). In the present paper, we argue that the specification of word stress, as discussed in Riad (1999, 2012, 2014, 2015) also has an effect on the processing of derivations, and that derivations are either processed holistically or combinatorially, depending on the nature of words stress assignment of stems.

ANOVA indicated that the congruent derivation of lexically stressed stem elicited a significantly larger MMN than the incongruent derivation in both frontal and central ROIs at around 100–150 ms. This frontocentrally-distributed negativity (Fig. 3) is considered to be a lMMN response (Pulvermüller et al., 2009; Alexandrov et al., 2011; Hanna & Pulvermüller, 2014), reflecting the whole word storage of *vegan-sk*. *T*-tests verify this finding by indicating a statistically significant difference between MMN responses elicited by the word (*vegan-sk*) and pseudoword (*began-sk*) stimuli in the lexical stress block for the congruent derivation in the central ROI (Table 5, *t*-test – I). Moreover, *-sk* elicited a larger positive response as incongruent deviant in the phonological stress block compared to as congruent deviant in the lexical stress block, at around 200–250 ms (Supplementary Table 3, *t*-test – II). The positive activation seems to be the typical P3a response following the MMN response (Escera, Alho, Schröger, & Winkler, 2000; Jacobsen & Schröger, 2003; Polich, 2007). Since P3a indexes involuntary allocation of attention to novel and salient changes (Polich, 2007) and is elicited by illegal phonological sequences (Ylinen et al., 2016), we believe *-sk* in the context of phonological stress block (*vulkan-sk**) was more attention catching than in the context of the lexical stress block (*vegan-sk*). We argue that this interaction between derivational suffixes and the specification of word stress in stems is related to the faithfulness principle of OT. We believe that faithfulness to the lexical information minimizes the distance between suffix and stem, and that therefore no epenthesis takes place when the suffix attaches to a lexically stressed stem (unless e.g. phonotactics requires it) (Riad, 2014). Accordingly, we argue that stems that are specified for lexical stress and derivational suffixes are stored together and accessed holistically. Larger negativity to congruent derivation is therefore consistent with a lMMN, and indicates holistic processing of the sequence of a lexically stressed stem and derivational suffix. This result is consistent with the above-presented research (e.g., Hanna & Pulvermüller, 2014; Leminen et al., 2013), which suggested the holistic processing theory for derivations.

On the other hand, phonologically stressed stems and their derivations seem to be processed as morpheme chains. Although not reaching significance, there is an increased MMN activation to the incongruent deviant (Table 1). Moreover, although again not statistically significant, the decomposable suffix *-isk* elicited a large negativity in pseudowords at around 300–350 ms (Fig. 2A and B, Supplementary Table 5, *t*-test I). This larger negativity may reflect both a failed integration of morpheme strings similar to N400 response (Leminen et al., 2010; 2011) and a full-blown activation of the suffix *-isk* in the pseudoword context and thus decomposition

Table 4

Results for two-way repeated-measures ANOVA with factors of Specification and Congruency; Results for follow-up analysis to two-way interaction of Specification and Congruency with pairwise comparisons; Results of paired samples *t*-test between the word and pseudoword stimuli, *t*-test I; Results of paired samples *t*-test between the congruent and incongruent realization of the suffix -(i)sk, *t*-test II; Mean values (M) and standard deviations (SD); LSB, Lexical stress block; PSB, Phonological stress block; *p < 0.05

Two-way repeated-measures ANOVA – 1st time window, frontal

Factor	F	p	η^2
Specification	F (1,13) = 0.295	0.596	0.022
Congruency	F (1,13) = 1.040	0.326	0.074
Specification X Congruency	F (1,13) = 5.592	0.034*	0.301

Follow-up

Factor	F	p	η^2
Congruency - LSB	F (1,13) = 12.224	0.004*	0.485
Congruency - PSB	F (1,13) = 1.381	0.261	0.096

Descriptive values

Congruency Level	M	SD	
Congruent deviant - LSB	−0.504	1.271	
Incongruent deviant - LSB	0.445	1.732	
Congruent deviant - PSB	0.484	1.462	
Incongruent deviant - PSB	−0.049	0.859	

t-test – I

	t	Word		Pseudoword	
	t	M	SD	M	SD
LSB congruent	t (13) = −1.483, p = 0.162	−0.970	0.916	−0.466	1.392
LSB incongruent	t (13) = 0.961, p = 0.354	−1.031	1.374	−1.476	1.521
PSB congruent	t (13) = 1.240, p = 0.237	−1.428	1.497	−1.912	2.151
PSB incongruent	t (13) = −0.212, p = 0.835	−0.503	1.620	−0.454	1.184

t-test – II

	t	LSB congruent		PSB incongruent	
	t	M	SD	M	SD
-sk	t (13) = −1.419, p = 0.179	−0.970	0.916	−0.503	1.620
-isk	t (13) = 1.317, p = 0.211	−1.031	1.374	−1.428	1.497

(Pulvermüller, 2002; Shtyrov et al., 2003; Pulvermüller & Knoblauch, 2009; Bakker et al., 2013; Leminen et al., 2013). Since there is no connection between the pseudoword and the suffix -*isk*, larger activation to the -*isk* in pseudowords is in line with the inter-pretation of -*isk* as causing decomposition. This is also in line with previous research, which indicated increased N400 response to derived pseudowords in comparison to derived words reflecting a failed lexical-semantic integration of morpheme chains at around 300 ms after suffix onset (Leminen et al., 2010). We believe that when the suffix -*(i)sk* attaches to a phonologically stressed stem, the overall prosodic word shape is optimized by the epenthesis. The omission of the epenthesis therefore leads to an unprimed suffix, i.e., -*sk*, which results in a full-blown activation, and accordingly elicits a larger MMN response. Since there is no connection between the phonologically stressed stem and the suffix -*sk*, we do not see any priming effect as suggested for frequently co-activated morphemes in the case of combinatorial sequences (e.g., Bakker et al., 2013). Due to its full-blown activation, the unprimed suffix -*sk* therefore elicited a larger MMN response in comparison to the primed suffix -*isk*, reflecting combinatorial processing of phonologically stressed stem and derivational suffix. This is comparable to previous investigations on the processing of inflected words, which indicated that inflected words are processed combinatorially as morpheme chains (i.e., stems and suffixes), following morphological rules (Bakker et al., 2013; Leminen et al., 2013). This result should however be taken with caution since it does not reach statistical significance. One might argue that derivations of frequent phonologically stressed words might also have whole form representations (see Lehtonen & Laine, 2003; Lehtonen, Vorobyev, Hugdahl, Tuokkola, & Laine, 2006b; Schremm et al., 2018), and therefore they could elicit a lMMN response, whereas phonologically stressed words with lower frequency might require combinatorial processing. It should also be emphasized that the absence of lMMN response to the congruent derivation in the phonological stress block might index combinatorial processing of the -*isk* despite the absence of combinatorial MMN to the incongruent derivation.

The present study, in combination with previous research (Zora et al., 2016b), indicates that there is a contrast in how lexical stresses and phonological stresses are processed in the brain, and indicates different neural activation to the same derivational suffix depending on this prosodic specification. The findings support the assumption that phonologically stressed stems and derivational suffixes do not have strongly connected memory traces, and are thus morphologically parsed as sequences, whereas lexically stressed stems and derivational suffixes are stored as single lexical representations. The present findings also provide experimental evidence for a faithfulness effect with lexical stress in Swedish, and indicate that in contrast to the traditional analysis, stress placement in Swedish is mostly determined by morphological marking. Prosodic specification in the morphology has important implications for

Table 5
Results for two-way repeated-measures ANOVA with factors of Specification and Congruency; Results for follow-up analysis to two-way interaction of Specification and Congruency with pairwise comparisons; Results of paired samples *t*-test between the words and pseudoword stimuli, *t*-test I; Results of paired samples *t*-test between the congruent and incongruent realization of the suffix -(i)sk, *t*-test II; Mean values (M) and standard deviations (SD); LSB, Lexical stress block; PSB, Phonological stress block; *p < 0.05

Two-way repeated-measures ANOVA – 1st time window, central			
Factor	*F*	*p*	η^2
Specification	F (1,13) = 0.333	0.573	0.025
Congruency	F (1,13) = 2.685	0.125	0.171
Specification X Congruency	F (1,13) = 4.966	0.044*	0.276
Follow-up			
Factor	*F*	*p*	η^2
Congruency - LSB	F (1,13) = 9.485	0.009*	0.422
Congruency - PSB	F (1,13) = 1.842	0.198	0.124
Descriptive values			
Congruency Level	*M*	*SD*	
Congruent deviant - LSB	−0.709	1.223	
Incongruent deviant - LSB	0.528	2.153	
Congruent deviant - PSB	0.579	1.427	
Incongruent deviant - PSB	−0.128	1.245	

t-test – I		Word		Pseudoword	
	t	*M*	*SD*	*M*	*SD*
LSB congruent	t (13) = −2.170, p = 0.049*	−1.026	2.092	−0.317	1.345
LSB incongruent	t (13) = 0.917, p = 0.376	−0.997	1.491	−1.525	1.859
PSB congruent	t (13) = 1.517, p = 0.153	−1.233	1.703	−1.812	2.400
PSB incongruent	t (13) = −0.385, p = 0.706	−0.617	1.807	−0.489	1.317

t-test – II		LSB congruent		PSB incongruent	
	t	*M*	*SD*	*M*	*SD*
-sk	t (13) = −1.201, p = 0.251	−1.026	1.092	−0.617	1.807
-isk	t (13) = 0.763, p = 0.459	−0.997	1.491	−1.233	1.703

the interplay between stems and derivational suffixes in the mental lexicon. Moreover, given that it eliminates the need for exceptional features employed in traditional phonological analyses, such as extrametricality and direct marking, and also considering that tone is lexically specified in Swedish (Riad, 1999; 2012, 2014), we believe assigning morphology a central role in the Swedish stress system is crucial and unavoidable. Supporting this reasoning, the present findings offer new experimental evidence for the involvement of morphology in the Swedish stress system, besides bringing a new aspect to the neural processing of morphologically complex words and a new constraint to the dual-system approach of derivational morphology, namely specification of stress assignment. Further research is however needed to validate the significance of stress assignment information in the neural representation of morphologically complex words, and to extend it to other languages. Stress assignment in Germanic languages has typically been analyzed as phonologically driven. The present study provides evidence for the lexical nature of much of the stress system, for Swedish, and for the direct involvement of prosodic specification in the processing of complex morphological forms. Thereby, the present study would encourage the field to examine data from other Germanic languages and to scrutinize the relevance of specification of word stress assignment in morphology and the processing of it.

5. Conclusion

With regard to the processing of morphologically complex words, the dual-system model argues for the decomposition or whole word storage depending on certain factors such as the type and productivity of affixes, and the semantic transparency. The present study introduces a new constraint on derivational morphology, namely the specification of word stress, and suggests that in Swedish, derivations are processed either holistically or combinatorially based on the source of stress as lexical or phonologically assigned, respectively. Forms that receive stress through a phonological rule do not have strongly connected memory traces between stem and derivational suffix, and are thus processed combinatorially as morpheme chains, whereas in forms that have stress as part of their lexical representation, the stem and derivational suffix are stored together and accessed holistically.

Funding

Declaration of interest

None.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jneuroling.2019.100856.

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