Research paper

Brain responses to morphologically complex verbs: An electrophysiological study of Swedish regular and irregular past tense forms

Andrea Schremm[*], Mikael Novén, Merle Horne, Mikael Roll

Department of Linguistics and Phonetics, Lund University, Box 201, 22100, Lund, Sweden

A B S T R A C T

The present electrophysiological study investigated irregular versus regular verb form processing in Swedish during reading. In line with previous results from other languages, overregularized verbs, i.e. incorrect irregular stem + regular past tense suffix combinations (e.g. **stjäl + de* 'steal + past tense'), elicited a left-lateralized negativity (LAN) relative to correct irregulars (*stal* 'stole'), suggesting rule-based decomposition of regularly inflected words. Lack of a similar effect for misapplication of the irregular stem formation pattern on regular verbs (e.g. **löft* 'lifted' instead of *lyfte*) suggests the involvement of different processing mechanisms, possibly whole word access, for irregular items, at least to some degree. A P600 showing reprocessing was seen for all incorrect forms. The results add cross-linguistic support for morphological decomposition in the verbal inflection of a language where results from previous neurolinguistic studies of nominal inflection have only suggested the use of full-form access to words.

1. Introduction

Cognitive mechanisms and brain networks involved in processing regular and irregular word classes during language comprehension have been the subject of intense study and controversy. Investigating the issue in different languages with varying morphological properties could provide valuable insights into the way the brain handles idiosyncratic word forms as well as rule-governed sequences (Leminen, Smolka, Duñabeitia, & Pliatsikas, 2019). It has been suggested that many languages differentiate regularly inflected words like *walked*, which listeners understand by decomposing them into stem (*walk*) and suffix (*-ed*) from irregular words like *brought*, which would rather be retrieved from the mental lexicon as whole units (Pinker, 1999). For Swedish, hemodynamic (Lehtonen et al., 2009) and electrophysiological (Roll, Horne, & Lindgren, 2010) studies have tested nominal morphology and found evidence for only whole wordform storage, most likely the result of the lack of a truly regular nominal suffixation paradigm. However, the Swedish verbal system exhibits clearly rule-based suffix application. This study investigated for the first time whether regular versus irregular verb forms in Swedish elicit different electrophysiological brain signals, which would suggest distinct processing mechanisms. Specifically, it is unknown whether misapplication of the Swedish regular verbal inflection, unlike nominal inflection, would yield a left anterior negativity (LAN), an effect previously argued to be consistent with rule-based decompositional analysis of regular complex word forms in a number of languages (e.g. Morris & Holcomb, 2005; Penke et al., 1997;

---

* Corresponding author. Department of Linguistics and Phonetics, Centre for Languages and Literature, Lund University, Box 201, 221 00, Lund, Sweden.

E-mail addresses: andrea.schremm@ling.lu.se (A. Schremm), mikael.noven@ling.lu.se (M. Novén), merle.horne@ling.lu.se (M. Horne), mikael.roll@ling.lu.se (M. Roll).

Rodriguez-Fornells, Clahsen, Lleó, Zaake, & Münte, 2001).

In English, the past tense of the majority of verbs is predictively formed by attaching an *-ed* suffix to the stem (e.g. *walk - walked*), whereas a smaller set of words displays more idiosyncratic morphological variation (e.g. *go - went*). Much of the controversy in the psycholinguistic literature has focused on the question as to whether the neural processing of such morphologically complex forms actually involves two distinct mechanisms, as proposed by dual route models (Clahsen, 1999; Pinker, 1999). Alternatively, it has been suggested that the production and comprehension of all inflected words are processed by a single cognitive system operating on full word forms (Joanisse & Seidenberg, 1999; Justus, Larsen, de Mornay Davies, & Swick, 2008; Kielar & Joanisse, 2011; Smolka, Khader, Wiese, Zwitserlood, & Rösler, 2013). Yet other models propose rule-based decomposition of all forms, including irregular words, supported by priming effects for different morphological forms of irregular words (Stockall & Marantz, 2006; Fruchter, Stockall, & Marantz, 2013). Findings of electrophysiological studies reporting different ERP patterns for regular versus irregular word form processing (Gross, Say, Kleingers, Clahsen, & Münte, 1998; Morris & Holcomb, 2005; Münte, Say, Clahsen, Schiltz, & Kutas, 1999; Newman, Ullman, Pancheva, Waligura, & Neville, 2007; Penke et al., 1997; Rodriguez-Fornells et al., 2001; Weyerts, Penke, Dohrn, Clahsen, & Münte, 1997) have been typically interpreted to be consistent with the distinction assumed by dual route models: irregular forms are proposed to be directly accessed as whole word representations in the mental lexicon, whereas regular items might undergo rule-governed decomposition (Clahsen, 1999; Pinker, 1999). Specifically, the observation of a LAN in the electrophysiological brain signal for overregularization of verbs or nouns (*go* > **goed*), an effect commonly seen as an index of morphosyntactic anomaly detection (Friederici, 2002), has been argued to be suggestive of the productive operation of a combinatorial rule (Krott & Lebib, 2013). Such a mechanism appears to be associated with the regular inflection, as irregularization of regular verbs (*walk* > **welk*) tends to elicit different, or no effects.

Nevertheless, the cross-linguistic generalizability of the proposed distinction between morphological processing routes is still unclear as electrophysiological data are available only for a limited set of languages (mainly English, German, Italian and Catalan), and there has been some degree of variation across studies and languages concerning, for instance, the scalp distribution of the observed LAN effect (Krott, Baayen, & Hagoort, 2006) and the exact conditions that elicit anterior negativities. For example, in Catalan where verb stems are composed of a root as well as a thematic vowel, rule violations associated with incorrectly using the default thematic vowel within a stem (i.e. the incorrect application of the 1st conjugation theme vowel *-a-* to a 2nd or 3rd conjugation verb: e.g. **dorm-a-t* 'slept' instead of correct *dorm-i-t*), but not the misapplication of the regular inflection (i.e. using the regular participle inflection *-t* in a verb with irregular participle form, e.g. **admetat* 'admitted' instead of correct *admès*), resulted in a LAN (Rodriguez-Fornells et al., 2001).

It could be the case that the processing route employed in a given context might depend on cross-linguistic differences in morphology. Importantly, in Swedish, there is no default plural suffix for nouns, and imaging evidence points towards full-form access, since no hemodynamic increase in Broca's area has been found for inflected medium-to-high frequency words, in stark contrast to the processing of nouns in morphologically richer Finnish (Lehtonen et al., 2009). Pointing in the same direction, an ERP study showed an N400 increase for incorrectly inflected nouns in Swedish (Roll et al., 2010). However, increased processing load has been found for inflection in low frequency nouns in a response time study (Lehtonen, Niska, Wande, Niemi, & Laine, 2006). Likewise, cortical thickness of Broca's area has been observed to correlate with speed of processing inflection in pseudo words (Schremm et al., 2018). The increased morphological processing in low frequency and pseudo words suggests that decomposition can be used even for Swedish nouns if full forms are not readily available.

In contrast to the nominal inflection system, Swedish verbal inflection is more clearly rule-based. The first three conjugations use a phonologically determined *-de/te* suffix for past tense. This can be seen as the default past tense suffix, which Swedish speakers would be likely to apply to new words, e.g. unintegrated loanwords such as *leasa + de* 'leased.' Even verbs of the non-default class exhibit somewhat regular patterns in stem vowel alternations that distinguish present and past tense forms, a fact which raises the question as to whether regular versus irregular classes would still display distinctly different brain responses as seen in previous studies. Findings so far are inconclusive as regards this question, pointing towards the role of language- and morphology-specific factors: whereas in Catalan, misapplication of the non-default stem formation did not produce a LAN (Rodriguez-Fornells et al., 2001), violation of subregularities associated with irregular verb stem formation in German was reported to yield a widespread negativity preceding the syntax-related P600 effect (Regel, Opitz, Müller, & Friederici, 2015).

Dual system views were originally formulated with reference to English (Pinker, 1999), a language that is characterized by an especially clear-cut distinction between regular and irregular forms. Languages with relatively richer morphology, however, tend to have several noun or verb classes displaying varying degrees of regular inflection. In such cases, it has been argued that only one class can be considered as the default, which is in turn processed through decomposition as opposed to direct lexical access (Rodriguez-Fornells et al., 2001; Sonnenstuhl, Eisenbeiss, & Clahsen, 1999). An important characteristic of the default class has been suggested to be the lack of changes in the word stem form, and in turn a straightforward applicability of a productive suffix concatenation rule (e.g. Weyerts et al., 1997). Non-default classes might display changes in the word stem such as vowel alternations (e.g. *sit* > *sat*). Nevertheless, considering that misapplication of regularities pertaining to the morphological form of stems of the default verb class yielded a left-lateralized negativity in Catalan (Rodriguez-Fornells et al., 2001), there is some indication that LANs might not only be elicited by violations of rules associated with attaching the regular suffix to an invariable stem. MEG studies have even shown evidence for decomposition of irregular verbs in English (Stockall & Marantz, 2006), especially for subgroups where analogical formation patterns can be identified, e.g. *lend/lent, send/sent* (Fruchter et al., 2013). More recent observation of LAN-like responses to well-formed regular participles has challenged the traditional view of LAN as a signal of rule violation, raising the possibility that such negativities might in fact generally index morphological rule application (Krott & Lebib, 2013). From this perspective, LAN effects that were observed for regularized irregular words could be interpreted to reflect morphological processing as such,

Table 1
The four experimental conditions with examples and predictions concerning the expected LAN effect.

	Correct	Incorrect (Irregularized)
Regular	*lyft+(t)e* 'lift + ed'	**löft* 'lifted' (no LAN)
		Incorrect (Overregularized)
Irregular	*bar* 'bore'	**bär + de* 'bear + past tense' (LAN)

presumably triggered by a regular inflection.

In the present study, we investigated Swedish verb form processing by recording ERP responses to overregularized irregular versus irregularized regular verbs, visually presented in sentences (see Table 1 for the experimental conditions and examples). In Swedish, a distinction can be made between default (i.e. regular) versus non-default (i.e. irregular) verb classes based on the above described considerations. Regular verbs (1st to 3rd conjugations) are inflected in the past tense with a productive suffix (*-te/-de*), which induces no changes in the verb stem (e.g. *hjälp + te* 'help + ed', base form: *hjälp-a* 'to help'). In line with previous results, overapplication of the regular past tense suffix to an irregular stem (irregular incorrect (overregularized): **bär + de* 'bear + past tense') is expected to elicit a LAN relative to the correct form (irregular correct: *bar* 'bore'). Verbs in the irregular 4th conjugational class in Swedish display stem vowel alternations, a past tense formation pattern typically not generalized to novel words. Nevertheless, vowel changes in the stem tend to follow predictable patterns in the majority of cases (e.g. y > ö: *flyger* 'fly' > *flög* 'flew'; i > a: *binder* 'bind' > *band* 'bound') (Teleman, Hellberg, & Andersson, 1999). Regular verbs were thus irregularized in the present study by changing the stem vowel on analogy to the vowel alternations in the non-default class (regular incorrect: *lyfter* 'lift' > **löft*). If the resulting regular incorrect (irregularized) forms constitute unfamiliar words for Swedish speakers, with an internal structure opaque to rule-based decomposition, no LAN would be expected in this condition relative to the correct variant (regular correct: *lyfte* 'lifted') as previously seen in several studies (Gross et al., 1998; Morris & Holcomb, 2005; Penke et al., 1997; Rodriguez-Fornells et al., 2001; Weyerts et al., 1997). Alternatively, the presence of a potentially recognizable regularity within the stem of regular incorrect (irregularized) words, i.e. the stem vowel alternation patterns of the irregular class, might promote some degree of morphological processing, which, considering the proposal of LAN as a general index of morphological rule application (Krott & Lebib, 2013), could conceivably be reflected in an increased left anterior negativity. In addition, since verbs were presented in sentence context, a P600 effect was predicted for both incorrect conditions, reflecting reanalysis processes or increased difficulties integrating an incorrect verb into the sentence structure (Friederici, 2002; Kaan, Harris, Gibson, & Holcomb, 2000).

2. Methods

2.1. Participants

Twenty-three right-handed Swedish native speakers (12 females) participated in the experiment. Mean age was 24.3 years, SD = 3.0. All participants gave informed consent in accordance with the Declaration of Helsinki. The study procedures were approved by the Lund Regional Ethical Review Board (approval number 2016/871).

2.2. Stimuli

Each of the four test conditions involved 30 unique verbs with a monosyllabic stem, embedded in sentences. In the Regular correct condition, a verb from the regular (2nd) conjugational class was correctly inflected with the past tense suffix *-te/-de* (e.g. *skräm + de* 'frighten + ed'). Verbs in the Regular incorrect (irregularized) condition appeared in an incorrect form (**skram*), created by changing the vowel of the infinitive stem ('ä' in *skräm*), on analogy to the vowel alternation (e.g. *ä > a*) characterizing irregular past tense verbs. This strategy was chosen since Swedish does not have a class of irregular verbs with suffix-based conjugation. The Irregular correct condition involved verbs in the irregular (4th) conjugational class in correct past tense forms (e.g. *stal* 'stole'). Verbs appearing in the Irregular incorrect (overregularized) condition were created by inflecting the infinitive stem of the irregular verb (e.g. *stjäl + a* 'to steal') with the regular past tense suffix *-te/-de* (*stjäl + de*). There was no difference between verbs in the Regular/Irregular conditions considering mean lemma frequency (t(58) = 0.276, p = 0.784) based on the Stockholm-Umeå corpus (Stockholm-UmeaCorpus SUC 1.0, 1996). The word form frequencies of correct past tense verbs in the Regular (M = 25.60 per million words, SD = 40.63) and Irregular conditions (M = 44.37 per million words, SD = 60.56) showed no significant difference (t(58) = −1.409, p = 0.165) in the PAROLE corpus (https://spraakbanken.gu.se/eng/resources/corpus). Regular verb items (correct and regularized) were disyllabic, whereas irregular items (correct and irregularized) were monosyllabic. This intrinsic difference between regular and irregular verbs was the main reason to present the sentences visually, in order to minimize length effects.

Even though stem vowel changes in 4th conjugational class verbs tend to follow specific patterns, the regular-irregular distinction is made here between 2nd and 4th conjugational verbs based on the following considerations. First, belonging to the 4th conjugational class is an idiosyncratic property of the verb, which cannot be determined based on the infinitive form of the word. Regular verbs, however, always receive a specific allomorph of the past tense suffix *-te/-de*, depending solely on the phonological form of the stem-final segment. Moreover, unlike the stem vowel alternation rules of the 4th conjugational class, the past tense suffix *-te/-de* is

productive, and as such can be applied, for instance, to novel verbs or loanwords (e.g. *blogga* + *de* 'blogged').

All test sentences had the same structure: a single word subject, followed by the target verb and a sentence final adverb or object (one or two words), e.g. *Tjejen skar frukterna* 'The girl sliced the fruits' (see Appendix for a list of target verbs with sentence examples). The same subjects were used across the four conditions, for the same target verb where possible, i.e. the same subject for regular correct and incorrect test items, and the same subject for irregular correct and incorrect items. In addition, a further 40 sentences, which were not considered during the analysis, were included to decrease the predictability of the stimulus material. In a manner analogous to test item construction, verbs in these sentences appeared in regular correct/incorrect and irregular correct/incorrect past tense forms, 10 times per form. However, it was not the case that each lexical verb appeared once in a correct and once in an incorrect version, but rather the verb form manipulation followed a more unpredictable pattern. For instance, some lexical verbs appeared only as correct past tense verbs, while other verbs were presented several times in their incorrect past tense form. Repetition was balanced across regularity and correctness. The purpose of including these sentences was to prevent participants from relying on the strategy of expecting an incorrect/correct verb after already having seen the correct/incorrect version of the same verb stem during the experiment.

2.3. Procedure

Sentences were presented at the centre of a computer screen, in white font against a dark blue background, one phrase at a time: i.e. the subject, the target verb and the final phrase of the sentence were presented separately in succession. Stimulus onset asynchrony was 450 ms including 50 ms of interstimulus interval with blank screen. A fixation cross displayed for 1000 ms preceded each trial. The grammaticality judgement question ("Correct or Incorrect") was shown immediately after each sentence, for 2000 ms. Participants responded by pressing a left- or a right-hand key. Hand-response associations were counterbalanced within participants. Sentences were presented in a randomized order, distributed across two blocks of 80 sentences each.

2.4. Behavioural data

Response times (RTs) were calculated from the verb presentation. RTs of incorrect answers (8.6% of all test items), and items that were not responded to before the offset of the question presentation (i.e. within 2900 ms following the verb, 7.8%) were excluded from the analysis. Repeated measures ANOVAs with the factors Regularity (regular, irregular) and Correctness (correct, incorrect) were carried out on reaction time and accuracy values for irregular and regular verbs separately. Accuracy values were expressed as the proportion of correct responses to the grammaticality judgement questions, which participants were required to respond to after each sentence presentation.

2.5. EEG recording

EEG data was recorded from 32 electrodes (Braincap-MR from Easycap) using BRAINAMP MR PLUS Amplifier and Brainvision Recorder (BrainProducts), at a sampling rate of 250 Hz. Online, a high-pass filter set at 0.1 Hz and a low-pass filter with a cut-off frequency of 70 Hz were used, and impedances were kept at 5 kΩ. Recording reference was FCz. Offline, reference was re-calculated to the average of the mastoid electrodes and a 30 Hz low-pass filter was applied. A low-pass filter of 16 Hz was used for presentation only.

2.6. ERP analysis

EEGLAB was used for ERP analysis (Delorme & Makeig, 2004). Epochs of 1000 ms were extracted following verb presentation onset, and a prestimulus period of 200 ms was used as a baseline. EEG portions with large artifacts were first rejected through visual inspection. Then independent component analysis (ICA) was used to correct for ocular artifacts (Jung et al., 2000). Epochs where signal amplitude exceeded ± 100 μV after ocular artifact correction were discarded before averaging (3.55% of trials). There was no significant difference, ($F(3, 66) = 0.714$, $p = 0.547$), between the remaining number of epochs per condition.

For statistical analysis, two time windows were created based on previous literature: 350–500 ms for the LAN and 600–1000 ms for the P600 (Morris & Holcomb, 2005). To find electrode clusters with significant effects of correctness, mean amplitude values per participant and condition for each electrode were submitted to a permutation test using Fieldtrip (Monte Carlo method, cluster entry alpha = 0.05, permutation alpha = 0.025, minimum number of electrodes required for a cluster = 2, randomizations = 1000). All electrodes except mastoid channels (TP9 and TP10) and those closest to the eyes (Fp1 and Fp2) entered the analysis. Both interactions (Regular incorrect – correct vs. Irregular incorrect – correct) and planned comparisons of Regular incorrect vs. correct and Irregular incorrect vs. correct were contrasted.

3. Results

3.1. Behavioural results

The ANOVA carried out on reaction time (RT) values detected a Regularity × Correctness interaction, $F(1, 22) = 8.67$, $p = 0.007$, $\eta_p^2 = 0.283$. For regular verbs, incorrect (irregularized) items ($M = 1210$ ms, $SD = 228$) elicited significantly faster responses, $F(1,$
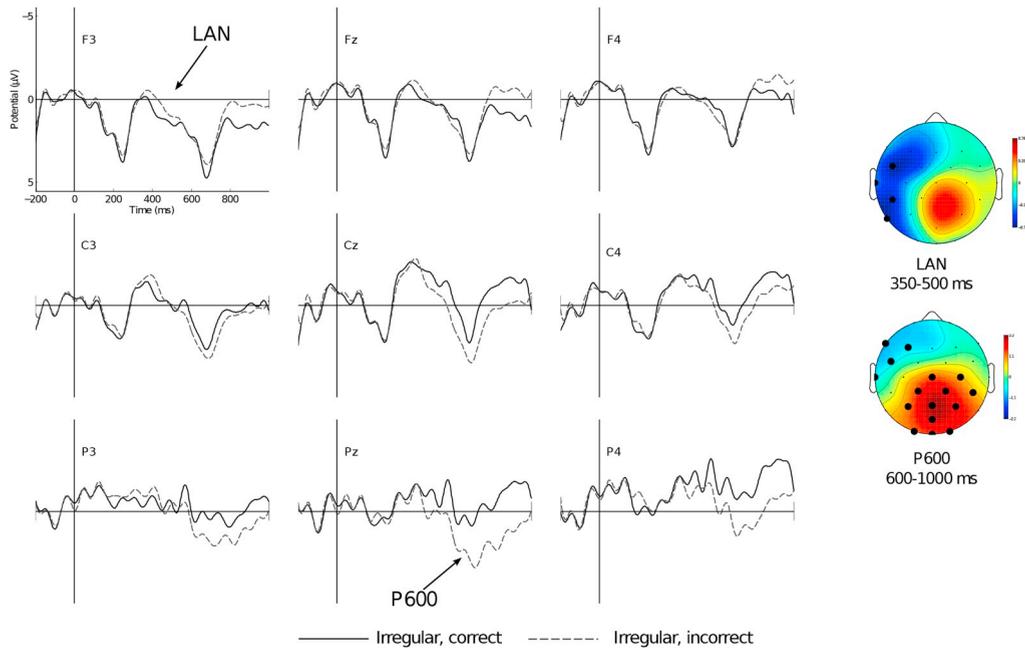
Fig. 1. Left: ERPs at 9 electrodes for the target verb in the Irregular correct (solid line) and the Irregular incorrect (overregularized) (dashed line) conditions. Irregular incorrect verbs elicited a LAN between 350 and 500 ms and a P600 between 600 and 1000 ms. Right: topographic maps showing the scalp distribution of the LAN (top) and the P600 effects (bottom) for irregular incorrect verbs. Electrodes in significant clusters are represented as large dots.

22) = 12.867, $p = 0.002$, $\eta_p^2 = 0.369$, than correct ones ($M = 1284$ ms, $SD = 221$). There was no difference between correct ($M = 1251$ ms, $SD = 217$) and incorrect (overregularized) irregular verbs ($M = 1255$ ms, $SD = 234$).

The analysis of accuracy values (the proportion of correct responses to the grammaticality judgement questions) found a Regularity × Correctness interaction, $F(1, 22) = 5.64$, $p = 0.027$, $\eta_p^2 = 0.204$. Correctness had an effect on irregular items, $F(1, 22) = 15.706$, $p = 0.001$, $\eta_p^2 = 0.417$, as irregular correct verbs ($M = 0.92$, $SD = 0.07$) received more accurate responses than irregular incorrect ones ($M = 0.86$, $SD = 0.10$). For regular verbs, the difference between correct items ($M = 0.95$, $SD = 0.06$) and incorrect items ($M = 0.93$, $SD = 0.07$) did not reach significance.

3.2. ERP

3.2.1. LAN time window (350–500 ms)

Incorrect irregular (overregularized) verbs elicited an increased left-lateralized negativity relative to correct irregular verbs between 350 and 500 ms (Fig. 1). A permutation test found no interaction between Regularity and Correctness. Planned comparison of Irregular correct and incorrect conditions showed a significant cluster of left-lateralized electrodes (FC5, T7, CP5, P7), $p = 0.037$. The Regular incorrect vs. correct contrast did not produce any significant cluster (Fig. 2).

3.2.2. P600 time window (600–1000 ms)

In the 600–1000 ms time window, regular and irregular incorrect items displayed a centroposterior positivity (see Figs. 1 and 2). Irregular (overregularized) verbs also produced a left-anterior negativity in this time window. The permutation test showed no interaction between regularity and correctness. However, planned comparison for irregular verbs showed one centroposterior (Cz, C4, CP1, CP2, CP6, Pz, P3, P4, POz, O1, O2, Oz), $p = 0.001$, and one left anterior (F3, F7, FC5, T7) cluster, $p = 0.046$. A centroposterior cluster, but no anterior cluster, appeared in the permutation test for regular verbs, $p = 0.002$. It involved the same electrodes as the equivalent cluster for irregular verbs, with the addition of two left electrodes (C3, CP5). For ERPs at all channels without visualization filter, please see supplementary materials.

4. Discussion

The present study investigated Swedish readers' ERP responses to correct regular and irregular verbs as well as irregularized and overregularized verb forms. The obtained results were largely in line with findings of previous studies on regular/irregular morphology processing in a number of other languages (Gross et al., 1998; Morris & Holcomb, 2005; Penke et al., 1997; Rodriguez-Fornells et al., 2001; Weyerts et al., 1997). Attaching a regular suffix to an irregular verb stem yielded an increased left-lateralized negativity relative to the correct irregular form, between 350 and 500 ms (Fig. 1). This effect, most prominent at left central sites, is
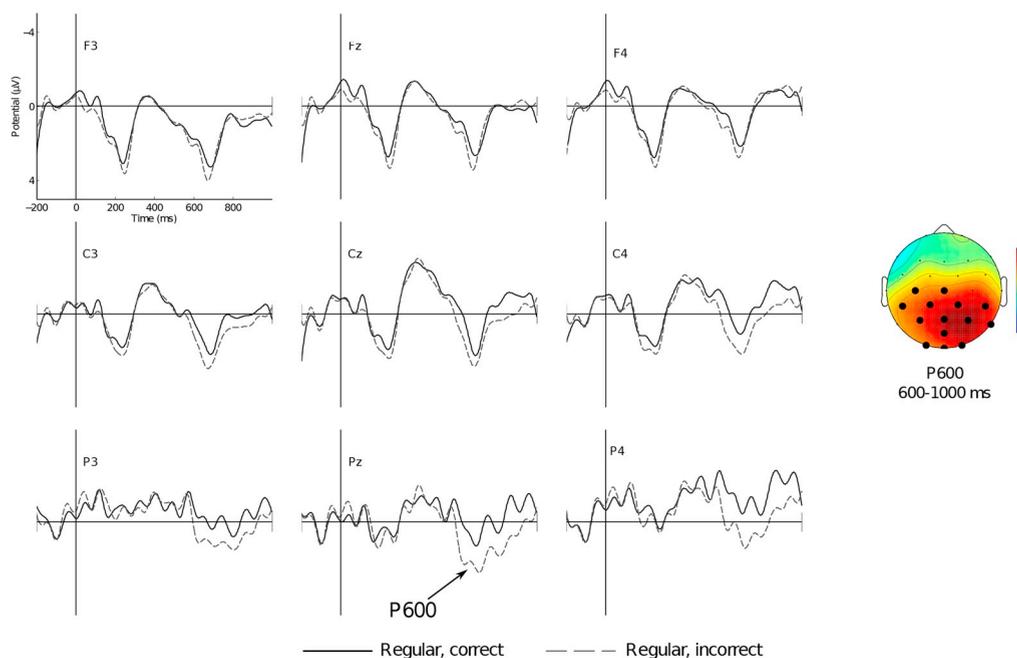
Fig. 2. Left: ERPs at 9 electrodes for the target verb in the Regular correct (solid line) and the Regular incorrect (irregularized) (dashed line) conditions. Regular incorrect verbs elicited a P600 between 600 and 1000 ms. Right: topographic map showing the scalp distribution of the P600 effect for regular incorrect verbs. Electrodes in the significant cluster are represented as large dots.

interpreted as a LAN, which has commonly been seen as a signal of morphological anomaly detection or as morphological rule application in general (Krott & Lebib, 2013). It has been argued that overregularized word forms elicit a LAN as a result of the misapplication of a suffixation rule to a stem that is assumed to block the default morphological mechanism due to the presence of stored whole word representations of irregular inflected forms in the mental lexicon (Penke et al., 1997; Pinker & Ullman, 2002; Rodriguez-Fornells et al., 2001). The LAN observed in the present case thus implicates that regular Swedish verbs might undergo morphological parsing based on the default past tense formation rule. The clearly left-lateralized but slightly more central than frontal distribution is similar to the LAN found also for regularization in English (Morris & Holcomb, 2005) and for morphosyntactic violation in Swedish (Roll, Gosselke, Lindgren, & Horne, 2013). The fact that behavioural accuracy was slightly lower for over-regularized words could be related to automatic morphological decomposition of the incorrect forms, leading to felicitous inter-pretation and some hesitation about their incorrectness.

No effect was obtained for irregularized verbs relative to correct regular items in the early time window (Fig. 2), possibly indicating that misapplication of the irregular stem formation pattern to a regular verb was not processed as a morphological rule violation. This interpretation would suggest that the vowel alternations characterizing the irregular past tense verbs in Swedish, even if these are largely predictable, might not be treated as productive morphological regularities, and that existing irregular forms are rather accessed as whole words. In this vein, irregularized verbs were quickly and accurately discarded, speaking in favour of their treatment as whole word forms. Finally, as expected, incorrect verbs elicited a late positivity between 600 and 1000 ms, a P600 (Figs. 1 and 2), possibly reflecting reanalysis of sentence structure or increased processing efforts during integration of the incorrect verb forms (Friederici, 2002; Kaan et al., 2000). The anterior negativity observed in the P600 time window for incorrect irregular items, but not for incorrect regular ones, might potentially represent the continuation of the LAN obtained in the irregular condition, concentrated on more frontal electrodes due to the simultaneous P600 effect, or alternatively, the dipole inversion of the posterior P600 effect.

The findings for regularization (LAN) are consistent with dual route and full decomposition models, where regular words are decomposed into stem and suffix parts (Clahsen, 1999; Pinker, 1999). Results from irregularization support dual route models in that irregularized forms do not seem to increase morphological processing as compared to correct regular verbs. The rapid and accurate rejection of incorrect irregularized words suggests that they are perceived as unknown whole word forms, and by extension, that irregular verbs are directly retrieved from the mental lexicon in their inflected form. Even stronger support for dual route models would have been an N400 effect for irregularized verbs as found in a previous study (Regel et al. 2017). A possible explanation for the lack of N400 in the present and other previous verb studies (Gross et al., 1998; Morris & Holcomb, 2005; Penke et al., 1997; Rodriguez-Fornells et al., 2001) might be that even irregularized verbs could undergo some degree of decompositional morphological processing, considering the fact that it would, in principle, be possible for test participants to restore an existing verb stem from the irregularized incorrect verb forms by changing the stem according to the vowel alternation patterns that tend to occur in irregular verbs and activating the appropriate suffix (e.g. *löft > lyfte* 'lifted'). Further, the presence of a regular inflection could perhaps trigger rule-based decompositional processing even in correct regular verbs, which would cancel out any left negativities in the

comparison with irregularized verbs and attenuate the use of whole word form access. In contrast, in the study by Regel et al. (2017), only irregular forms were used, thus potentially biasing participants more towards whole word form access. The absence of inter-action between regularity and correctness in the LAN time window relative to the clear LAN effect in the overregularized condition could be due to some variation in the processing of irregularized verbs. Future studies could shed light on the question of how different irregular forms are processed by testing verb forms with different vowel alternations to see whether a relation between frequency of vowel alternation and lexical frequency can predict the ERP response. Thus, more frequent forms are more prone to be stored as whole forms (Lehtonen & Laine, 2003; Pinker, 1991).

Another factor that could have influenced less stable effects is the fact that due to the verbal system of Swedish, regular items (correct and regularized) were disyllabic, whereas irregular items (correct and irregularized) were monosyllabic. However, word length does not seem to have had any obvious effect on either response times or ERPs. Thus, response times were shorter for monosyllabic incorrect (irregularized) verbs than for regular disyllabic words but not for monosyllabic correct (irregular) verbs in comparison with disyllabic (overregularized) forms. LAN and P600 effects were also rather strongly influenced by correctness and regularity.

In sum, overregularized verbs in Swedish elicited a LAN effect, which, in line with previous studies, was interpreted as suggesting detection of morphological violation, and in turn rule-based processing related to the regular inflection. No LAN was found for irregularized verbs suggesting no increase in morphological processing as compared to correct regular verbs. Both overregularized and irregularized verbs produced a P600, indicating that the incorrect form was reprocessed. Together with previous findings of noun processing, the results provide support for the assumption that both whole word access as well as decompositional processing are available during the comprehension of morphologically complex items in Swedish.

Conflicts of interest

The authors declare that there are no conflicts of interest.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jneuroling.2019.01.006.

References

Clahsen, H. (1999). Lexical entries and rules of language: A multidisciplinary study of German inflection. *Behavioral and Brain Sciences, 22*, 991–1060.
Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods, 134*, 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009.
Friederici, A. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences, 6*, 78–84. https://doi.org/10.1016/S1364-6613(00)01839-8.
Fruchter, J., Stockall, L., & Marantz, A. (2013). MEG masked priming evidence for form-based decomposition of irregular verbs. *Frontiers in Human Neuroscience, 7*, 1–16. https://doi.org/10.3389/fnhum.2013.00798.
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. https://doi.org/10.1016/S0304-3940(97)00971-3.
Joanisse, M., & Seidenberg, M. (1999). Impairments in verb morphology after brain injury: A connectionist model. *Proceedings of the National Academy of Sciences, 96*, 7592–7597.
Jung, T.-P., Makeig, S., Humphries, C., Lee, T.-W., McKeown, M. J., Iragui, V., et al. (2000). Removing electroencephalographic artifacts by blind source separation. *Psychophysiology, 37*, 163–178. https://doi.org/10.1111/1469-8986.3720163.
Justus, T., Larsen, J., de Mornay Davies, P., & Swick, D. (2008). Interpreting dissociations between regular and irregular past-tense morphology: Evidence from event-related potentials. *Cognitive, Affective, & Behavioral Neuroscience, 8*(2), 178–194. https://doi.org/10.3758/CABN.8.2.178.
Kaan, E., Harris, A., Gibson, E., & Holcomb, P. (2000). The P600 as an index of syntactic integration difficulty. *Language & Cognitive Processes, 15*, 159–201. https://doi.org/10.1080/016909600386084.
Kielar, A., & Joanisse, M. F. (2011). The role of semantic and phonological factors in word recognition: An ERP cross-modal priming study of derivational morphology. *Neuropsychologia, 49*, 161–177. https://doi.org/10.1016/j.neuropsychologia.2010.11.027.
Krott, A., Baayen, R., & Hagoort, P. (2006). The nature of anterior negativities caused by misapplications of morphological rules. *Journal of Cognitive Neuroscience, 18*, 1616–1630. https://doi.org/10.1162/jocn.2006.18.10.1616.
Krott, A., & Lebib, R. (2013). Electrophysiological evidence for a neural substrate of morphological rule application in correct wordforms. *Brain Research, 1496*, 70–83. https://doi.org/10.1016/j.brainres.2012.12.012.
Lehtonen, M., & Laine, M. (2003). How word frequency affects morphological processing in monolinguals and bilinguals. *Bilingualism: Language and Cognition, 6*(3), 213–255.
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. https://doi.org/10.1007/s10936-005-9008-1.
Lehtonen, M., Vorobyev, V., Soveri, A., Hugdahl, K., Tuokkolae, T., & Laine, M. (2009). Language-specific activations in the brain: Evidence from inflectional processing in bilinguals. *Journal of Neurolinguistics, 22*, 495–513. https://doi.org/10.1016/j.jneuroling.2009.05.001.
Leminen, A., Smolka, E., Duñabeitia, J. A., & Pliatsikas, C. (2019). Morphological processing in the brain: The good (inflection), the bad (derivation) and the ugly (compounding). *Cortex*. https://doi.org/10.1016/j.cortex.2018.08.016 (in press).
Morris, J., & Holcomb, P. (2005). Event-related potentials to violations of inflectional verb morphology in english. *Cognitive Brain Research, 25*, 963–981. https://doi.org/10.1016/j.cogbrainres.2005.09.021.
Münte, T. F., Say, T., Clahsen, H., Schiltz, K., & Kutas, M. (1999). Research report: Decomposition of morphologically complex words in English: Evidence from event-

related brain potentials. *Cognitive Brain Research, 7*, 241–253. https://doi.org/10.1016/S0926-6410(98)00028-7.

Newman, A. J., Ullman, M. T., Pancheva, R., Waligura, D. L., & Neville, H. J. (2007). An ERP study of regular and irregular English past tense inflection. *NeuroImage, 34*(1), 435–445. https://doi.org/10.1016/j.neuroimage.2006.09.007.

Penke, M., Weyerts, H., Gross, M., Zander, E., Münte, T., & Clahsen, H. (1997). How the brain processes complex words: An event-related potential study of German verb inflections. *Cognitive Brain Research, 6*, 37–52. https://doi.org/10.1016/S0926-6410(97)00012-8.

Pinker, S. (1991). Rules of language. *Science, 253*, 530–535. https://doi.org/10.1126/science.1857983.

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. https://doi.org/10.1016/S1364-6613(02)01990-3.

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. https://doi.org/10.1162/jocn_a_00818.

Rodriguez-Fornells, A., Clahsen, H., Lleó, C., Zaake, W., & Münte, T. (2001). Event-related brain responses to morphological violations in Catalan. *Cognitive Brain Research, 11*, 47–58. https://doi.org/10.1016/S0926-6410(00)00063-X.

Roll, M., Gosselke, S., Lindgren, M., & Horne, M. (2013). Time-driven effects on processing grammatical agreement. *Frontiers in Psychology, 4*, 1–8. https://doi.org/10.3389/fpsyg.2013.01004.

Roll, M., Horne, M., & Lindgren, M. (2010). Word accents and morphology—ERPs of Swedish word processing. *Brain Research, 1313*, 114–123. https://doi.org/10.1016/j.brainres.2010.03.020.

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. https://doi.org/10.1016/j.bandl.2017.12.001.

Smolka, E., Khader, P. H., Wiese, R., Zwitserlood, P., & Rösler, F. (2013). Electrophysiological evidence for the continuous processing of linguistic categories of regular and irregular verb inflection in German. *Journal of Cognitive Neuroscience, 25*(8), 1284–1304. https://doi.org/10.1162/jocn_a_00384.

Sonnenstuhl, I., Eisenbeiss, S., & Clahsen, H. (1999). Morphological priming in the German mental lexicon. *Cognition, 72*, 203–236. https://doi.org/10.1016/S0010-0277(99)00033-5.

Stockall, L., & Marantz, A. (2006). A single route, full decomposition model of morphological complexity: MEG evidence. *The Mental Lexicon, 1*(1), 85–123. https://doi.org/10.1075/ml.1.1.07sto.

Stockholm-Umeå Corpus SUC 1.0 (1996). *Stockholm University: Department of linguistics and University of Umeå; Department of linguistics.*

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

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