CORTEX XXX (2018) 1–11

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Journal homepage: www.elsevier.com/locate/cortex

Special issue: Research report

Processing inflectional morphology: ERP evidence for decomposition of complex words according to the affix structure

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ARTICLE INFO

Article history:
Received 10 December 2017
Reviewed 2 May 2018
Revised 10 June 2018
Accepted 3 October 2018
Published online xxx

Keywords:
Event-related potentials (ERPs)
Inflectional morphology
Morphosyntax
Language processing
LAN
P600

ABSTRACT

This study investigated the processing of inflectional morphology by registrating event-related brain potentials (ERPs) during sentence reading. In particular, we examined nouns combined with affixes that have distinct structural characteristics as proposed by morphological theory. Affixes were either complex consisting of functionally distinguishable subparts as occurring for German plural morphology, or simple consisting of one part only. To test possible differences in processing these affixes we compared grammatical nouns [e.g., *Kartons* (cartons)] to ungrammatical ones (e.g., **Kartonen*) in two different syntactic contexts represented by a complex, or simple affix. The ERPs showed that ungrammatical nouns consisting of complex affixes elicited a left anterior negativity (LAN) reflecting enhanced morphosyntactic processing, which was absent for equivalent nouns consisting of simple affixes. This finding suggests that inflected words are decomposed dependent on the affix structure, whereby the affixes themselves seem to consist of morphological subparts in accordance with current morphological theories (Müller, 2007; Noyer, 1992). Moreover, ungrammatical nouns elicited early (reduced P200) and late (P600) ERP components relative to their grammatical equivalents, which implies an engagement of syntactic processes presumably based on intially enhanced pre-lexical processing of these irregularized nouns. The findings are discussed with respect to theoretical and neuropsychological accounts to inflectional morphology.

1. Introduction

Human language not only consists of single words, but the combination of words into phrases and sentences realized by means of rules. Morphological systems are crucial for this task as they describe how words are modified by internal changes (e.g., by the addition of affixes as in *read-s*) in order to express grammatical functions and, thereby, build grammatical

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https://doi.org/10.1016/j.cortex.2018.10.003
0010-9452/

relations. Thus, words often have more complex structures than their mere word stems (e.g., *read*). How morphologically complex words are represented and processed is a pivotal issue since it sheds light on the mechanisms underlying our human language processing and the possible reliance on general cognitive capabilities. Languages having a rich morphology, such as German, are ideal for testing those capabilities. In the current study, we investigate the processing of inflectional morphology (i.e., inflected word forms expressing grammatical categories) by focusing on different types of affixes, and address an ongoing debate on whether the processing of words depends on dual or single systems. Neurocognitive research on inflectional morphology has mainly focused on the coarse issue of whether complex words are decomposed into stem and affix (e.g., *open-ed*), or rather processed holistically with respect to regular and irregular inflection. Therein, regular inflection applies by grammatical rules, such as addition of *-ed* to the word stems for English past tense. Irregular inflection, in contrast, is less predictable and comprises various alternations of the word form (e.g., *sleep – slept*). While for most words regular inflection patterns apply, there are exceptions from those rules that denote irregular inflection patterns (e.g., *caught*). According to dual-system accounts (e.g., Marslen-Wilson & Tyler, 2007; Pinker & Prince, 1988; Ullman, 2001), regular words are decomposed (or computed) by a procedural system, and irregular words are primarily holistically stored and retrieved by an associative system. Both systems recruit distinct brain regions including the frontal cortex and the basal ganglia in case of procedural processing, and the temporal lobe in case of associative processing. In contrast, single system accounts (e.g., Rumelhart & McClelland, 1986) assume the same memory-based mechanism to subserve both regular and irregular inflection thereby engaging a network of neural connections. More recent accounts propose fully decomposed processing of all complex words into separate constituents regardless of inflection patterns (Stockall & Marantz, 2006). By focusing on the principles of transparency and similarities, the Augmented Addressed Morphology (AAM) model (Caramazza, Laudanna, & Romani, 1988) proposes two access systems consisting of whole-word access in case of known words, and decomposed access for unfamiliar words. However, the morphological characteristics of the affixes combined with the word stems, that is, their morphophonological and morphosyntactic features have been largely ignored within this debate.

Current morphological theories propose fine-grained analyses of affixes with regard to their functional and structural characteristics. Functionally, affixes may either clearly correspond to one particular syntactic context [e.g., *dies(e)-n* ('this-$_{DAT.SG.MASC}$')], or refer to more than one syntactic context [i.e., an inflectional paradigm may exhibit instances of syncretism, such as *dies-e* ('this-$_{NOM/ACC.SG/PL}$')]. This phenomenon is accounted for by abstract feature decomposition and the concept of underspecification in almost all current morphological frameworks (e.g., Bierwisch, 1967; Blevins, 1995; Wiese, 2008; Wunderlich & Fabri, 1995). According to their internal structure, affixes are considered as simple or complex by consisting of either one [e.g., */-n/* as in *Muscheln (shells)*] or more distinguishable subparts [e.g., */-r-n/* as in *Feldern (fields)*, *Kindern (kids)*]. Those subparts of complex affixes may represent a single morphosyntactic feature, such as plural, which is referred to as extended structure (or multiple exponence) (e.g., Anderson, 1992; Halle & Marantz, 1993; Müller, 2007; Stump, 2001). In order to describe morphological (sub)regularities, in recent approaches a more fine-grained morphological analysis, that is, a subanalysis (or fission) of complex affixes into smaller morphological units is carried out (Müller, 2007; Noyer, 1992). Insights into when and how words containing affixes that apply by morphological rule are processed can be gained by event-related brain potentials (ERPs). In the present study, ERPs were used to scrutinize the processing of inflectional morphology, and to characterize the neurocognitive mechanisms underlying our human language as proposed by the different accounts.

1.1. *Inflectional rules: German plural and case morphology*

Noun inflection is typically constrained by grammatical categories, such as number, gender, or case. For German, the category number is distinguished into singular ($_{SG}$) and plural ($_{PL}$), whereas the category case consists of nominative ($_{NOM}$), accusative ($_{ACC}$), dative ($_{DAT}$), and genitive ($_{GEN}$). These categories are morphophonologically realized either by addition of an affix to the noun stem, or by diverse internal alternations of the noun stems (e.g., vowel alternations).[1] German plural morphology is typically characterized by addition of mainly five different affixes (i.e., */-Ø/*, */-e/*, */-er/*, */-n/*, */-s/*) to the noun stem [e.g., *Zweig-e* ('branch-$_{PL}$'), *Tasche-n* ('bag-$_{PL}$')]. Among those plural forms, noun plural by addition of */-s/* has been identified as the productive default or regular plural since this type of plural formation is chosen whenever none of the other affixes is applicable (e.g., for loan words, novel nouns, names, abbreviations) (Marcus, Brinkman, Clahsen, Wiese, & Pinker, 1995). Additional stem alternations do not occur for s-plural marking. Noun plural formation by addition of any other affix than */-s/* is described as non-default or irregular plural[2] that is resistant to morphological rules and has a lexically restricted scope (e.g., Clahsen, 1999; Clahsen, Eisenbeiss, & Sonnenstuhl-Henning, 1997). Remarkably, s-plural denotes the default plural form, despite being less frequent than the irregular plurals and applying merely to a minority of nouns.[3]

With respect to case morphology of nouns, case is formed by addition of the affixes */-Ø/*, */-s/*, */-(e)n/* to singular noun stems [e.g., *Raum-Ø* ('room-$_{NOM/ACC/DAT}$'), *Segel-s* ('sail-$_{GEN}$'), *Prinz-en* ('prince-$_{ACC/DAT}$')], whereas case marking for noun plurals is largely reduced. Notably case formation for noun plurals still occurs in dative contexts, whereby an additional case marking morpheme (i.e., */-n/*) is added to pluralized noun stems [e.g.,

[1] In a complex noun phrase, all these categories are also morphologically realized on dependent words that are in grammatical agreement with the noun, such as determiners, demonstratives, and adjectives.

[2] Note that the term 'irregular plural' is traditionally used for every non-productive plural formation despite the fact that such forms can be analyzed as stem + affix linguistically.

[3] The frequency of German non-feminine plurals varies between the different forms. In an analysis of the CELEX database, Bartke et al. (2005), for instance, identified /s/ plurals as having a low type-frequency of 5.83 (845), while the */(e)n/* plurals have a type-frequency of 9.56 (1387).

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Kind-er-n ('child-$_{PL\text{-}DAT.PL}$'), *Boot-e-n* ('boat-$_{PL\text{-}DAT.PL}$')] thereby creating complex affixes, such as /*-er-n*/ and /*-e-n*/.[4] Since this affix applies only to nouns in dative contexts that are already marked for plural, plural is expressed multiply (e.g., by both /*-er*, *-e*/, and the additional /*-n*/) (see Müller, 2007). The occurrence of additional case marking for noun plurals is restricted to irregular noun inflection (i.e., the plurals /*-e*/ and /*-er*/), and does not affect the regular *s*-plural. In terms of structural morphological analysis of complex affixes, different accounts have been proposed. Eisenberg (2000), for instance, argues in favor of a subanalysis of such forms into functionally motivated subparts (e.g., into /*-e-n* /and /*-er-n*/), whereas in the account of Alexiadou and Müller (2008) complex forms are analyzed holistically (e.g., /*-en* /and /*-ern*/).

The question of whether fine-grained morphological analysis is reflected in language processing has barely been addressed from a neuropsychological perspective. Although there is first neurophysiological evidence that, at least for the functional aspects, morphosyntactic parsing indeed relies on abstract concepts (i.e., on abstract feature decomposition and the principle of underspecification) (Opitz, Regel, Müller, & Friederici, 2013; Regel, Opitz, Müller, & Friederici, 2015), there is a lack of research concerning the analysis of structural aspects.

1.2. ERPs related to morphosyntactic processing

Brain potentials are time sensitive and spatial measurements of the neural activity, and provide an ideal tool for investigating the processing of inflectional morphology. For the processing of (morpho)syntactic information typically a biphasic ERP pattern consisting of a left anterior negativity (LAN) and a P600 component has been observed. The LAN component emerges approximately between 300 and 500 msec post-stimulus onset, and reveals either a left lateralized, or bilateral scalp distribution. LAN effects have been frequently reported for disagreements in number marking in several languages (for review see Molinaro, Barber, & Carreiras, 2011), but also for disagreements in case marking (e.g., Coulson, King, & Kutas, 1998; Friederici & Frisch, 2000). Since the LAN was reliably seen for morphosyntactic violations in languages with a relatively rich morphological system, it has been associated with morphosyntactic analysis processes (Fiebach, Schlesewsky, & Friederici, 2002; Friederici, 2002). This interpretation is supported by findings that LAN effects depend on the presence of sentential contexts defining grammatical relations between words, and are absent for unrelated words inhibiting morphosyntactic analysis (Morris & Holcomb, 2005). Subsequently to LAN, a later positivity, the P600, emerges around 500 msec post-stimulus with a centroparietal scalp distribution (Hagoort, Brown, & Groothusen, 1993; Osterhout & Holcomb, 1992; for overview see; Friederici, 2011). The P600 was seen for agreement violations (e.g., number or case information) across numerous languages, such as English (Coulson et al., 1998), German (Friederici & Frisch, 2000; Münte, Matzke, & Johannes, 1997; Rossi, Gugler, Hahne, & Friederici, 2005), Dutch (Hagoort, 2003; Hagoort & Brown, 2000; Kaan & Swaab, 2003), Spanish (Barber & Carreiras, 2005; Silva-Pereyra & Carreiras, 2007), and Italian (Kasparian, Vespignani, & Steinhauer, 2017; Molinaro, Vespignania, & Job, 2008). Besides, P600 responses have also been observed for various syntactic (e.g., Friederici & Meyer, 2004; Osterhout, Holcomb, & Swinney, 1994), as well as semantic–pragmatic anomalies (e.g., Regel, Gunter, & Coulson, 2010; Regel, Gunter, & Friederici, 2011). The functional significance of the P600 is still debated. As recently shown by Regel, Meyer, and Gunter (2014), P600s in response to syntactic and pragmatic information are distinguished in topography as well as neural oscillatory activity [i.e., different changes in the theta frequency band (4–7 Hz)] suggesting reflections of different neurocognitive processes. While the P600 seen for syntactic anomalies have been related to syntactic repair and reanalysis processes (Friederici, 2002; Kaan & Swaab, 2003), P600 effects for pragmatic anomalies might be associated with pragmatic reanalysis (Regel et al., 2014). With regard to the processing of inflectional morphology, the finding of LAN-P600 effects in response to violated irregular words by addition of regular inflection patterns have been interpreted in favor of dual-mechanism accounts (e.g., Morris & Holcomb, 2005; Newman, Ullman, Pancheva, Waligura, & Neville, 2007; Weyerts, Penke, Dohrn, Clahsen, & Munte, 1997).

Besides syntax-related ERP effects, a robust ERP component seen for lexico-semantic anomalies is the N400 component, a centroparietal negativity with a peak latency of around 400 msec post-stimulus onset. The N400 has been interpreted as reflection of semantic integration and lexical access to the mental lexicon (for review see Kutas & Federmeier, 2011). On basis of their topography and sensitivity LAN and N400 are considered as indices of different neurocognitive processes. Alternatively, due to the more left hemispheric topography the LAN has been suggested to be a variant of N400 resulting from individual differences in morphosyntactic processing (Tanner & Van Hell, 2014), attested by a type of morphosyntactic violation that entailed a semantic interfering factor (for critical discussion see Molinaro, Barber, Caffarra, & Carreiras, 2015). Besides for lexico-semantic anomalies, N400 effects have also been reported for morphological anomalies (Hahne, Müller, & Clahsen, 2006; Leinonen, Brattico, Jarvenpaa, & Krause, 2008). For ungrammatical relative to grammatical plural inflection (e.g., **Waggon-en* vs. *Waggon-s*) an N400 emerged (Lück, Hahne, & Clahsen, 2006; Weyerts et al., 1997). The authors take this to indicate enhanced lexical processing during retrieval of an appropriate word meaning, and, thus, as evidence for memory-based mechanisms engaged in the processing of irregular words.

1.3. The present study

In this study, we characterize the morphological analysis of complex words as a function of the type of affix in order to contribute to the debate on the neurocognitive mechanisms underlying human language. More precisely, the question is examined whether affixes consisting of more than one definable subpart as proposed by morphological theories (Müller, 2007; Noyer, 1992) are morphophonologically parsed into separate morphological units, (e.g., /*-e*/ and /*-n*/), or are rather

[4] Note that, in this context, the additional affix /*-n*/ cannot simply be related to dative case per se since it is absent for respective nouns in singular.

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processed as inseparable units (e.g., /-*en*/ and /-*ern*/). In order to approach this question, we investigate the two factors *grammaticality* (i.e., grammatical vs. ungrammatical nouns) and *syntactic context* (i.e., represented by complex vs. simple affixes). Regarding the factor *grammaticality*, the processing of grammatical nouns [e.g., *Karton-s* (cartons)] was compared to ungrammatical ones (e.g., **Karton-en*), whose stems were combined with an irregular plural affix (e.g., -*en*) and, thus, irregularized, instead of being marked by the grammatical regular one (i.e., -*s*). Further, we manipulated the syntactic context in which the nouns appeared. According to these contexts, the ungrammatical nouns (e.g., **Karton-en*) either contained a potentially complex affix (i.e., /-*e-n*/) as part of dative plural marker when occurring in dative context presumably involving morphological subanalysis, or the same word form (e.g., **Karton-en*) contained a simple affix (i.e., /-(*e*)*n*/) as part of an irregular plural when occurring in an accusative context. The status of the /-*n*/ affix may differ in the two contexts leading to the following hypotheses: If ungrammatical nouns are processed holistically and treated as nonwords having no lexical entry in the mental lexicon, we hypothesize an N400 component relative to grammatical nouns (see Lück et al., 2006; Weyerts et al., 1997). If, however, ungrammatical nouns rely on decomposed processing, a syntax-related ERP pattern of LAN-P600 in relation to grammatical ones is predicted. With respect to the syntactic context we expect that: In case complex affixes are indeed decomposed into smaller units in dative context, ungrammatical nouns consisting of complex affixes should reveal an amplitude modulation of LAN, whereas equivalent nouns consisting of simple affixes should not reveal such an effect in accusative context. If the complex /-*n*/ affix in dative plural contexts denotes a regular morphological process, this type of morphological anomaly would yield a morphosyntactic rule violation, and should therefore elicit an enhanced LAN. In contrast, if those affixes are parsed holistically (as predicted for simple affixes in accusative contexts), no morphosyntactic rule violation would be present, and, thus, no enhanced LAN should emerge. Moreover, we expect a P600 component associated with structural repair processes for both ungrammatical nouns (i.e., containing either a complex, or simple affix) relative to the grammatical ones.

2. Methods

2.1. Participants

Thirty native German-speaking students [15 female, mean age 25.5 years (standard deviation (SD) 2.75)] participated in the experiment. All of them were right-handed with a normal or corrected-to-normal vision, and received payment for their participation. Prior to the experiment, all participants gave signed informed consent in accordance with the declaration of Helsinki. The study was approved by the ethics committee of the medical department at the University of Leipzig.

2.2. Stimulus material

The stimuli consisted of 320 German sentences containing embedded prepositional phrases, 80 in each of the four conditions (see Table 1). Critical words were 40 non-feminine German regular nouns [e.g., *Kartons*, (cartons), *Details* (details)], for more examples see Appendix) appearing in mid-sentence position. These nouns were chosen with regard to linguistic criteria (i.e., word frequency, structure, and gender), and repeated once in different sentence contexts resulting in 80 items per condition (e.g., *Die Professoren sprechen über die Details der Studie* (The professors speak about the details of the study), *Der Artikel informiert über neue Details zum Erbrecht* [The article informs about the details of the legacy law)] in order to enhance the signal-to-noise ratio. All nouns were prepositional complements and appeared either in dative, or accusative plural [e.g., *…ohne die*$_{ACC}$*/mit den*$_{DAT}$ *Kartons…* (with/without the cartons)]. In the ungrammatical conditions, the regular plural affix /-*s*/ was replaced by the irregular /-(*e*)*n*/ plural affix (e.g., *… ohne die*$_{ACC}$*/mit den*$_{DAT}$ **Karton-en…*). According to morphological subanalysis (Müller, 2007), the same word form (e.g., *Karton-en*) should be treated differently due to complex marking in the dative context and simple marking in the accusative context. If application of /-*n*/ is a regular, rule based morphosyntactic process, nouns consisting of complex affixes as in /-*e-n*/ in dative context should be decomposed into distinguishable morphological units (i.e., /-*e*/ and /-*n*/). In accusative context, however, additional overt case marking does not occur, so that the /-*en*/ affix should be analyzed as simple affix representing a single morphosyntactic feature (i.e., $_{PL}$). All critical nouns were bisyllabic masculine or neuter nouns with an average word length of 5.5 letters (SD 1.30), and a mean frequency class of 12.3 (SD 1.44) according to the Leipzig vocabulary project (http://wortschatz.uni-leipzig.de). The experimental sentences had an average length of about 9 words (SD .70). As filler items, 320 filler sentences [e.g., *Die Schüler rennen über die Flure des Internats* (The pupils are running along the hallway of the college)] were constructed that contained grammatical irregular non-feminine nouns [e.g., *Flure* (hallway), *Zweigen* (branches)].

For experimental presentation, the stimuli were pseudorandomized and divided into two versions of 320 items each (i.e., 160 experimental items and 160 filler items). Thus, critical words were repeated four times within an item version in different sentence contexts either as grammatical, or ungrammatical word form. All conditions were equally distributed within a version (i.e., four conditions with 40 items each).

2.3. Procedure

Each participant was tested individually within a session (lasting about 70 min), and saw one item version only. During EEG recording participants were seated in a soundproof cabin. Participants' task was to read attentively all sentences and to reply as accurately as possible to the grammaticality judgment task with a *yes* or *no* response (via button press). 50% of the trials were correct. To avoid decision-related expectancy, the answers were completely balanced across all experimental conditions. Before the experiment, participants received a short training.

The beginning of a trial was signaled by the presentation of a fixation cross for 500 msec in the middle of the monitor. Following an interstimulus interval (ISI) of 100 msec, the visual presentation of the target sentences started with

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Table 1 – The experimental design including the factors *Context* and *Grammaticality* applied to German nouns. Depending on the syntactic context, the structure of the affix alters. While in accusative contexts simple affixes occur, in dative contexts complex affixes are present.

Grammaticality (of *s*-plural nouns)		
Context	grammatical	ungrammatical
accusative	*ohne die Karton-s* (without the cartons)	*ohne die *Karton-en* (without the cartons)
dative	*mit den Karton-s* (with the cartons)	*mit den *Karton-e-n* (without the cartons)

Note: Nouns with ungrammatical inflection are marked by an asterisk.

300 msec per word and an ISI of 700 msec. After stimulus presentation and an ISI of 1500 msec participants had to perform the experimental task (maximum response time of 3000 msec). The intertrial-interval was 1000 msec.

2.4. *Data recording and analysis*

Statistical analysis of the behavioral data included a repeated-measures analysis of variance (ANOVA) with the within-subject factors *Context* (accusative/dative), and *Grammaticality* (grammatical/ungrammatical).

The electroencephalogram (EEG) was recorded continuously from 52 Ag–AgCl electrodes[5] referred to the left mastoid with a sampling rate of 500 Hz. To control for eye movements bipolar horizontal and vertical electrooculograms (EOG) was recorded. Electrode impedance was kept below 5 kΩ. Average ERPs were computed for the critical word (i.e., the regular noun at the sentence middle position) for each electrode position for each of the experimental conditions. Averages were aligned to a 200 msec pre-stimulus baseline, and calculated for a period of 1000 msec after stimulus onset. Only correctly answered and artifact-free trials were included in the analysis (exclusion of approximately 12% of the trials due to ocular artifacts (automatic EOG rejection ± 40 μV), which were equally divided across all conditions [$F(3,116) = .23$, $p = .87$)].

After visual inspection of the present ERPs we employed two latency windows of: 300–600 msec (LAN and N400), and 600–1000 msec (P600) for statistical analysis of the ERP data. Moreover, an additional time window of 150–250 msec (P200) was analyzed since early differences in the ERPs seemed to be present. ERPs were analyzed in repeated-measures multivariate analyses of variance (MANOVAs) and included the within-subject factors *Context* (accusative/dative), and *Grammaticality* (grammatical/ungrammatical). In order to analyze the scalp distribution of the ERPs two topographical factors *Anterior/Posterior* (2) and *Hemisphere* (left/right) were defined and completely crossed, resulting in four different Regions of Interest (ROIs): left anterior (FT7, FC5, T7, C5, TP7, CP5), right anterior (FC6, FT8, C6, T8, CP6, TP8), left posterior (P7, P5, P3, PO7, PO3, O1), and right posterior (P4, P6, P8, PO4, PO8, O2). Midline electrode positions (FCZ, CZ, CPZ, PZ, POZ, OZ) were analyzed separately. Main effects and interactions having an alpha level of < .05 were assessed as significant, and those having an alpha level of < .10 were evaluated as marginally significant. Whenever interactions between the two experimental factors were obtained, additional analyses by the factor *Context* were carried out. Whenever interactions between the experimental and topographical factors were found, additional analyses by the respective topographical factor were conducted.

[5] FP1, FPZ, FP2, AF7, AF3, AFZ, AF4, AF8, F7, F5, F3, FZ, F4, F6, F8, FT7, FC5, FC3, FCZ, FC4, FC6, FT8, T7, C5, C3, CZ, C4, C6, T8, TP7, CP5, CP3, CPZ, CP4, CP6, TP8, P7, P5, P3, PZ, P4, P6, P8, PO7, PO3, POZ, PO4, PO8, O1, OZ, O1, and right mastoid.

3. Results

3.1. *Behavioral data*

Participants' performance on the grammaticality judgment was excellent [mean accuracy rate 97.5% (SD 1.98)]. Statistical analysis showed a main effect of context [$F(1,29) = 10.15$, $p = .003$] indicating that nouns in accusative context [mean error rate .8% (SD .81)] were slightly less difficult than those in dative context [mean error rate 1.6% (SD 1.50)]. In the analysis an interaction of context with grammaticality [$F(1,29) = 12.10$, $p = .002$] was also present. Resolving this interaction by context revealed for dative context an effect of grammaticality [$F(1,29) = 4.07$, $p = .05$], and for accusative context a trend for this effect [$F(1,29) = 3.55$, $p = .07$]. Ungrammatical nouns in dative context caused more errors [1.1% (SD 1.28)] than their correct equivalents [mean error rate .6% (SD .73)]. This pattern tended to be reversed for nouns in accusative context by showing slightly less errors for ungrammatical [mean error rate .3% (SD .34)] than grammatical ones [mean error rate .6% (SD .71)].

3.2. *Electrophysiological data*

ERPs at the critical word showed for ungrammatical nouns a left anteriorly distributed negativity (LAN) followed by a late centroparietal positivity (P600) in comparison to grammatical nouns (see Fig. 1). The emergence of the LAN, however, depended on the morphosyntactic context, and, thus, on the assumed structural characteristics of affixes. A LAN response for ungrammatical nouns was observed only for dative plural context, in which by assumption nouns ending of */-en/* should be analyzed as a complex affix (see Fig. 1B). No such negativity was seen for the same nouns consisting of a simple affix in accusative context (see Fig. 1A). The P600, by contrast, appeared to emerge in both contexts, and emerged for ungrammatical nouns consisting of simple as well as complex affixes. Besides, differences in the P200 amplitude seemed to

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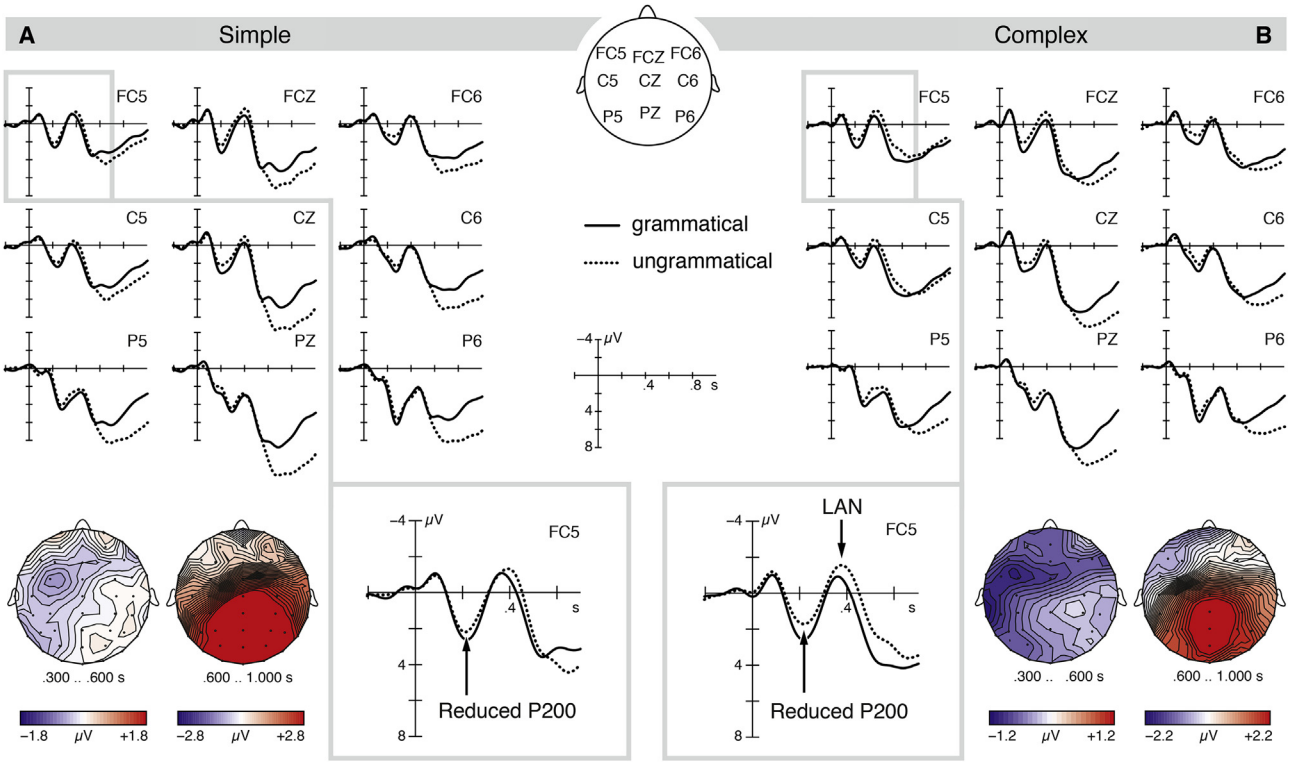

Fig. 1 – Grand average ERPs evoked by nouns consisting of simple (column A) and complex affixes (column B). For ungrammatical nouns (dotted line) relative to grammatical ones (solid line) an N400 component was absent. Instead, a P600 preceded by a reduced P200 amplitude was elicited independent of the type of affix. Further, the zoom of the FC5 electrode illustrates the emergence of a LAN component solely for nouns consisting of complex affixes. The topographic maps show the scalp distribution of the ERP effects.

be present between ungrammatical and grammatical nouns independent of the morphological marking.

3.2.1. *ERP data*

With respect to our hypothesis, the ERPs seen for the critical nouns were analyzed in the LAN/N400 and P600 latency windows. In the 300–600 msec latency window, we tested for an effect of grammaticality on the central electrode sites indexing the emergence of a potential N400 for ungrammatical relative to grammatical nouns. Further, in this latency window tests for a left anterior effect of grammaticality were conducted in order to investigate whether an enhanced LAN for respective nouns emerged as well as a potential modulation of this component when observed in a particular syntactic context only (i.e., presumably the dative context).

In the statistical analysis of the 300–600 msec latency window a two-way interaction of grammaticality with hemisphere [$F(1,29) = 7.38$, $p = .01$] was found. Further, trends for an effect of grammaticality [$F(1,29) = 3.55$, $p = .07$], as well as a four-way interaction of context, grammaticality, anterior/posterior, and hemisphere [$F(1,29) = 2.86$, $p = .10$] were seen. Based on our hypothesis we conducted a planned comparison of ungrammatical vs. grammatical nouns in the respective contexts for the left anterior ROI: While in dative context a reliable effect of grammaticality [$F(1,29) = 13.05$, $p = .001$] was obtained, in accusative context no such effect was present [$F(1,29) < .69$, $p = .41$]. The analysis confirms the emergence of a LAN merely for ungrammatical nouns in dative context with assumed complex affixes relative to their grammatical nouns.

The statistical analysis of the midline electrodes showed neither an effect of grammaticality [$F(1,29) < 1.46$, $p = .23$], nor an interaction between context and grammaticality [$F(1,29) < .71$, $p = .39$] suggesting the absence of an enhanced N400 in response to the ungrammatical nouns.

In the 600–1000 msec latency window, we tested for a centroparietal effect of grammaticality that would imply the emergence of an increased P600 presumably for ungrammatical relative to grammatical nouns. Statistical analysis of the 600–1000 msec latency window showed a main effect of grammaticality [$F(1,29) = 32.34$, $p < .0001$], and a three-way interaction of grammaticality, anterior/posterior, and hemisphere [$F(1,29) = 6.13$, $p = .02$]. A two-way interaction between context and grammaticality [$F(1,29) = 4.82$, $p = .04$] was also significant. Resolving the three-way interaction by the topographic factors revealed effects of grammaticality over the left posterior [$F(1,29) = 41.21$, $p < .0001$], and both right hemisphere electrode sites [RA: ($F(1,29) > 19.06$, $p < .0001$), RP:

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($F(1,29) = 44.18$, $p < .0001$)]. These findings confirm the presence of a P600 response for ungrammatical nouns relative to equivalent grammatical ones. The above-mentioned two-way interaction of context with grammaticality was resolved by context, and revealed for nouns in both dative [$F(1,29) = 7.39$, $p = .01$] and accusative context [$F(1,29) = 34.27$, $p < .0001$] significant effects of grammaticality. This analysis implies that P600 effects were reliably evoked by ungrammatical nouns consisting of a morphological anomaly. The P600 amplitude, however, seemed to be modulated by syntactic context represented by the affixes' morphological structure in showing larger amplitude for nouns containing simple than complex affixes. Thus, an additional analysis of the amplitudes of the ERP difference waveforms obtained in the P600 latency window was carried out by using *t*-test (corrected by the Bonferroni–Holm procedure). This analysis showed that the P600 for ungrammatical nouns containing simple affixes differed from the P600 for equivalent nouns containing complex affixes [$t(30) = 4.82$, $p < .04$] thereby confirming the P600 modulation by the morphological structure.

In the statistical analysis of the midline electrodes an effect of grammaticality [$F(1,29) = 54.17$, $p < .0001$] was found. An interaction of context with grammaticality [$F(1,29) = 3.40$, $p = .07$] reached marginal significance. Resolving the interaction by context showed an effect of grammaticality for nouns in both dative [$F(1,29) = 15.96$, $p = .0004$] and accusative context [$F(1,29) = 56.14$, $p < .0001$]. The analysis substantiates the presence of a P600 for ungrammatical nouns, as well as a modulation of the P600 amplitude dependent on syntactic context, and, thus, the nouns' morphological structure.

Since visual inspection suggests the presence of early differences in the ERPs, an additional latency window of 150–250 msec covering the P200 component was analyzed. In this latency window, the main analysis revealed an effect of grammaticality [$F(1,29) = 7.90$, $p = .01$], as well as a three-way interaction of grammaticality, context and anterior/posterior [$F(1,29) = 5.69$, $p = .02$]. The resolution of this interaction by context showed an effect of grammaticality for nouns in dative context [$F(1,29) = 4.74$, $p = .04$], and a trend for such an effect for nouns in accusative context [$F(1,29) = 3.78$, $p = .06$]. This finding indicates a reduced amplitude of the P200 component for ungrammatical compared to grammatical nouns. Since for nouns in dative context a subsequent LAN was seen, this effect might have superimposed the earlier reduction of P200. The presence of a main effect of grammaticality in the overall analysis rather suggests that the reduced P200 emerged for nouns in both contexts regardless of their morphological structure.

The statistical analysis of the midline electrodes revealed an effect of grammaticality [$F(1,29) = 7.80$, $p = .01$] thereby confirming a reduction of P200 for ungrammatical compared to grammatical nouns. An interaction of context and grammaticality was not obtained [$F(1,29) = .05$, $p = .82$] confirming that the P200 in response to ungrammatical nouns was unaffected by their morphological structure.

4. Discussion

The present study examined the processing of inflected words with respect to their internal affix structure in order to characterize the engaged neurocognitive mechanisms. We addressed the question of whether structurally complex affixes (e.g., */-er-n/*, or */-e-n/*) are parsed into separate morphological units, or processed holistically in comparison to simple affixes. To this aim, regular nouns were embedded either in accusative, or dative context, and irregularized by application of the affix */-en/* to the noun stems [e.g., for accusative **Detail-en* ('details-$_{PL}$'), for dative **Detail-e-n* ('details-$_{PL\text{-}DAT.PL}$')] resulting in ungrammatical noun inflection. While the affix */-e-n/* represents a more complex affix consisting of functionally distinguishable subparts (i.e., */-e/* and */-n/*) in dative context, the affix */-(e)n/* represents a simple affix in accusative context (Müller, 2007; Noyer, 1992). ERPs observed for ungrammatical compared to grammatical nouns revealed a reduced amplitude of P200 independent of the type of affixes. Later ERP responses, however, were modulated by their morphological structure: A P600 emerged for ungrammatical nouns in relation to grammatical ones, whereby P600 amplitude was larger for nouns in accusative context consisting of simple than for nouns in dative context consisting of complex affixes. Most importantly, an additional left anterior negativity (LAN) was merely elicited for ungrammatical nouns in dative context represented by complex affixes as well as increased error rates behaviorally. Interestingly, an N400 effect for irregularizations as reported previously (cf., Lück et al., 2006; Weyerts et al., 1997) was absent for ungrammatical relative to grammatical nouns. In the following, the findings are discussed with regard to the processing of inflectional morphology, as well as the morphological properties of affixes.

4.1. *Processing of inflectional morphology*

Brain potentials in response to nouns comprising a complex affix revealed an enhanced LAN component that was absent for nouns accompanied by a simple affix. This LAN showed a left-lateralized distribution and had an onset latency of around 300 msec. In previous studies, comparable LAN effects have been observed for violations of overt case marking information (Coulson et al., 1998; Friederici & Frisch, 2000), and associated with morphosyntactic analysis (Friederici, 2002). In relation to the observed increased error rates, such an interpretation holds for the present finding of LAN suggesting that a violation of overt case marking as in dative context involves enhanced morphosyntactic analysis, in contrast to covert case marking as in accusative context. Importantly, the current finding implies that the LAN is not only sensitive to morphosyntactic analysis, but seems to be a reflection of morphophonological parsing processes as prerequisite for such an analysis. Whenever the morphophonological structure of words appears to match with the syntactic constraints given by the sentential context, these superficial structural aspects of the words and affixes are taken into account. In comparison to simple affixes, complex affixes seemed to be decomposed (i.e., subanalyzed in

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morphological terms) into morphological subunits, such as /-*e*/ and /-*n*/. With regard to current morphological theories, the present results substantiate a fine-grained morphological analysis and representation of complex affixes according to their structural characteristics (Halle & Marantz, 1993; Müller, 2007; Noyer, 1992). The current findings imply that complex affixes may consist of a combination of functionally distinguishable subparts, and are likely to constitute separable morphological units. These structural characteristics of affixes have an impact on the neurocognitive processes engaged in the processing of inflectional morphology: Morphophonological parsing processes are apparently restricted to decomposable morphological units. Moreover, with regard to the sensitivity of the LAN, the findings imply that morphosyntactic analysis may depend on morphophonologically analyzable word structures relevant for the sentential contexts, thereby emphasizing the role of syntactic contexts as reported previously (Morris & Holcomb, 2005). Since in the present experiment the presence and absence of LAN for the same ungrammatical nouns embedded in different syntactic contexts was observed within-group, the suggestion that LANs result from individual differences cannot be supported (cf. Tanner & Van Hell, 2014).

Subsequently to LAN, a P600 was present for ungrammatical nouns containing complex affixes suggesting an engagement of syntactic reanalysis processes (e.g., Friederici, 2002). The amplitude of this P600 was less pronounced than that of the P600 for ungrammatical nouns containing simple affixes, although both effects showed comparable centroparietal amplitude maxima typically reported for syntax-related P600 (Friederici, 2011; Hagoort et al., 1993; Münte et al., 1997). This difference in P600 amplitude suggests that whenever morphosyntactic analysis is engaged (i.e., as indicated by the presence of LAN), subsequent reanalysis processes may be less effortful as indicated by the smaller amplitude of P600 for irregularizations including complex affixes. In contrast, the larger P600 amplitude for irregularizations including simple affixes may reflect more effortful processing since the morphophonological structure of those words did not match with the syntactic constraints of the sentential context, and possibly caused an outright morphological anomaly. At first view, behavioral findings indicating less difficulty in grammaticality judgment for nouns containing simple than complex affixes seems to be odd with this explanation. However, based on those words' morphophonological structure, it may have rather been easier to judge their grammaticality when being less consistent with the syntactic context. Alternatively, the LAN preceding the P600 may have partially overlapped resulting in more confined and less pronounced amplitude of P600 for ungrammatical nouns containing complex than simple affixes (Luck & Kappenman, 2012). In any case the emergence of P600 implies that both variants of ungrammatical nouns engage syntactic reanalysis, and, thus, rely at least on partially similar neurocognitive processes during later stages of processing. The findings imply that the processing of inflectional morphology seems to be rather affected by the words' structural characteristics as determined by the syntactic context than purely by the distinction into regular and irregular inflection.

4.2. *Neurocognitive modeling of irregular inflection*

Previous research has presented ample evidence in favor of dual-systems accounts assuming that regular inflection involves rule-based processes, whereas irregular inflection relies on lexical storage (for overview see Marslen-Wilson & Tyler, 2007; Ullman, 2001). The present findings for irregularizations as in the ungrammatical nouns (i.e., /-*(e)n*/ instead of /-s/ plural affix) differ from previously reported results of an N400 (for overview see e.g., Newman et al., 2007). In the present study, a reduced amplitude of P200 followed by a P600 was found for ungrammatical inflection (e.g., **Karton-en*). The amplitude of P600 was more pronounced for nouns combined with simple than with complex affixes indicating an influence of morphological marking. Such an influence also appeared on the preceding ERPs: An additional LAN component was merely observed for ungrammatical nouns consisting of complex affixes. This effect had a left anterior topography, in contrast to a potential N400 effect, and preceded the P600. The finding of a syntax-related ERP pattern (i.e., P600, and LAN depending on the word's structural characteristics) in response to irregularizations implies that even irregular words may involve rule-based processing mechanisms rather than lexical retrieval as presumably reflected by N400. Ungrammatical plural inflection was apparently reanalyzed as indicated by the observation of P600, which corresponds to the findings by Lück et al. (2006) showing enhanced P600 for equivalent ungrammatical German nouns. At least, with regard to the German plural morphology, this implies that the processing of inflectional morphology cannot be accounted for by the pure distinction into regular and irregular plurals but rather by their structural characteristics. Besides, a modulation of the P200 amplitude was observed for ungrammatical compared to grammatical nouns implying an involvement of different neurocognitive processes already during initial phases of processing. This early positive ERP response was shown to be sensitive to pre-lexical processes, such as analysis of phonological and orthographic characteristics of words, initiated by the visual presentation of the stimuli (e.g., Carreiras, Vergara, & Barber, 2005; de Vega, Urrutia, & Dominguez, 2010). Differences in the amplitude of the P200 might be associated with the segmentation of the affix (i.e., the /*en*/ syllable) of ungrammatical nouns that occurred already before lexical information was accessed. Due to irregularization of those nouns enhanced pre-lexical access of the word forms' phonological and morphological properties might have been involved. Successful pre-lexical access of the word forms' morphological features apparently prevented from a non-word effect as indicated by the absence of an enhanced N400 (cf., Bartke, Rosler, Streb, & Wiese, 2005; Weyerts et al., 1997).

The present data challenge dual-system accounts regarding the processing of irregular morphology (Clahsen,

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1999; Marslen-Wilson & Tyler, 2007; Pinker & Prince, 1988; Ullman, 2001). Irregular words may not necessarily be lexically stored as whole forms in the mental lexicon – at least in a highly inflected language. Since an N400 component in response to ungrammatical nouns representing an irregular inflection pattern was absent in the present experiment, difficulty in lexical access of those word forms might not have occurred. Either because those forms are not stored in the lexicon, or grammaticality is judged on a rule-based process. Instead, a reduced P200 followed by P600 emerged suggesting an enhanced pre-lexical processing that apparently enabled an engagement of syntactic processes during later stages of processing. Such pre-lexical processes have been assumed, for instance, in the augmented addressed morphology model (Caramazza et al., 1988) based on the words' transparency of the surface form as well as similarity with stored lexical representations. Information encoded on the surface of the word form guides morphological processing and activates a decomposed access unit when superficial structural characteristics do not correspond with stored whole-word representations. With regard to single system accounts (e.g., Rumelhart & McClelland, 1986), evidence for an involvement of purely memory-based mechanism subserving both irregular inflection was not found. Rather, the present results suggest that even irregular words apparently involve rule-based processes as proposed by full decomposition accounts (Stockall & Marantz, 2006). Accordingly, all word forms are decomposed into stems and functional morphemes regardless of regular or irregular inflection patterns. Irregular inflection seems to be rather structured and predictable, and might be based on morphological principles as shown for nominal inflection (Bartke et al., 2005; Opitz et al., 2013) as well as verb inflection (Regel et al., 2015; Regel, Kotz, Henseler, & Friederici, 2017; Stockall & Marantz, 2006).

To conclude, the present study investigated the processing of inflectional morphology, with respect to the type of affixes (i.e., either complex, or simple affixes). The observed ERP data suggest that complex affixes, such as the German /-*e*-*n*/ dative plural affix, are morphosyntactically decomposed into smaller morphological units as proposed by current morphological theories (Halle & Marantz, 1993; Müller, 2007; Noyer, 1992). Moreover, the present results imply that processing nouns carrying an irregular inflection affixes not necessarily involve enhanced lexico-semantic processes, since syntax-related ERP effects (i.e., P600) were obtained for irregular morphology in absence of an N400 component. Irregular inflection may rather rely on rule-based processes in favor of full decomposition models (Stockall & Marantz, 2006), and asks for an adaptation of dual-system accounts (e.g., Marslen-Wilson & Tyler, 2007).

Acknowledgments

We thank Conny Schmidt and Heike Boethel for her support with the acquisition of the EEG data. Further, we are thankful to all the participants for their willingness and commitment to our research. This research was supported by the German Science Foundation Grant (FR 519/19-1) to Angela D. Friederici and Gereon Müller.

Appendix. List of all critical nouns in grammatical and ungrammatical inflection chosen as stimuli (the orthography of the affixes is identical in both accusative and dative contexts, and, thus, included only once here). Ungrammatical nouns are indicated by an asterisk.

Critical nouns (with English translation)		
Kartons	*Kartonen	(Cartons)
Ballons	*Ballonen	(Balloons)
Details	*Detailen	(Details)
Tickets	*Ticketen	(Tickets)
Etats	*Etaten	(Budgets)
Designs	*Designen	(Designs)
Debüts	*Debüten	(Debuts)
Cockpits	*Cockpiten	(Cockpits)
Slogans	*Sloganen	(Slogans)
Popstars	*Popstaren	(Pop stars)
Porträts	*Porträten	(Portraits)
Shuttles	*Shuttlen	(Shuttles)
Depots	*Depoten	(Depots)
Ressorts	*Ressorten	(Departments)
Transfers	*Transferen	(Transfers)
Salons	*Salonen	(Lounges)
Ratings	*Ratingen	(Ratings)
Slaloms	*Slalomen	(Slaloms)
Workshops	*Workshopen	(Workshops)
Dossiers	*Dossieren	(Dossiers)
Endspurts	*Endspurten	(Final spurts)
Budgets	*Budgeten	(Budgets)
Meetings	*Meetingen	(Meetings)
Waggons	*Waggonen	(Waggons)
Sheriffs	*Sheriffen	(Sheriffs)
Jacketts	*Jacketten	(Jackets)
Cocktails	*Cocktailen	(Cocktails)
Parfums	*Parfumen	(Perfumes)
Airbags	*Airbagen	(Airbags)
Gourmets	*Gourmeten	(Gourmets)
Joghurts	*Joghurten	(Yoghurts)
Desserts	*Desserten	(Desserts)
Remakes	*Remaken	(Remakes)
Buffets	*Buffetten	(Buffets)
Trikots	*Trikoten	(Shirts)
Notebooks	*Notebooken	(Notebooks)
Covers	*Coveren	(Covers)
Hotels	*Hotelen	(Hotels)
Contests	Contesten	(Contests)
Trainings	*Trainingen	(Trainings)

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Please cite this article in press as: Regel, S., et al., Processing inflectional morphology: ERP evidence for decomposition of complex words according to the affix structure, Cortex (2018), https://doi.org/10.1016/j.cortex.2018.10.003