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Inter-individual variability in morphological processing: An ERP study on German plurals

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ABSTRACT

Previous studies on the neuro-cognition of language have provided a strong case for systematic inter-individual variability in event-related potentials (ERPs) evoked during language processing. In the present study, we aimed at extending this evidence to the processing of morphologically complex words. We focused on German plural forms and tested two types of morphological violations: overapplications of regular plural morphemes ('regularizations') and of irregular plural morphemes ('irregularizations'). The group-level results showed a biphasic LAN-P600 response for regularizations, and a P600 for irregularizations. In line with previous reports, our analyses of inter-individual variability suggested that biphasic responses consisting of a negativity followed by a positivity are unlikely to exist at the individual level. Importantly, when analyzing the scalp distribution of ERPs elicited in participants supposed to show negativity-dominant responses, we found this to vary as a function of the type of morphological form: regularizations elicited a left-hemisphere response (LAN), while irregularizations a more widespread negativity (N400). Our results are consistent with dual-route accounts of morphological processing that distinguish between rule-based processing for regular inflection and memory retrieval for irregular inflection. At a more general level, our study shows that complementing group-level results with analyses of inter-individual variability can crucially contribute to a more detailed understanding of brain signatures of language.

1. Introduction

Much research in cognitive neuroscience has traditionally focused on characterizing and explaining average performance and behavior in a given sample assuming that the sample's average performance generalizes to the entire population (Amenta & Crepaldi, 2016). Yet, it has long been recognized that differences between individuals or groups of individuals in their (neuro)-cognitive abilities or their experience may yield variability in performance and behavior (Just & Carpenter, 1992; MacDonald & Christiansen, 2002; Swets et al., 2008). Inter-individual variability has been shown to be systematic and stable over time (Kanai & Rees, 2011; Miyake & Friedman, 2012; Seitzman et al., 2019), to the point that, for some cognitive abilities, it is possible to identify sub-groups of individuals with specific neuro-cognitive profiles; see, for example, Miyake and Friedman (2012) on executive functions, and DeYoung et al.

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(2010) on brain markers of personality traits. In addition to providing insights into the flexibility of the neuro-cognitive system, the study of inter-individual variability may help to better understand differences across studies (Kanai & Rees, 2011; Lebreton et al., 2019; Valizadeh et al., 2019).

The interplay between inter-individual differences and group-level performance has been the focus of several recent studies on the neuro-cognition of language (see e.g. Tanner, 2019; Tanner & van Hell, 2014). These have complemented standard group-level analyses of event-related potentials (ERPs) with analyses of inter-individual variability in participants' responses, showing that this approach can contribute, among other things, to a better understanding of language-related brain-potentials. The same approach is at the heart of the present work, which specifically focuses on the case of morphological processing, i.e., the processing of morphologically complex forms (e.g. 'plays', consisting of the stem 'play' and the affix '-s').

An ERP component which may particularly benefit from analyses of individual differences is the Left-Anterior Negativity (LAN). The LAN is an ERP component that many studies have reported in response to a range of morpho-syntactic violations, particularly agreement violations (e.g. Barber & Carreiras, 2005; De Vincenzi et al., 2003; Gunter et al., 2000; Leinonen et al., 2008; Linares et al., 2006; Roehm et al., 2005; see Molinaro et al., 2011 for review), as well as in response to morphological violations, such as for incorrect generalizations of past-tense or past-participle formation rules (Morris & Holcomb, 2005; Penke et al., 1997; Schremm et al., 2019) and of stem formation rules (Rodriguez-Fornells et al., 2001). The LAN has therefore been linked to mechanisms involved in the processing of morpho-syntactic and morphological rules (Lück et al., 2006; Penke et al., 1997). It is supposed to be elicited by a mismatch between expected and encountered grammatical features (Molinaro et al., 2011) or alternatively – in the case of morphological violations – by a mismatch between the encountered (incorrect) word form and its lexically stored (correct) representation (e.g. Krott et al., 2006).[1] The LAN has often been found to be followed by a P600 (see Molinaro et al., 2011), which is believed to reflect later re-analysis of grammatical violations (Hagoort et al., 1993; Osterhout & Holcomb, 1992).

Recent research focusing on individual differences has claimed that the LAN, or better the biphasic LAN-P600 response, may be an artifact resulting from variability across individuals in their ERP responses. In a study on morpho-syntactic violations, Tanner and van Hell (2014) found a typical biphasic LAN-P600 response at group level, but a negative correlation between the size of each participants' negativity in the LAN time-window and the size of their positivity in the P600 time-window (see also Tanner, 2019). This was taken to suggest that the biphasic LAN-P600 response reported for the entire group is unlikely to exist at the individual level, and that some participants predominantly show a negativity in both time-windows, while others rather show a positivity. When analyzing the scalp distribution of the ERP response in negativity-dominant individuals, the authors found that the negativity was widely distributed, resembling an enhanced N400, which is typically associated with the processing of lexical-semantic information (see Kutas & Federmeier, 2011; Kutas & Hillyard, 1984). In positivity-dominant individuals, they found a widespread positivity, compatible with a P600, with an early onset at right anterior sites. The authors therefore concluded that not only is the biphasic LAN-P600 not reflected at the individual level, but also the LAN as such is an illusory ERP component, resulting from averaging the widespread negativity of some individuals with the early right-anterior positivity of other individuals. This would critically challenge the validity of any previous reports of LANs in response to morpho-syntactic and morphological violations, which highlights the importance of further investigations.

Inter-individual variability in ERP responses, particularly with regard to the LAN, N400, and P600 components, has been largely investigated in the domain of morpho-syntax and syntax (Bornkessel et al., 2004; Fraga et al., 2021; Grey, 2022; Grey et al., 2017; Tanner, 2019; Tanner et al., 2013; Tanner et al., 2014; Tanner & van Hell, 2014), as well as in other linguistic subdomains, such as the processing of semantically anomalous words (Fromont et al., 2020; Grey, 2022; Kim et al., 2018; Nakano et al., 2010). For the processing of morphologically complex words, and more specifically morphological violations, however, there is, to our knowledge, not yet any study of this kind. Therefore, the question whether previous (group-level) reports of LAN effects in morphological violation studies (e.g. Lück et al., 2006; Penke et al., 1997) could be real and substantial or illusory (as suggested by Tanner & van Hell, 2014 and Tanner, 2019) remains unresolved.

Addressing the debate about the nature of the LAN vs. N400 by testing the domain of morphological violations is particularly relevant because, in previous ERP studies on morphological processing, both LANs and N400 effects have been obtained at group-level. The occurrence of a LAN versus a N400 response has been interpreted in terms dual-route accounts of morphology, which posit distinct neuro-cognitive mechanisms and representations for rule-based ('regular') vs. lexicalized ('irregular') morphological forms (e.g. Clahsen, 1999; Pinker, 1999; Pinker & Ullman, 2002). Assuming the common functional interpretation of LAN and N400 effects, according to which the former signal primarily grammatical and the latter lexical-semantic processing (Leminen et al., 2019 for review), a dual-route account of ERP responses to morphological violations predicts LANs for morphological regularizations, i.e. for overapplications of regular forms (e.g. **teached* vs. *taught*) and enhanced N400s for the reverse case, 'irregularizations', i.e. overapplications of irregular morphological forms or patterns (e.g. **sept* vs. *seeped*), which do not involve grammatical rules but can instead be understood as genuine lexical violations. Several (group-level) ERP studies testing morphological phenomena in different languages have indeed reported LAN/N400 contrasts in line with dual-route morphology accounts, showing a selective LAN for regularizations, and sometimes (though not always) an enhanced N400 for irregularizations; see e.g. Morris and Holcomb (2005) for English past tense; Rodriguez-Fornells et al. (2001) for Catalan participles and stem formation rules; Schremm et al. (2019) for Swedish past tense;

[1] In addition, a LAN-type ERP effect has also been reported for the processing of syntactically complex sentences (e.g., Felser et al., 2003; Fiebach et al., 2002; Kluender & Kutas, 1993; Matzke et al., 2002), in which case the LAN has been taken to reflect increased demands of working-memory access. However, as pointed out by Molinaro et al. (2011) and Fiebach et al. (2002), the 'working-memory' LAN tends to be more sustained than the 'grammar' LAN, which generally returns back to baseline around 450 ms.

Weyerts et al. (1997) for German plural forms.

Notably, dual-route accounts of the LAN vs. N400 occurrence in morphological violations are also in line with a recent account of the LAN/N400 distinction proposed by Molinaro et al. (2015). The authors suggested that LAN and N400 effects, rather than being two completely different components, should be understood as a negativity continuum occurring in the 300–500 ms time-window, the scalp distribution of which varies depending on the kinds of linguistic stimuli under study (Molinaro et al., 2015). In particular, the more the processing of a linguistic stimulus relies on lexical-semantic (relative to grammatical) cues, the more widely distributed the negativity, thus shifting a focal left-lateralized negativity to a more widely distributed N400 (see also Barber & Carreiras, 2005).

The current study aims at extending the research on inter-individual variability in the neurocognition of language to the domain of morphological processing, which we believe will also contribute to a better understanding of LAN effects in language processing. To this end, we selected a morphological system, i.e. plural noun formation in German, which, due to its characteristics, has been argued to be particularly revealing for understanding morphological processing (e.g. Clahsen, 1999).

1.1. German plural forms

German noun plurals have been investigated in a considerable number of psycholinguistic studies and have featured prominently in the controversy between associative models of language (e.g. McClelland & Patterson, 2002) and dual-morphology models (e.g. Pinker, 1999; Pinker & Ullman, 2002). The appealing property of the German plural system for this controversy is that it has been claimed to contain a 'minority default', i.e. the plural *-s*. Although the plural *-s* is highly productive serving as a default form for pluralizing novel and otherwise unusual words in German (much like the regular plural *-s* in English), it is not very frequent in German usage relative to other plural forms (unlike *-s* plural in English); see Marcus et al. (1995) for further details. Given these properties, research on German noun plurals potentially allows for teasing apart the role of morphological productivity and regularity in language processing and learning from effects of frequency of use and exposure, which may help to decide between the conflicting models. Yet, both associative and dual-morphology models have presented accounts of the German plural system, and the controversy is still unresolved (Clahsen, 1999; Goebel & Indefrey, 2000; Hahn & Nakisa, 2000; McCurdy et al., 2020). Despite this theoretical controversy, the factual linguistic and distributional differences between *-s* vs. other plural forms remain. The main difference is that while the *-s* plural is *lexically unrestricted* in that it can apply to any noun or nominalized element irrespective of their particular sound or meaning properties, the use of other (non *-s*) plural forms is *lexically restricted*, i.e. confined to nouns with specific phonological, gender features or other lexical properties. In the following, we refer to this contrast with the terms 'regular' (i.e., lexically unrestricted) vs. 'irregular' (i.e., lexically restricted).

There is a considerable number of neurocognitive studies investigating German plural nouns, most of which used ERPs (Bartke et al., 2005; Clahsen et al., 2007; Hahne et al., 2006; Lück et al., 2006; Regel et al., 2019; Son, 2020; Weyerts et al., 1997; Winter et al., 2014) in addition to one fMRI study (Beretta, Campbell, et al., 2003). Our present work builds on this previous ERP research, of which we provide an overview in Table 1 (including the contrasts tested and the corresponding results).[2] These studies are comparable in that they used similar designs presenting correct vs. incorrect plural forms in sentence contexts. Apart from Bartke et al.'s (2005) work on non *-s* plural forms, all the studies shown in Table 1 examined 'regularizations', i.e. *-s* plural overapplications to nouns that require other plural forms and/or the reverse case, 'irregularizations', i.e. incorrect other plural forms on nouns that require *-s* plurals; see Table 1 for examples.

Three major language-related ERP components were reported in these studies, (i) a LAN (in most studies) elicited by *-s* plural overapplications ('regularizations'), (ii) enhanced N400s, albeit exclusively for irregularizations, and (iii) a late positivity (P600) in response to both types of plural violation. These findings have been taken to support dual-morphology models (see e.g. Lück et al., 2006).[3] From this perspective, the LAN found for *-s* plural overapplications – as well as for other morphological violations in German and other languages (e.g. Morris & Holcomb, 2005; Penke et al., 1997; Rodriguez-Fornells et al., 2001; Schremm et al., 2019) – is taken to reflect an incorrect application of a grammatical rule. By contrast, the enhanced N400 seen for irregularizations is claimed to signal a lexical violation (e.g. **Auton* instead of *Autos*), in line with much previous research showing an enhanced N400 as the brain response to incorrect/unusual lexical items; see Kutas and Hillyard (1984) and subsequent research. The P600 reported in some (but not all) studies for both types of plural violation arguably reflects later repair mechanisms taking place before the correct noun is integrated into the sentence; see, for example, Regel et al. (2019). It should be noted, however, that some findings reported in Table 1 are not immediately reconcilable with this interpretation. Three studies obtained LANs for *-n* and/or *-e* overapplications, which they ascribed to different sources. Bartke et al. (2005) ascribed them to participants self-correcting the violations, Lück et al. (2006) to the 'sequential dimension' of auditory stimulus presentation, which may promote combinatorial processing of the stem and the subsequent incorrect affix, and Regel et al. (2019) to the specific properties of (dative) case marking. Furthermore, unlike other studies reporting an N400 for *-n* overapplications, Regel et al. (2019) did not find an N400 for such cases. Taken together, although ERP violation studies have revealed some consistent trends, some questions remain open, especially with regard to the LAN as selectively marking grammatical rule violations ('regularizations').

[2] We did not include the study by Winter et al. (2014) in Table 1, because this study yielded a rather unclear pattern of results.

[3] Beretta, Campbell, et al. (2003) reported distinct patterns of brain activation for *-s* vs. non *-s* plural formation in their fMRI study, which they interpreted as consistent with Clahsen's (1999) dual-morphology account of German noun plurals. See Seidenberg and Arnoldussen (2003), Beretta et al. (2003b), and Jaeger (2003) for a discussion of these findings.

Table 1
Overview of ERP violation studies of German plurals.

Study	Modality	Population	Correct Affix	Incorrect Affix	Example	Effects
Weyerts et al. (1997)	visual	adult L1	-s	-n	Aperitivs 'aperitifs' vs. *Aperitiven	N400
			-s (proper names)	-n	Heiners vs. *Heineren	N400
			-n (masculine/neuter)	-s	Psalmen 'psalms' vs. *Psalms	LAN
			-n (feminine)	-s	Algen 'seaweed' vs. *Algs	LAN
Bartke et al. (2005)	visual	adult L1	-n (masculine/neuter)/-n (feminine)/-e (masculine/neuter)	-e/-e/-n	Burgen 'castles' vs. *Burge/Bären 'bears' vs. *Bäre/Deiche 'dikes' vs. *Deichen	LAN°
Lück et al. (2006)	auditory	adult L1	-s	-n	Aperitivs 'aperitifs' vs. *Aperitiven	LAN + N400 + P600
			-s (proper names)	-n	Heiners vs. *Heineren	N400
			-n (masculine/neuter)	-s	Psalmen 'psalms' vs. *Psalms	LAN + P600
			-n (feminine)	-s	Algen 'seaweed' vs. *Algs	LAN + P600
Hahne et al. (2006)	auditory	adult L2	-s	-n	Aperitivs 'aperitifs' vs. *Aperitiven	N400
			-s (proper names)	-n	Heiners vs. *Heineren	N400
			-n (masculine/neuter)	-s	Psalmen 'psalms' vs. *Psalms	P600
			-n (feminine)	-s	Algen 'seaweed' vs. *Algs	P600
Clahsen et al. (2007)	auditory	children L1 (age 6–7)	-n (feminine)	-s	Algen 'seaweed' vs. *Algs	broad negativity
		children L1 (age 8–9)	-n (feminine)	-s	Algen 'seaweed' vs. *Algs	LAN
		children L1 (age 11–12)	-n (feminine)	-s	Algen 'seaweed' vs. *Algs	LAN + P600
Regel et al. (2019)	visual	adult L1	-s (accusative)	-n	ohne die 'without the' Kartons (ACC) 'cartons' vs. ohne die *Kartonen	P600
			-s (dative)	-n	mit den 'with the' Kartons (DAT) 'cartons' vs. mit den *Kartonen	LAN + P600
Son (2020)	visual	adult L2 low-proficiency	-s	-n	Autos 'Autos' vs. *Auton	N400
			-n (feminine)	-s	Minuten 'minutes' vs. *Minutes	LAN
		adult L2 high-proficiency	-s	-n	Autos 'Autos' vs. *Auton	N400
			-n (feminine)	-s	Minuten 'minutes' vs. *Minutes	LAN + P600

Note. L1 = native speakers; L2 = non-native speakers; ° = Main effect across all affix types; the authors did not test for interactions of correctness and affix type. The study contains additional contrasts that are not directly relevant for the purposes of the present study.

1.2. *The present study*

The present study investigates brain signatures to violations of morphological forms, specifically German plural forms. Our study addresses a controversy in language-related ERP research, namely the question of whether the LAN is an independent ERP component or a by-product of group-level analyses averaging across individuals with different responses (e.g. Tanner, 2019).

We adopted the design of two previous ERP experiments on German plurals (Lück et al., 2006; Weyerts et al., 1997) that compared brain responses to morphological regularizations and irregularizations (i.e., *-s* vs. non *-s* plural overapplications). We used visual stimulus presentation, analogously to Weyerts et al. (1997) and much of the ERP literature on inter-individual variability (e.g. Tanner, 2019). We predicted that group-level analyses would replicate the earlier findings of Lück et al. (2006) and Weyerts et al. (1997), i.e. a LAN for regularizations (i.e. overapplications of *-s* plural forms to non *-s* nouns), an enhanced N400 for irregularizations (i.e. overapplications of non *-s* plural forms to *-s* nouns), and a P600 for both types of violation. In line with previous reports of inter-individual variability in ERPs to linguistic anomalies (Fromont et al., 2020; Grey et al., 2017; Kim et al., 2018; Nakano et al., 2010; Tanner et al., 2013, 2014; Tanner & van Hell, 2014), we expected to find a negative correlation between the size of the individuals' negativity in the LAN/N400 time-window and the size of their positivity in the P600 time-window. Based on this, and following the rationale by Tanner and van Hell (2014), we would then divide participants into two subgroups: those who are assumed to have a predominantly negative ERP effect in response to morphological violations ('negativity dominant individuals') and those with a predominantly positive ERP effect ('positivity dominant individuals').

Note that the effect size in the second (P600) time-window is likely to depend on the effect size in the first (LAN/N400) time-window, and therefore the ERP activity in the earlier and later time-window are probably inherently correlated independently from the activity specifically evoked by morphological violations. Therefore, the division into positivity-dominant and negativity-dominant individuals may not truly reflect morphological processing mechanisms; we will address this concern in an additional analysis (see Footnote 5). However, what is crucial for our purposes is the analysis of the *scalp distributions* of the ERP responses in the negativity-dominant and positivity-dominant individuals, which we expected to indicate differences in how these subgroups of speakers process the different types of morphological violations. For the positivity-dominant individuals, we expected to observe a broad P600-like distribution of the positivity for both types of plurals. For the negativity-dominant individuals instead, two different outcomes are possible. One possibility would be a widespread N400 for both types of violations, similarly to what Tanner (2019) and Tanner and van Hell (2014) found in their studies. This would be in line with the idea that LAN effects found in group-level analyses are illusory (Tanner, 2019; Tanner & van Hell, 2014). Alternatively, negativity-dominant individuals may be characterized by a left-distributed negativity (LAN) for overapplications of grammatical rules ('regularizations') and an enhanced N400 for lexical violations ('irregularizations'), in line with Molinaro et al.'s (2015) account of the LAN/N400 distinction and with dual-route morphological processing accounts (e.g. Lück et al., 2006; Pinker & Ullman, 2002).

2. Method

2.1. Participants

Forty native speakers of German (29 women; 11 men; 1 other) participated in the study in exchange for payment or course credit. All participants signed an informed consent form before participating in the experiment. Their mean age was 26.02 years (SD = 5.13, range = 18–36). All participants had completed high-school level education; 11 of them additionally held a university degree and 8 a vocational training certificate. All participants were right-handed (although one reported being a retrained left-hander).

2.2. Materials

We selected 160 German plural nouns belonging to two plural types: 80 nouns affixed with the plural *-s* (e.g., *Festivals* 'festivals'), henceforth '*-s* plural nouns', and 80 nouns affixed with one of the plural forms *-n* (e.g., *Zwiebeln*, 'onions'), *-e* (e.g., *Pilze*, 'mushrooms'), or *-er* (e.g., *Lieder* 'songs'), henceforth 'non *-s* plural nouns'. To avoid sub-regularities, we did not include feminine nouns ending with schwa. The nouns in the two plural types were matched as closely as possible for length in letters and syllables, and for word-form and lemma frequency; see descriptive statistics in Table 2. None of the items contained any stem changes. The 'non *-s*' plural type included items with different affixes to allow for appropriate matching between conditions and to avoid items with stem alternations. Word-form and lemma frequency were extracted from the dlex database (Heister et al., 2011) and are provided in the Zipf scale, which approximately spans from 1 to 7; values below 3 indicate relatively low frequency, while values above 4 indicate high frequency (van Heuven et al., 2014).

For each of the 160 critical nouns, we created an incorrect plural form. For the 80 items of the non *-s* plural type, the incorrect forms were created by adding the regular plural ending *-s* to the stem of the nouns (e.g., **Zwiebels*, 'regularizations'; correct form: *Zwiebeln*). Analogously, for the 80 *-s* nouns, the incorrect plurals were formed by adding the irregular (non *-s*) ending *-n* to the stem (e.g., **Festivalen*, 'irregularizations'; correct form: *Festivals*). This yielded a *correct* and an *incorrect* plural form for each noun, resulting in a 2 × 2 design with the factors Plural Type (*-s* vs non *-s*; between-item) and Correctness (correct vs. incorrect; within-item). Following previous ERP studies of German plural nouns (Lück et al., 2006; Regel et al., 2019; Weyerts et al., 1997), the critical nouns were presented embedded in sentences, which contained seven to ten words. The critical noun was always the direct object, appearing in mid-sentence position (see Examples 1 and 2 below). Each noun was presented three times to each participant in different sentence contexts. For each sentence, two versions were created, one with the correct plural form (1a, 2a) and another one (otherwise identical) with the incorrect plural form of the same noun (1b, 2b). This resulted in a total of 960 experimental sentences, which we distributed across two presentation lists following a Latin-Square design. Each presentation list thus included 480 experimental trials, containing half correct and half incorrect plural forms, distributed equally among the two plural types (*-s* vs. non *-s*). Sentence presentation was pseudo-randomized. All experimental materials are available at the following repository: https://osf.io/v87c2/

(1) Regularizations (overapplications of *-s* forms to non *-s* nouns)
  a. Petra schneidet die frischen *Zwiebeln* für den Auflauf.
     'Petra is cutting the fresh onions for the casserole'
  b. Petra schneidet die frischen **Zwiebels* für den Auflauf.
(2) Irregularizations (overapplications of non *-s* forms to *-s* nouns)
  a. Die Stadt Berlin organisiert die musikalischen *Festivals* jeden Sommer.
     'The city of Berlin organizes the musical festivals every summer'
  b. Die Stadt Berlin organisiert die musikalischen **Festivalen* jeden Sommer

Table 2
Summary of the item characteristics (mean, SD, and range).

Plural Type	N. Letters	N. Syllables	Word-Form Freq.	Lemma Freq.
-s Plural Nouns	7.31 (1.83)	2.59 (0.72)	3.28 (0.76)	3.81 (0.69)
	4–13	2–4	1.21–4.81	1.95–5.43
Non *-s* Plural Nouns	6.88 (1.81)	2.35 (0.89)	2.52 (0.86)	3.11 (0.85)
	4–13	1–5	0–4.16	0.91–4.83

2.3. Procedure

Each participant was tested individually in a single session. Before the testing session, participants filled out a biographic questionnaire. In the lab, participants additionally completed a German translation of the Edinburgh Handedness Inventory (Oldfield, 1971) and took part in a short working memory task (operation span task; see Foster et al., 2015; Unsworth et al., 2005), which was administered using OpenSesame software (Mathôt et al., 2012) and lasted about 15 min. The ERP experiment took place in a soundproof cabin and lasted about 60 min, including two breaks. The experiment was presented on a computer monitor using Presentation (Version 16.2, Neurobehavioral Systems, Inc.). Each participant was assigned to one of the two presentation lists.

Each trial began with a blank screen, presented for a period jittered between 700 and 1000 ms, followed by a fixation cross, also presented for a jittered range of time between 200 and 500 ms. Then, the experimental sentences were visually presented word by word in the center of the screen. Each word remained on screen for 500 ms, preceded by a 200 ms blank screen. Words at the end of a sentence appeared with a full stop. Following Weyerts et al. (1997) and most other ERP studies on German plurals, we assigned a probe verification task to participants. After blocks of ten experimental sentences, a 'control' sentence appeared on screen together with the question whether this sentence was included in the previous block of items. This remained on screen until participants provided a response. Control sentences were included to ensure that participants were actually reading the sentences during the experiment. There were 48 control sentences in total, of which half were exact repetitions of one of the sentences presented in the previous block (requiring a 'yes' response), and half were a slightly modified version of one of the previous sentences (requiring a 'no' response).

Before the experiment, participants received a short training containing three practice sentences. They were informed that they would see a series of sentences presented word by word and that a question would appear after some of the sentences. They were instructed to read all the sentences attentively, to answer the questions as accurately as possible by pressing a 'yes' or 'no' button, and to relax and minimize body and eye movements during the EEG recording. Participants could take a short break after, respectively, one third and two thirds of the experimental trials.

All participants signed written informed consent before starting the experiment. The experimental procedure was carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.4. EEG acquisition and pre-processing

The EEG of the participants was recorded using Brain Vision Recorder software (version 1.20.0701; Brain Products, GmbH). Sixty electrodes were positioned according to the international 10–20 system using active electrodes (ActiCap; Brain Products, GmbH): Fp1, Fp2, AF7, AF3, AF4, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FC2, FC4, FC6, FT8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP9, TP7, CP5, CP3, CP1, CPz, CP2, CP4, CP6, TP8, TP10, P7, P3, P1, Pz, P4, P6, P8, PO9, PO7, PO3, POz, PO4, PO8, PO10, O1, Oz, and O2. FCz was used as the reference electrode during the recording. The EEG signal was recorded continuously with an on-line band-pass filter between 0.1 and 70 Hz, with a sampling rate of 500 Hz. Electrode impedances were kept below 20k Ω (following guidelines for ActiCaps).

We preprocessed the signal in MATLAB (R2019a, The Mathworks, Inc.), using the EEGLAB toolbox (Delorme & Makeig, 2004). We first filtered the data with a high pass filter at 0.02 Hz (Kaiser windowed sinc FIR filter, order = 40034, beta = 4.9898, transition bandwidth = 0.04 Hz) and a low pass filter at 40 Hz (Kaiser windowed sinc FIR filter, order = 162, beta = 4.9898, transition bandwidth = 10 Hz). After this, signals were re-referenced offline to the average of the left and right mastoids, and the continuous signal was segmented into epochs of 1400 ms, from −200 ms before the onset of the critical plural nouns to 1200 ms after onset.

Artifacts related to blinks or horizontal eye movements were identified and corrected using independent components analysis (ICA). In order to improve ICA decomposition, we created a different dataset with larger epochs (3s, from -1s to 2s before and after stimulus onset). In this dataset, we checked manually for noisy epochs, which were excluded before applying ICA decomposition (mean epochs excluded by participant = 8.4, range = 0–32). The obtained demixing matrix was then applied to the original dataset.

We removed between one and two individual components per participant, based on visual inspection. Epochs were then baseline-corrected using a 100 ms window before stimulus onset. We then performed additional data preprocessing in a semi-automatic way. First, channels with an amplitude above +100 μV or below −100 μV were identified and, if they exceeded this threshold on more than 10% of all epochs (= 48/480 experimental trials), they were interpolated on all epochs. We then visually inspected the signal and additionally interpolated electrodes with bad quality, i.e., showing sudden peaks or excessively noisy signals (mean of channels interpolated by participant = 6.6, range = 0–17). We finally automatically excluded all remaining epochs with peaks of amplitude exceeding ±100 μV, and again screened all remaining epochs visually and excluded them if the signal was too noisy (e.g., artifacts related to muscle movements).

At the end of this procedure, we excluded five participants who still showed very noisy signal, as also indexed by the lack of the P100 component. We further excluded one participant because their remaining epochs were below two thirds of the total number of experimental trials. The final dataset comprised 34 participants, and the average number of trials retained for the analysis for each participant was 212.5/240 for the *-s* plural type (range 160–237) and 210.3/240 for the non *-s* plural type (range 157–236). The entire preprocessing process, including exclusion of participants, was decided on and performed prior to analyzing any data.

2.5. Data analysis

Participants responded correctly to control questions with a mean of 78.9% (range = 52.1–97.9%). ERP data analysis involved two steps: a *group-level* analysis, and an analysis of *inter-individual variability*.

Both types of analyses involved the same time-windows and regions of interest (ROIs). Before conducting any descriptive or inferential statistics on the data, we selected two time-windows of interest, an early time-window between 300 and 500 ms,[4] and a later time-window between 500 and 800 ms. We opted for these time-windows to keep maximal consistency with the study by Tanner and van Hell (2014; see also Tanner, 2019). To test for LAN effects, we selected a left anterior ROI (F7, FT7, F5, FC5, FC3), in which we would expect a significant LAN for regularizations only. We additionally selected a right anterior ROI (F8, FT8, F6, FC6, FC4) to better inspect the laterality of the LAN. The electrodes included in these ROIs are the same as in Lück et al. (2006), except that our set-up involved more electrodes. To test for N400 and P600 effects, we used the same large, centro-parietal ROI at which N400 and P600 are typically maximal (C3, Cz, C3, CP1, CP2, P3, Pz, P4) used by Tanner and van Hell (2014) and Tanner (2019). Average signal amplitudes in the two time-windows were computed separately for each electrode in each trial (see Frömer et al., 2018). We subsequently averaged the signal of the electrodes in each of the ROIs, in order to obtain one data point for each participant and trial in each ROI. These data were then used as dependent variable in mixed-effects linear regression models as well as to compute correlations.

For the group-level analysis, we fitted a series of linear mixed-effect models to test for LAN, N400, and P600 effects. For analyses of the LAN, the dependent variable was the average signal per participant and trial in the left-anterior ROI. To inspect the laterality of the effect, we further considered the right-anterior ROI. In the case of the N400 and P600 analyses, the dependent variable was the average signal per trial in the centro-parietal ROI in, respectively, the 300–500 and the 500–800 time-window. All models contained the fixed effects Correctness (incorrect vs. correct forms) plus, when required or applicable, Plural Type (non *-s* vs. *-s*) and Hemisphere (right vs. left), as well as the interaction terms between all factors.

All models were fitted using the package lme4 (Bates et al., 2015) in R (version 4.2.0; R Core Team, 2020). Parameters were estimated with restricted maximum likelihood. We used deviation coding for all the contrasts for the fixed effects (i.e., -0.5, 0.5). As a consequence, the intercept represents the grand mean, and estimates for the predictors represent the mean differences in μV between the two levels of the predictor. All models included random intercepts for participants and items. In order to determine a random structure justified by the data, random slopes by participant and item were step-wise tested for inclusion via likelihood ratio tests (see Matuschek et al., 2017). We started with the intercept-only model. We tested for inclusion of each relevant random slope separately, by comparing the model with and without the additional slope. The random slope was included only if it significantly improved the model fit. If more than one slope produced a significantly better model, we first added only the one which produced the greatest improvement (as measured by the Akaike information criterion), to prevent convergence issues. With the resulting model, we then repeated the procedure, testing for inclusion of each additional random slope, until no further slope improved the fit. We calculated *p*-values with the package 'lmerTest' (Kuznetsova et al., 2017). More detailed information about each model are provided in the Results section.

For the analyses of individual differences, we strictly followed the analyses described in Tanner and van Hell (2014). Within the centro-parietal ROI, we computed, for each individual, and separately for the two plural types: (i) the effect size in the 300–500 ms time-window (mean amplitude for correct forms minus mean amplitude for incorrect forms), which we labeled 'early negativity score'; (ii) the effect size in the 500–800 ms window (mean amplitude for incorrect forms minus mean amplitude for correct forms), which we labeled 'late positivity score'. For both scores, positive values indicate larger effect magnitudes, and negative values indicate smaller effect magnitudes. Individual early negativity scores and late positivity scores were first submitted to a simple correlation analysis, to test whether they are negatively correlated. Then, we divided participants into groups of 'positivity-dominant' and 'negativity-dominant'. To this end, we computed the Response Dominance Index (RDI; Tanner & van Hell, 2014; Grey et al., 2017; Qi et al., 2017; Tanner, 2019; Tanner et al., 2014) using the formula below (3).

$$\mathrm{RDI} = \frac{LatePositivityScore - EarlyNegativityScore}{\sqrt{2}} \tag{3}$$

According to Tanner and van Hell (2014), the RDI provides an index reflecting the predominance of negative-going or positive-going ERPs across the two selected time-windows. A negative RDI score indicates that an individual is characterized by a predominance of negative-going ERPs, while a positive RDI score indicates predominance of positive-going ERPs. Based on the RDI, participants were therefore grouped into 'negativity-dominant' and 'positivity dominant'. This was done separately for each plural type based on the different results we obtained for these two conditions at group-level, and again analogously to the procedure described by Tanner and van Hell (2014).

As a next step, we analyzed the ERP responses in the different sub-groups of participants with linear mixed-effects models, following the same procedure as for the group-level analyses. For the negativity-dominant participants, the main goal of this analysis was to assess the scalp distribution of the brain signatures (negativities) elicited by the plural violations in individuals, i.e. whether the negativity was left-lateralized. Therefore, models were fitted on the signal in the left-anterior and right-anterior ROIs, in order to compare the results in the two ROIs. For the positivity-dominant individuals, we just expected to confirm a broadly distributed positivity. The models were therefore fitted on the average signal in the centro-parietal ROI.

Finally, because of the increasing number of recent studies reporting correlations between working memory and the N400/P600 ERP components (e.g. Kim et al., 2018), we additionally performed a simple correlation test between the individual working memory scores and the individual early negativity, late positivity, and RDI scores.

[4] Technically, this time-window included the data points between 300 and 498 ms, as the data points at latency 500 ms were part of the following time-window. We will stick to the wording '500' instead of '498' for simplicity.

3. Results

3.1. Group performance

Fig. 1 shows grand mean ERP waveforms for our participant group for correct and incorrect forms for the two violation types: overapplications of *-s* forms to non *-s* plurals (regularizations; panel A), and overapplications of non *-s* forms to *-s* plurals (irregularizations; panel B). The plots suggest that both types of violations produced a late posterior positivity (P600). Furthermore, results for regularizations additionally suggest an early negativity at left-anterior sites (LAN). The full model outputs of the group-level analyses, together with the random structure of the best-fit models, are provided in the supplementary materials (Tables S1–S10) at the following repository: https://osf.io/v87c2/.

In the left-anterior ROI, previous studies led us to expect a LAN for regularizations (overapplications of *-s* forms to non *-s* nouns), but not for irregularizations (overapplications of non *-s* forms to *-s* nouns). We fitted two separate models on regularizations and irregularizations, on the averaged data from the left-anterior ROI in the early time-window (300–500 ms), with the fixed effect Correctness. We found a significant effect of Correctness for regularizations ($b = -0.449$, SE $= 0.179$, $t = -2.510$, $p = .012$), with the negative coefficient signaling that this type of plural violation elicited an increased negativity (LAN) compared to the baseline (correct plurals). Instead, there was no significant effect for irregularizations ($b = -0.144$, SE $= 0.176$, $t = -0.818$, $p = .413$), i.e., no evidence for (or

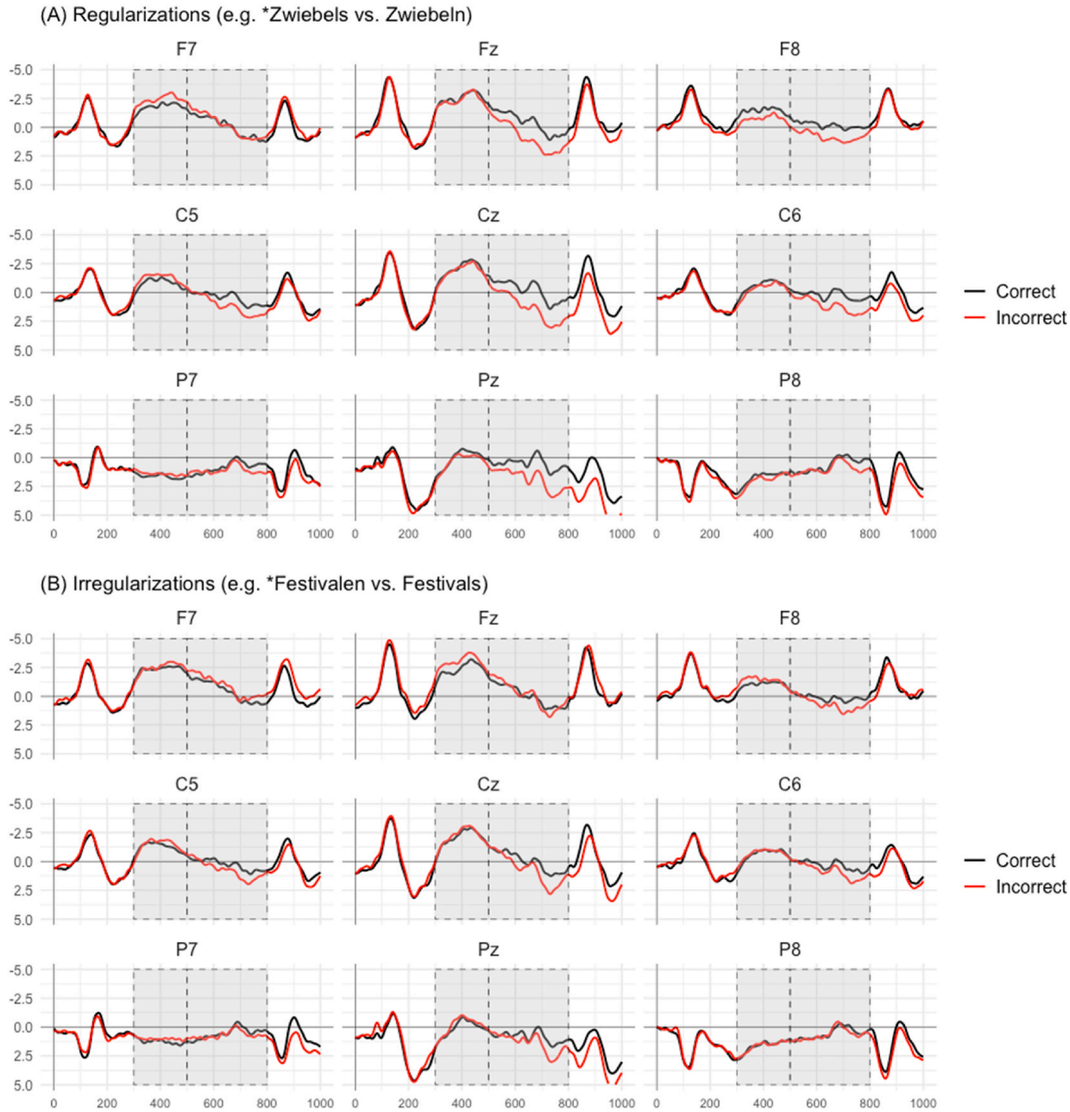

Fig. 1. Grand mean waveforms from nine representative electrodes for the correct (black line) and incorrect (red line) plural forms for regularizations (overapplications of *-s* forms to non *-s* nouns) and irregularizations (overapplications of non *-s* forms to *-s* nouns). The two shaded windows represent the two time-windows we analyzed.

against) the presence of a LAN for this type of violation. To confirm a difference between the two types of violation, we fitted a model with the factors Plural Type, Correctness, and Hemisphere on the data from the left-anterior and the right-anterior ROIs. This showed a three-way interaction between all factors ($b = -0.978$, SE = 0.359, $t = -2.725$, $p = .006$), indeed suggesting differences in the effect of violation for the two plural types with regard to the laterality of the effect. A model fitted only on regularizations with the factors Correctness and Hemisphere showed a significant interaction between them ($b = 0.907$, SE = 0.255, $t = 3.556$, $p = .0004$), confirming that the effect found for this type of violation was significantly different for left-anterior and right-anterior sites. The topographic plots in Fig. 2 present the distribution of the violation effect on the scalp at a latency of 400 ms.

We then analyzed the data from the centro-parietal ROI. We first tested for a modulation of the N400, which may especially be elicited by irregularizations. We fitted two models for the two types of violations on the averaged signal from the early time-window (300–500 ms), with Correctness as fixed effect. We did not find a significant effect of Correctness for either of the two types of violations (regularizations: $b = 0.071$, SE = 0.202, $t = 0.351$, $p = .726$; irregularizations: $b = -0.166$, SE = 0.199, $t = -0.834$, $p = .404$), i.e., no evidence for or against a modulation of the N400 (as we can also observe in Fig. 1). In the later time-window (500–800 ms), previous ERP studies of German noun plurals led us to expect a P600 for both types of violations. Again, we fitted two models on the averaged signal from the centro-parietal ROI for respectively, regularizations and irregularizations, with Correctness as fixed effect. We found a significant effect of Correctness for both types of violations (regularizations: $b = 1.133$, SE = 0.308, $t = 3.682$, $p = .001$; irregularizations: $b = 0.603$, SE 0.296, $t = 2.037$, $p = .050$). The positive coefficients indicate that plural violations elicited an increased positivity (P600) as compared to correct plural forms. The supplementary materials present further models also including interactions between the factors Correctness and Plural Type for both N400 and P600 analyses, to assess differences between the two types of violations; none of these interactions were significant.

3.2. Inter-individual variability

The results of our correlation analyses between participants' early negativity and late positivity effect magnitudes showed that these two were negatively correlated for both types of violations (regularizations: $r = -0.788$, $p < .00001$; irregularizations: $r = -0.668$, $p < .0001$).[5] We found no correlation between the individuals' working memory scores and, respectively, their RDI ($r = -0.156$, $p = .203$), early negativity ($r = 0.132$, $p = .284$), or late positivity scores ($r = -0.157$, $p = .201$).

Using the participants' RDIs, we divided the participants into subgroups of 'negativity-dominant' and 'positivity-dominant' individuals. This was done separately for the two types of violations. We then analyzed the ERP responses in the different sub-groups of participants with linear mixed-effects models. The full model outputs of these analyses, including the random structure of the best-fit models, are provided in the supplementary materials (Tables S11–S17) at the following repository: https://osf.io/v87c2/.

For the negativity-dominant individuals, we predicted two possible outcomes. If LAN effects are illusory, as claimed for example by Tanner (2019) and Tanner and van Hell (2014), then we should observe a widespread negativity for both plural types. Alternatively, in line with the account of the LAN/N400 distinction proposed by Molinaro et al. (2015) and with dual-route morphological processing accounts (e.g. Lück et al., 2006), we may observe a left-distributed negativity (LAN) for regularizations and a widespread negativity (N400) for irregularizations. Fig. 3 presents ERP waveforms averaged across participants of the negativity-dominant individuals for the two violation types. The plots suggest a left-lateralized negativity for regularizations and a broadly distributed negativity for irregularizations.

We fitted two models on the mean amplitude signal of the negativity-dominant individuals, for the two violation types, in the 300–500 ms time-window, at the left-anterior and right-anterior ROIs. Models included the fixed effects Correctness and Hemisphere, to characterize the scalp distribution of the elicited negativities. We were particularly interested in main effects of Correctness (i.e., the effect of plural violation), as well as in possible interactions between Correctness and Hemisphere, which would speak for a lateralized distribution of the negativity. For regularizations (overapplications of *-s* forms to non *-s* nouns), the model showed a significant main effect of Correctness ($b = 0.989$, SE = 0.233, $t = -4.244$, $p = .00002$), as well as a significant interaction between Correctness and Hemisphere ($b = 1.082$, SE = 0.465, $t = 2.328$, $p = .020$), due to a larger effect at left electrode sites. We tested for the presence of a negativity at left-anterior and right-anterior sites with two additional models. We found a significant effect of Correctness at left-anterior ($b = -1.512$, SE = 0.327, $t = -4.631$, $p < .00001$), but not right-anterior electrodes ($b = -0.426$, SE = 0.333, $t = -1.280$, $p = .201$). The left-lateralized negativity elicited by regularizations can therefore be interpreted as a LAN. For irregularizations (overapplications of non *-s* forms to *-s* nouns), we found a main effect of Correctness ($b = -0.879$, SE = 0.408, $t = -2.153$, $p = .042$), but no interaction between Correctness and Hemisphere: $b = -0.157$, SE = 0.421, $t = -0.374$, $p = .709$). The lack of interaction provides no evidence for (or against) a lateralized distribution of the negativity. The rather widespread negativity elicited in this subgroup is compatible with an enhanced N400. A larger model including Plural Type, Correctness, and Hemisphere as fixed effects

[5] Note that there is likely an inherent correlation between the ERP evoked in the earlier and later time-window, independently from the specific activity evoked by the morphological violations. To illustrate this point, we randomly assigned all trials to two fake conditions which we labeled 'fake correct' and 'fake incorrect'. With these two fake conditions, we then computed the early negativity and late negativity score for each subject, in the same manner as for the real data, and tested for a correlation between the two scores. This procedure was repeated 1000 times to check whether the correlation found for the real data is unlikely given the distribution of the correlations for the fake data. The 1000 correlations computed for the simulated early negativity and late positivity scores on the fake data showed an average correlation coefficient similar to the one for the real data (mean $r = -0.767$, 95% CI [-0.772, −0.762]). This suggests that the ERP data in the early and late time-windows are indeed inherently correlated.

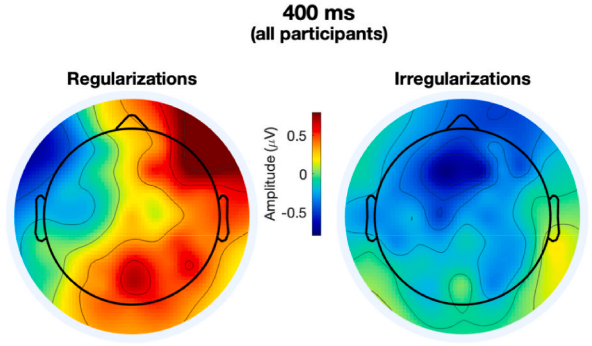

Fig. 2. Topographical distribution of the violation effect (subtraction incorrect-correct forms) in the entire participant group at 400 ms latency, for the two violation types.

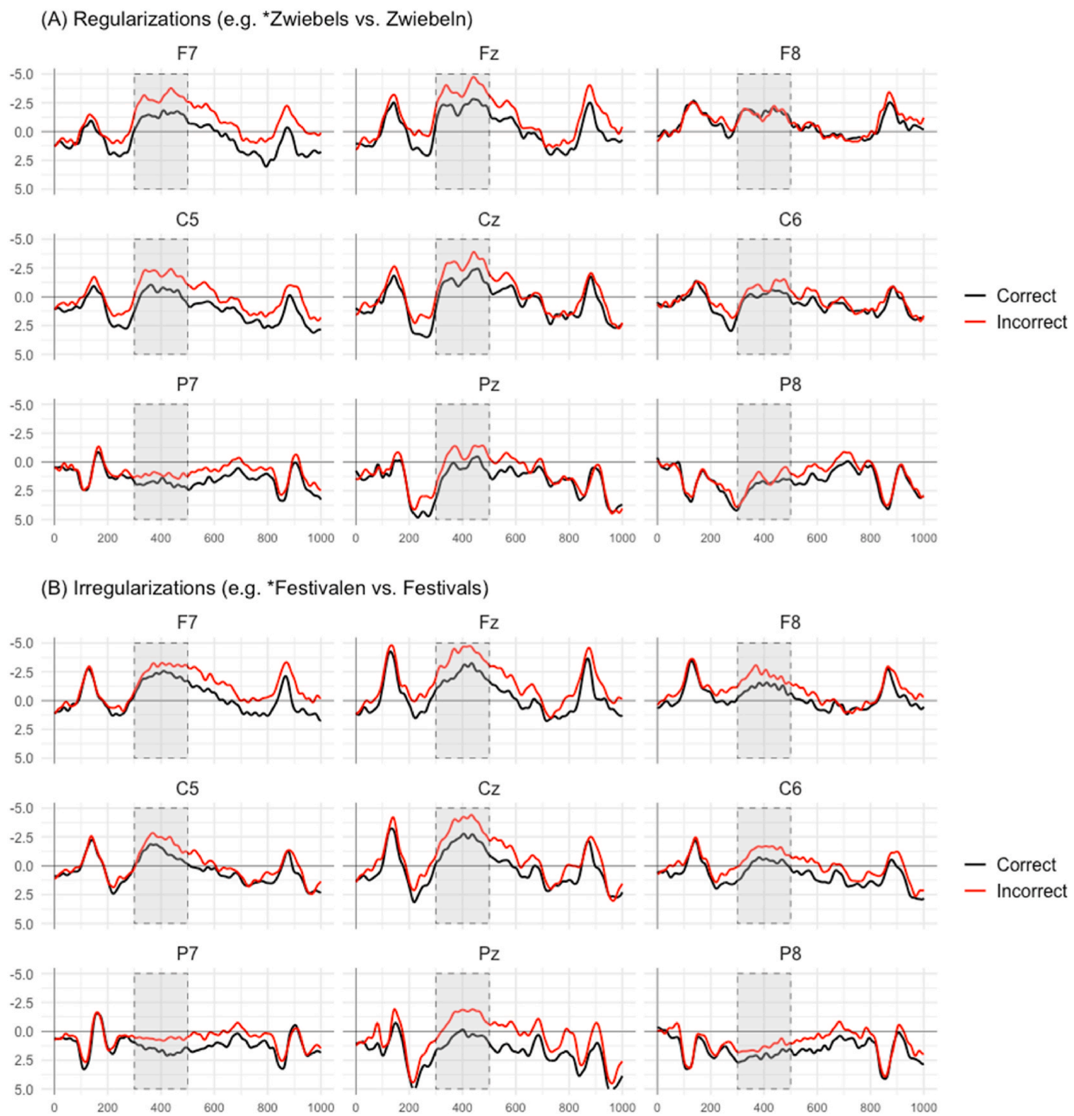

Fig. 3. Grand mean waveforms from nine representative electrodes for the correct (black line) and incorrect (red line) plural forms for the participants showing a negativity-dominant profile for regularizations (panel A; N = 12) and irregularizations (panel B; N = 13).

showed a three-way interaction between the three factors ($b = -1.244$, SE $= 0.625$, $t = -1.990$, $p = .047$), confirming a difference between the two plural types in the laterality of the effect. Fig. 4 presents topographic plots for the violation effect at a latency of 400 ms, in individuals showing a negativity-dominant response for, respectively, regularizations and irregularizations.

As for the positivity-dominant individuals, we just expected to find a significant positivity for both types of violations. Fig. 5, displaying ERP waveforms averaged across these participants, seems to confirm this prediction. We fitted two models, for the two violation types, on the mean amplitude signal in the 500–800 ms time-window in the centro-parietal ROI. Both models showed, as expected, a significant main effect of Correctness (regularizations: $b = 2.124$, SE $= 0.266$, $t = 7.995$, $p < .00001$; irregularizations: $b = 1.618$, SE $= 0.268$, $t = 6.035$, $p < .00001$), with positive coefficients reflecting the fact that the plural violations elicited significantly larger positivities as compared to the baseline (correct plural forms). Overall, the ERP component elicited in the positivity-dominant individuals can be interpreted as a P600.

4. Discussion

The present study investigated ERP responses to violations of morphological forms. We tested German plural forms, a linguistic phenomenon that has been investigated in a series of previous ERP studies (e.g. Lück et al., 2006; Regel et al., 2019; Son, 2020; Weyerts et al., 1997). We first analyzed the data for the entire participant group, with the goal of replicating previous group-level results (e.g. Lück et al., 2006; Weyerts et al., 1997). We then focused on the key aspect of our study, i.e. an analysis focusing on inter-individual variability, which followed the one proposed by Tanner and van Hell (2014; see also Tanner, 2019). The study extends previous ERP research on inter-individual variability in language processing (e.g. Bornkessel et al., 2004; Fromont et al., 2020; Kim et al., 2018; Nakano et al., 2010; Osterhout, 1997; Tanner et al., 2014) to the domain of morphology and contributes to the current ERP literature on inter-individual variability in two ways. First, it addresses the question whether biphasic responses consisting of a negativity followed by a positivity, more specifically the typical LAN-P600 response often reported for morphological and morpho-syntactic violations, are also reflected at the individual level. Secondly, our study seeks to contribute to a better understanding of LAN effects in language processing, by presenting analyses of the scalp distribution of the ERP responses elicited in sub-groups of individuals assumed to predominantly show, respectively, an early negativity or a late positivity in response to morphological violations. This allows us to address a current debate about the nature of the LAN: is the LAN a by-product of averaging across different individuals (e.g. Tanner & van Hell, 2014), or a genuine early negativity indexing combinatorial, rule-based mechanisms (e.g. Molinaro et al., 2011)?

Concerning the results observed at group-level, we found an early negativity between 300 and 500 ms, which was largest at left-anterior sites, for overapplications of the *-s* plural morpheme (regularizations), such as in **Zwiebels* (*Zwiebel* 'onion' + *-s*; correct form *Zwiebeln*), but not for overapplications of the *-n* plural morpheme (irregularizations), such as in **Festivalen* (*Festival* 'festival' + *-n*; correct form *Festivals*). In a later time-window (500–800 ms), both types of plural violations elicited a similar response, i.e. a centro-parietal positivity. The left-anterior negativity that we found for regularizations has been previously reported for overapplications of morphological rules, both for German plural forms (e.g. Lück et al., 2006; Son, 2020; Weyerts et al., 1997) and for other morphological phenomena (e.g. Morris & Holcomb, 2005; Penke et al., 1997; Schremm et al., 2019). In these studies, this response has been interpreted as a LAN, indexing mechanisms involved in processing morpho-syntactic or morphological rules (see e.g. Molinaro et al., 2011). It has been claimed that *-s* German plural forms are *rule-based* forms, while all other German plural forms do not follow a grammatical rule and should therefore considered to be irregular (e.g. Marcus et al., 1995). Assuming this distinction for German plural forms, our group-level results are in line with the predictions of dual-route models of morphological processing (e.g. Pinker, 1999; Pinker & Ullman, 2002). According to these models, a LAN is expected for *-s* regularizations, but not for *-n* irregularizations, because only regular morphological forms are processed through combinatorial mechanisms. Irregularizations, i.e. overapplications of the *-n* plural morpheme, can be instead considered to be lexical violations. As lexical violations, we may have expected these violations to elicit an enhanced N400, in line with previous studies (Hahne et al., 2006; Lück et al., 2006; Son, 2020; Weyerts et al., 1997). However, we did not observe a modulation of the N400 for this condition, at least at group-level.

Concerning the late centro-parietal positivity that we found for both types of plural violations, an analogous ERP response has

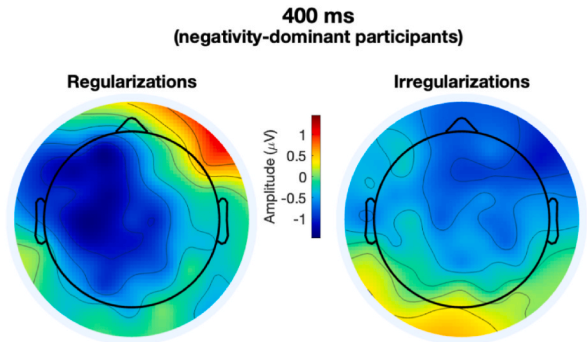

Fig. 4. Topographical distribution of the violation effect (subtraction incorrect-correct forms) at 400 ms latency, in the individuals with a negativity-dominant response for two violation types.

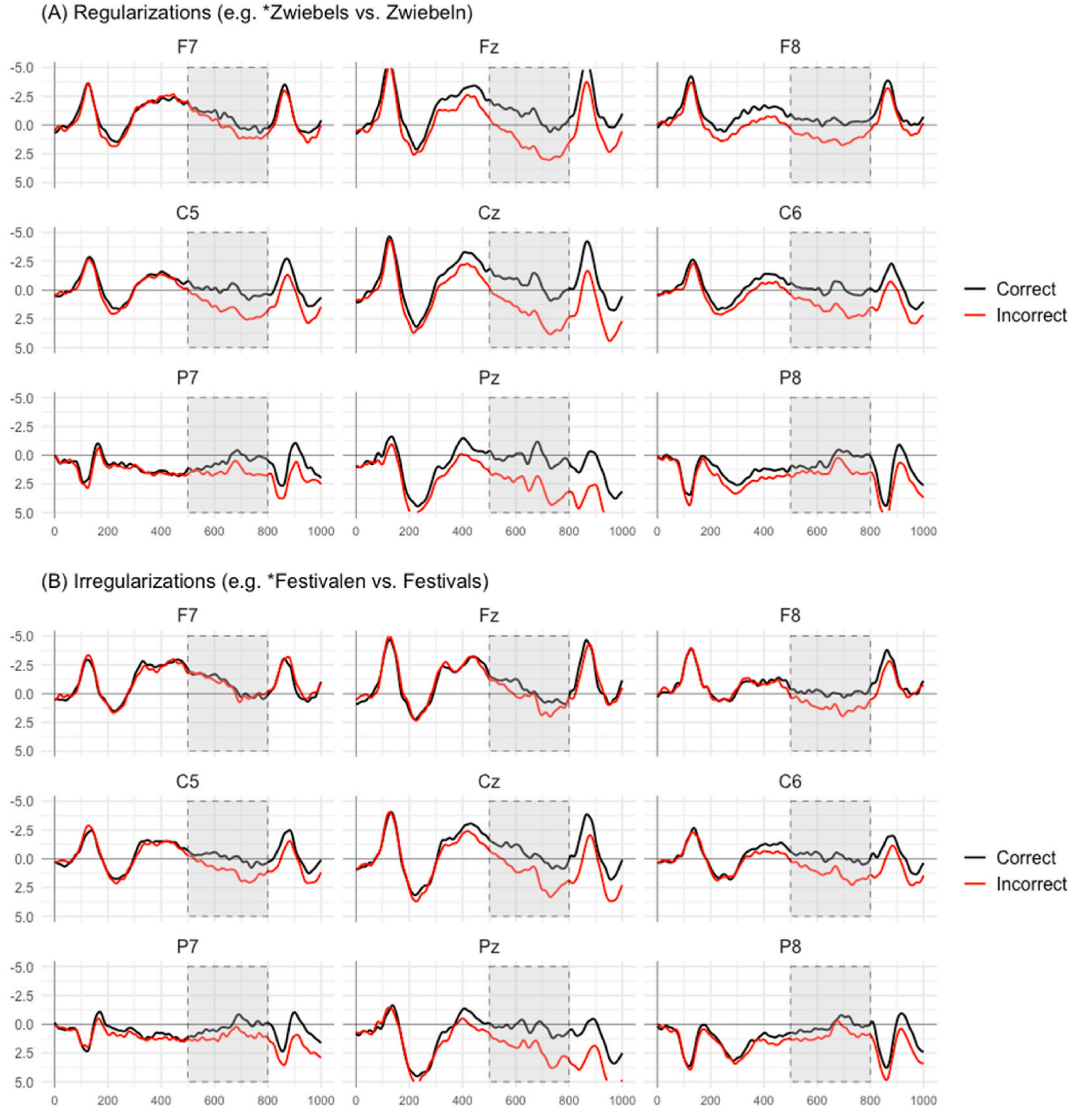

Fig. 5. Grand mean waveforms from nine representative electrodes for the correct (black line) and incorrect (red line) plural forms for the participants showing a positivity-dominant profile for regularizations (panel A; N = 22) and irregularizations (panel B; N = 21).

previously been reported in similar studies (e.g. Lück et al., 2006; Morris & Holcomb, 2005; Schremm et al., 2019). This has been interpreted as a P600, supposedly reflecting mechanisms involved in sentence repair or grammatical re-analysis (see e.g. Hagoort et al., 1993; Osterhout & Holcomb, 1992). Considering that the incorrect plural forms were embedded in complex noun phrases, presented in sentence contexts, the P600 we report for both types of plural violation may indeed index sentence-level mechanisms involved in repairing the incorrect form before integrating it with the corresponding sentence; see Lück et al. (2006) for a similar interpretation.

In sum, our group-level results contribute to previous group-level reports by reinforcing the evidence for general, late, repair mechanisms elicited by illicit linguistic material, indexed by the P600, and for selective effects of rule-based morphological processing, indexed by the LAN. In contrast, unlike previous studies, we did not find a selective N400 for irregularizations.

For the analyses of inter-individual variability in language-related ERPs, we computed, following Tanner and van Hell (2014), a measure of effect size in the early and in the late time-windows. As predicted, we found these two measures to be negatively correlated, similarly to previous studies on morpho-syntactic processing (see e.g. Bornkessel et al., 2004; Tanner, 2019; Tanner et al., 2014; Tanner & van Hell, 2014), sentence processing (Osterhout, 1997), and semantic processing (Fromont et al., 2020; Kim et al., 2018; Nakano et al., 2010). A negative correlation between the individuals' early negativity and late positivity suggests that biphasic responses consisting of a negativity (LAN) followed by a positivity (P600) are unlikely to exist at the individual level. This has previously been taken as evidence that, when confronted with the same linguistic materials, some individuals primarily show an enhanced negativity, while others primarily show a later positivity, therefore possibly engaging in different processing operations. Following this line of reasoning, the present study contributes to current research in the neurocognition of language by suggesting that such inter-individual variability also applies to the processing of morphologically complex forms.

The idea that different individuals may engage in different operations during the processing of morphologically complex words is not new to the morphological processing literature. However, evidence for this until now had only been provided from behavioral studies. For example, Andrews and Lo (2013) report that performance in a morphological priming experiment varies between participants, so that some are more sensitive to lower-level morpho-orthographic information, while others are more sensitive to morpho-semantic information. The former group showed larger priming effects than the latter group with prime-target pairs such as *corner-corn,* where *corner* is a pseudo-complex word with no morphological or semantic relationship to *corn.* Similar results have been obtained by Beyersmann et al. (2015) and Beyersmann et al. (2016).

Following the approach proposed by Tanner and van Hell (2014) and Tanner (2019) for morpho-syntactic violations, we analyzed the responses elicited in the negativity-dominant and positivity-dominant subgroups of participants for the two types of plural violations. Recall that this analysis focused on the *scalp distribution* of the negativities, specifically on whether they are left-lateralized or widely distributed. Tanner and van Hell (2014) found that, for both types of violations they tested, the response elicited amongst the negativity-dominant individuals was a widely distributed negativity, similar to an enhanced N400. The authors therefore suggested that the LAN observed for the entire sample was in fact an artifact, due to averaging across different types of individuals. Our analyses, by contrast, revealed different scalp distributions of the negativity in negativity-dominant individuals for the two types of plural violations. For the condition in which we observed a LAN at group-level, i.e. for overapplications of the *-s* morpheme (regularizations), we found the negativity to be left-lateralized, and therefore interpretable as a LAN (see e.g. Rodriguez-Fornells et al., 2001; Roll et al., 2013; and Schremm et al., 2019 for a similar scalp distribution). In the case of overapplications of the non *-s* plural morphemes (irregularizations), instead, the negativity was broadly distributed, therefore interpretable as an enhanced N400 (Tanner & van Hell, 2014). Finally, similarly to Tanner et al. (2014) and Tanner (2019), the positivity observed in the positivity-dominant individuals had a (centro-)parietal distribution for both types of plural forms, and was therefore compatible with a P600.

Our results show that, at least in the case of morphological violations, LANs are not necessarily an artifact of averaging across individuals, unlike claimed by Tanner and van Hell (2014) and Tanner (2019), since a left-lateralized negativity could be observed in negativity-dominant individuals, even by strictly following their analyses. Instead, we found the scalp distribution of the response elicited in negativity-dominant individuals to vary depending on the type of morphological forms, with regularizations, i.e. rule-based grammatical forms, eliciting a focused left-lateralized negativity (LAN), and irregularizations, i.e. non-combinatorial lexical units, resulting in a N400-like widely distributed negativity. This contrast for the different morphological types is in line with the predictions of dual-route accounts of morphology (see e.g. Lück et al., 2006; Pinker & Ullman, 2002). Furthermore, our results support the account provided by Molinaro et al. (2015) for the LAN/N400 distinction, according to which these two components belong to a family of negativities whose scalp distribution varies depending on the amount of lexical-semantic/grammatical information encoded in the stimuli (also see Barber & Carreiras, 2005).

Given the functional interpretation commonly associated with P600 effects (Hagoort et al., 1993; Osterhout & Holcomb, 1992), our results suggest that individuals with a positivity-dominant response (P600) are particularly sensitive to sentence-level grammatical reanalysis or revision processes, rather than lexical or morphological aspects. By contrast, negativity-dominant individuals are likely to be more sensitive to word-level properties, specifically to morphological-rule violations ('regularizations') or to lexical violations ('irregularizations'). Taken together, our results therefore complement previous ERP literature on individual profiles in language processing (e.g. Bornkessel et al., 2004; Qi et al., 2017; Tanner, 2019; Tanner et al., 2014) by showing that inter-variability in language-related ERPs is modulated by the linguistic properties and by the structure of the words that are being processed.

Some important caveats to the proposed interpretation need to be mentioned, however. First, note that the negative correlation between morphological violations effects in the LAN/N400 time-window and the P600 time-window may also arise for reasons that are unrelated to language processing. There seems indeed to be an inherent correlation between the ERP components in earlier and later time-windows. Therefore, the classification of individuals into 'negativity-dominant' and 'positivity-dominant' which follows from this negative correlation should be taken with caution as it may not truly reflect individual differences in morphological processing. Nevertheless, it is encouraging that the results we obtained on the different types of negativities are fully in line with theoretical expectations, specifically from dual-route morphology models (Pinker & Ullman, 2002) as well as Molinaro et al.'s (2015) account of the LAN/N400 distinction.

A further question concerns the source of the inter-individual variability we observed. In other words, why do some individuals show a larger early negativity than a late positivity, and others show the opposite pattern? Some of the previous studies from this line of research have identified differences in working memory capacity as the source for these differences (Bornkessel et al., 2004; Kim et al., 2018; Nakano et al., 2010). However, this was not replicated by Tanner and van Hell (2014), Tanner (2019), or in the present study. Future research should possibly try to better elucidate the relationship between working memory capacity and negativity-dominant vs. positivity-dominant responses, and for what type of linguistic material such relationship holds.

Besides their relevance for theories of morphological processing and the interpretation of the LAN component, our findings have broader implications for studies of the neurocognition of language. The evidence for individual differences in response to the same linguistic material implies that averaging across individuals may fail to reveal response patterns that are only observable for a (smaller) subset of participants. This is indeed what we found with regard to the enhanced N400 for irregularizations, which did not emerge at group-level, but was then observable when looking into the different subgroups of individuals. This may also explain why previous literature on German plural forms has shown inconsistent findings at group-level for this condition, with some studies reporting an enhanced N400 (e.g. Lück et al., 2006; Son, 2020; Weyerts et al., 1997), and others failing to do so (e.g. Regel et al., 2019; and the present study). Looking at inter-individual variability can therefore importantly contribute to understanding why different studies led to different results. Finally, analyzing inter-individual variability can also serve to a better understanding of the nature of ERP components, which have been previously described exclusively at group-level.

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Author contributions

Laura Anna Ciaccio: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Writing - original draft. Audrey Bürki: Funding acquisition, Methodology, Software, Supervision, Writing - review & editing. Harald Clahsen: Funding acquisition, Conceptualization, Methodology, Supervision, Writing - review & editing.

Declarations of competing interest

The authors declare none.

Data availability

All materials related to this study, including experimental items, data, and code for the analyses are available at the following link: https://osf.io/v87c2/.

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Appendix A. Supplementary data

Supplementary data to this article can be found online athttps://doi.org/10.1016/j.jneuroling.2023.101138.

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