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The influence of rhythmic (ir)regularities on speech processing: Evidence from an ERP study on German phrases

Karen Bohn*, Johannes Knaus, Richard Wiese, Ulrike Domahs

Institut für Germanistische Sprachwissenschaft, Philipps-Universität Marburg, Deutschhausstr. 3, 35032 Marburg, Germany

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ABSTRACT

The present study investigates the status of rhythmic irregularities occurring in natural speech and the importance of rhythmic alternations in cognitive processing. Previous studies showed the relevance of rhythm for language processing, but there has been only little research using the method of event-related potentials to investigate this phenomenon in a natural metrical context. To this end, an experiment was conducted in which the so-called Rhythm Rule (alternation of stressed and unstressed syllables) was either met or violated by stress clashes or stress lapses which are known to occur in German. The comparison of rhythmic well-formed conditions with the conditions including rhythmic irregularities revealed biphasic EEG-patterns for rhythmically marked structures, i.e., stress clashes and lapses.

The present results show that irregular but possible rhythmic variants are costly in language processing, reflected by an early negativity and an N400 in contrast to the well-formed control conditions. Supposedly, the early negativity reflects error detection in rhythmical structure and supports the view that the brain is sensitive to subtle violations of rhythmical structure. A late positive component reflects the evaluation process related to the task requirements.

The study shows that subtle rhythmical deviations from the Rhythm Rule are perceived and treated differently from well-formed structures during processing, even if the deviation in question is permitted and can therefore occur in language production.

1. Introduction

The processing of spoken language not only relies on the information from lexical accent but also on a harmonic rhythmical structure, i.e., an alternating sequence of stressed and unstressed syllables, the metric accent. It has been shown that a regular pattern of stressed and unstressed syllables is advantageous for speech perception not only for adults (e.g., Cutler & Foss, 1977) but also for infants in early language acquisition (Jusczyk, 1999; Nazzi & Ramus, 2003). Moreover, it is helpful for the speech segmentation process as it leads attention to stressed syllables in speech processing (Cutler & Norris, 1988; Pitt & Samuel, 1990). Various studies revealed that the brain not only reacts to clear metrical violations (e.g., Steinhauer, Alter, & Friederici, 1999; Knaus, Wiese, & Janßen, 2007; Magne et al., 2007; Domahs, Wiese, Bornkessel-Schlesewsky, & Schlesewsky, 2008), but also to even small deviations in language (Schmidt-Kassow & Kotz, 2009b; Rothermich, Schmidt-Kassow, Schwartze, & Kotz, 2010; Rothermich, Schmidt-Kassow, & Kotz; 2012) as well as in musical structures (Koelsch, Gunter, Friederici, & Schröger, 2000; Koelsch & Sammler, 2008; Geiser, Ziegler, Jancke, & Meyer, 2009). An important link between the structures of language and music is the notion of rhythm. A well-formed rhythmic structure is defined as a sequence of alternating strong and weak units. This holds true not only for music but also for prosodic structures in language. Therefore, the rhythmical organization of language seems to be comparable to rhythmical ideals of music which are determined by the Principle of Rhythmic Alternation (PRA) (Sweet, 1875/1876; Jespersen, 1933; Cooper & Meyer, 1960; Abercrombie, 1967; Selkirk, 1984). Put differently, linguistic rhythm results from a harmonious alternating string of stressed and unstressed syllables. Certainly, this principle reflects an ideal state of rhythm which cannot be reached constantly in natural language. A well-known contravention against the PRA is a so-called stress clash of two adjacent stressed syllables which would have to be separated by an unstressed syllable in order to fulfill the PRA. Furthermore, also a juxtaposition of unstressed syllables, a so-called stress lapse, infringes upon this principle (Selkirk, 1984). According strictly to the definition of the PRA and to metrical theories, even two adjacent unstressed syllables build a lapse structure. However, there is some dispute whether two adjacent unstressed syllables can be interpreted as a

* Corresponding author. Tel.: +49 6421 2824538; fax: +49 6421 2824558.
E-mail addresses: k.bohn@uni-marburg.de (K. Bohn), knaus@uni-marburg.de (J. Knaus), wiese@uni-marburg.de (R. Wiese), ulrike.domahs@uni-marburg.de (U. Domahs).

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real lapse (cf. Selkirk, 1984; Giegerich, 1985; Nespor & Vogel, 1989; Plag, 1999). In general, there is some consensus that rhythmic deviations in form of stress clashes are less acceptable than stress lapses (Nespor & Vogel, 1989; Kager, 1995).

1.1. Avoidance of rhythmic irregularities

In order to avoid stress clashes, a process called stress shift can be applied. That is, in a sequence of two adjacent stressed syllables, lower level stress can be moved away from primary stress in order to obtain a harmonic structure (e.g., English *thirtéen→thìrteen mén*; German *ánziehen→Róck anzìehen*). To this end, there are two options available: to shift the weaker of the involved stresses onto another stressable syllable (Reversal Analysis: RA) or to destress the weaker syllable (Deletion Analysis: DA) (Vogel, Bunnell, & Hoskins, 1995). Both options obtain a rhythmically alternating sequence of stressed and unstressed syllables. Since the motivation for these processes is rhythmic in nature, they can be subsumed and are thus also known as the Rhythm Rule (RR, Liberman & Prince, 1977). Hence, the Rhythm Rule represents a linguistic repair strategy which implements the demands of the general PRA. The avoidance of stress clashes is most often necessary in phrases since clashes most commonly appear when particular words are combined. A special difficulty lies in the fact that lexical word stress positions of combined words, i.e., the relative prominence patterns of the included words, are normally preserved under embedding. Thus, syllables which receive stress in a phrase are usually the same syllables that bear lexical stress on the word level (Liberman & Prince, 1977; Giegerich, 1985; Truckenbrodt, 2006). Despite this fact and although the application of stress shifts is optional, such shifts seem to operate highly systematically in languages like English and German (albeit to varying degrees; see Section 1.3). Therefore, there seem to be factors which override this stress preservation rule in the occurrence of a potential stress clash (Selkirk, 1995).

1.2. The importance of rhythmic regularity

The importance of an alternation of stressed and unstressed syllables in languages like German and English might also be motivated by the fact that both languages are stress-timed languages. In this speech rhythm type, the distance between stressed syllables has to be kept isochronous as opposed to syllable-timed languages in which stressed and unstressed syllables are isochronous (Pike, 1945; Abercrombie, 1965, 1967). This classification has turned out to be phonetically and physically untenable since no real temporal periodicity could be measured in various studies (e.g., Bolinger, 1965; Pointon, 1980; Roach, 1982; Dauer, 1983; Beckman, 1992). Still, some studies were able to show evidence for differences between the traditional rhythmic classes, even though it must be acknowledged that this classification cannot be categorical (Roach, 1982; Ramus, Nespor, & Mehler, 1999; Low, Grabe, & Nolan, 2000; Grabe & Low, 2002). Thus, the classification types have been maintained (Kleinhenz, 1996) as two extremes of a continuum (e.g., Roach, 1982; Auer & Uhmann, 1988). Irrespective of physical or psychological isochrony, the concept of rhythmic alternation plays an important role in stress-timed languages (cf. Liberman & Prince, 1977; Selkirk, 1984; Hayes, 1984; Couper-Kuhlen, 1986). Besides, German – as well as English – holds a trochaic standard pattern, i.e., metrical feet in which a stressed syllable precedes an unstressed syllable (Jessen, 1999; Domahs et al., 2008).

Despite the manifold variations that appear in spoken language and the fact that real articulatory homogeneous intervals of stressed syllables do not exist, many studies (Cutler & Foss, 1977; Cutler & Norris, 1988; Pitt & Samuel, 1990) were able to show that regular rhythmic alternations constitute an important and valuable factor in language processing. This is due to the fact that an alternating pattern helps in building up an expectation when the next stressed syllable might appear. Thereby, the predictability of rhythmic entities helps to segment speech (Cutler & Foss, 1977; Cutler & Norris, 1988). Moreover, attention is led to stressed syllables in speech processing ("attentional bounce hypothesis": Pitt & Samuel, 1990). Hence, the stressed syllable seems to be the reference point for segmenting the speech signal into smaller units. Further support for this assumption comes from an ERP study by Domahs et al. (2008) which showed that the position of the first perceived stressed syllable – rather than the destressed, originally stressed syllable – is crucial for the evaluation of words containing a stress violation. This is in line with the Metrical Segmentation Theory which states that stressed syllables guide word recognition (Cutler & Norris, 1988). Moreover, the aforementioned study by Pitt and Samuel (1990) not only showed the advantage of rhythmic regularity but also coincidentally delivered interesting insights into the processing of stress clashes by using a strict trochaic pattern as test stimulus. Violations against this pattern emerged by inserting an iambic structure (e.g., DIAper, *SUBway*, *REAson*, *deLUXE*, *PERmit*). Thus, this structure inherits also a proper stress clash (*deLUXE PERmit*). Therefore, its results not only speak for an advantage of rhythmically regular patterns but lead also to the assumption that rhythmic irregularities like stress clashes cause a decelerated reaction and thus an obstacle in language processing.

1.3. Production and perception studies

So far, the importance of the PRA and stress shifts have been mainly explored via perception and production studies regarding rhythmically motivated stress shifts.

Rhythmic regularity and hence the phenomenon of stress shifts was mainly investigated in English. Different studies revealed that for English speakers destressing seems to be the dominant strategy in order to avoid stress clash, i.e., although a proper stress shift can be perceived by listeners, there is no acoustic evidence for a real shift of prominence within a potential stress shift item (Grabe & Warren, 1995; Vogel et al., 1995).

Although previous studies do not fully agree on matters of the realization of the RR and its acoustic correlates, they all concur on the view that the RR and hence rhythmic alternation plays an important role in English.

Regarding the implementation of the RR in German, the occurrence and importance of stress shifts is not conclusive: While Mengel (2000) classifies the RR as a regular albeit purely perceptual phenomenon, other studies showed that stress shifts are not only perceived but also produced by German speakers (Wagner & Fischenbeck, 2002; Bohn, Knaus, Wiese, & Domahs, 2011). However, while Wagner and Fischenbeck (2002) conclude that its application is rather the exception than the rule, the results of Bohn et al. (2011) speak in favor of a highly regular usage of stress shifts in order to obtain a regular, alternating stress pattern. So far, only these few studies investigated the role of the RR and rhythmically motivated stress shifts in German. All studies agree that its application is optional. However, it seems to be the case that shifts can generally be perceived in German. Still, which repair strategy is predominantly used in production to avoid rhythmical deviations is not fully elucidated yet. This might also be due to the highly variable use in speakers and thus needs to be further studied and tested in future studies.

With regard to the on-line processing of this rhythmic phenomenon, which might shed light on this question more deeply, little is known yet. Assuming that the application of stress shifts is optional, stress clashes might be perceived as well-formed in German and therefore might not evoke different brain responses

Table 1
Experimental conditions and filler items.

Condition	Example
Correct SHIFT	Sie soll den **Terˈmin abˈsagen**, wie besprochen She is supposed to cancel the appointment, as discussed
Correct NO SHIFT	Sie soll die ˈ**Feierˈabsagen**, wie besprochen She is supposed to cancel the party, as discussed
CLASH	Sie soll den **Terˈminˈabsagen**, wie besprochen She is supposed to cancel the appointment, as discussed
LAPSE	Sie soll die ˈ**Feier abˈsagen**, wie besprochen She is supposed to cancel the party, as discussed
Filler correct	Sie soll die ˈ**Preise reduˈzieren**, wie immer She is supposed to reduce the prices, as usual
Filler incorrect	Sie soll die ˈ**Preise reˈduzieren**, wie immer She is supposed to reduce the prices, as usual

to either rhythmic deviations or shifted forms although the latter are forms that do not occur in isolation but only in phrases to resolve stress clashes (see Table 1). To investigate the role of shifted and non-shifted stresses in the processing of rhythmic structures, a study utilizing event-related potentials (ERPs) was conducted.

1.4. Previous ERP studies on rhythmic processing

Until recently, only a few psycholinguistic and especially neurolinguistic studies have been conducted on the role of rhythm and prosody, since for a long time the focus of linguistic research was put especially on syntactic or lexical processing. However, ERP studies of the last few years showed that prosodic information influence auditory processing on a lexical as well as on a structural stage (e.g., Steinhauer et al., 1999; Friedrich, Kotz, Friederici, & Alter, 2004; Knaus et al., 2007; Domahs et al., 2008). Moreover, the importance of rhythm and metrics has been revealed by various studies (Magne et al., 2007; Schmidt-Kassow & Kotz, 2009a,b; Rothermich et al., 2010, 2012; Marie, Magne, & Besson, 2011). These studies showed that the brain clearly reacts to rhythmic deviations and violations if an expected rhythmic structure is not met. In most studies using ERPs, this was reflected by a negativity followed by a positive component. However, the interpretation of the reported components varies. Knaus et al. (2007), Magne et al. (2007), and Marie et al. (2011) report an N400 effect for incorrect stress patterns which reflects higher costs in lexical retrieval. A similar negativity effect was found by Schmidt-Kassow and Kotz (2009a). They also consider increased costs in lexical retrieval as a possible source of this effect, but also suggest the possibility that this effect might be a subcomponent of an LAN (left anterior negativity). Accordingly, the higher efforts evoked by metrical violations may reflect a general rule-based error-detection, as postulated by Hoen and Dominey (2000). Therefore, the negativity found may be an instance of an LAN. Marie et al. (2011) conclude this interpretation for their negative component as well. Support for this interpretation comes from further studies which explain the reported negativity as a response to the detection of metrical errors in auditory processing (Brochard, Abecasis, Potter, Ragot, & Drake, 2003; Abecasis, Brochard, Granot, & Drake, 2005; Rothermich et al., 2010, 2012).

The second component, a subsequent positivity, only occurs if the participants' attention is directed towards the metrical structure by the given task (Domahs et al., 2008; Knaus et al., 2007; Magne et al., 2007; Marie et al., 2011; Schmidt-Kassow & Kotz, 2009b; Rothermich et al., 2012). A late positive component hence represents a task-sensitive evaluation and reanalysis mechanism, which is regarded as a general restructuring process by Domahs et al. (2008) and Schmidt-Kassow and Kotz (2009a). However, this component is labeled differently in the studies mentioned. While some researchers (Knaus et al., 2007; Magne et al., 2007; Domahs et al., 2008) assume their positivity effects to be members of the P300 family, Schmidt-Kassow and Kotz (2009a,b), Marie et al. (2011), and Rothermich et al. (2012) describe it as a P600. This is probably due to the fact that the 'classic' P600 is interpreted as a correlate of syntactic reanalysis processes (see e.g., Steinhauer et al., 1999).

1.5. The present study

As can be seen from the results presented above, the presence or absence of rhythmically motivated stress shifts remain to be tested with the help of the ERP technique. Therefore, the present study concentrated on the cognitive processing of rhythmical alternations to explore possible differences in the processing of rhythmically well-formed and rhythmically marked structures.

Since the reported off-line studies draw different conclusions on this topic, an ERP study should deliver a finer-grained picture of the acceptability of rhythmically ill-formed structures in language processing. As rhythmically induced stress shifts seem to be, according to Wagner and Fischenbeck (2002), an optional and rare phenomenon in German, the question is whether detectable general differences between well-formed structures and rhythmic deviations appear at all. In contrast, other studies state that stress shifts are predominantly perceived (Mengel, 2000; Bohn et al., 2011) and applied (Bohn et al., 2011) in German. The detection of processing differences between rhythmic deviations and their well-formed counterparts might therefore shed more light onto this topic. Furthermore, it is interesting to investigate how stress clashes are perceived and evaluated by listeners and how this evaluation might possibly differ from the brain's reaction. Moreover, since not only stress clashes but also stress lapses represent a rhythmic deviation, another question was whether differences between these two deviation types would appear. As mentioned earlier, stress lapses seem to be less problematic than clashes, therefore one might expect stronger reactions for stress clashes.

With regard to the results of previous related ERP studies, a further objective was to clarify the nature of the negativity effect by combining lexical and rhythmic deviations. Moreover, it was tested whether compliance with rhythmic ideals is advantageous for language processing and whether rhythmically induced stress shifts are an obligatory technique to fulfill these ideals.

2. Methods

2.1. Participants

Twenty-six (16 women) right-handed monolingual native speakers of German participated in the experiment. Their mean age was 24 years (age range 20–30 years). All participants had normal or corrected-to-normal vision and none of them had hearing deficits. Each subject was paid for participation on the study. Informed consent was obtained from all participants and privacy rights were always observed.

2.2. Stimuli

To investigate electrophysiological effects correlated with rhythmically motivated stress shifts and clashes, phonological phrases were chosen as stimuli which consisted of a noun and a phrasal verb. A characteristic feature of the selected German phrasal verbs is that they are initially stressed by default and that they allow for stress variation: According to Kiparsky (1966), their stress can and should be shifted to the next stressable syllable if it otherwise clashed with primary stress of a preceding noun. Thus, in a noun–verb phrase such as *Termín àbsagen* 'cancel appointment', initial stress of the complex verb shifts from the particle to the second syllable: *Termín absàgen*. If there is no adjacent syllable bearing primary stress, main stress remains on the initial syllable of the phrasal verb, as in *Féier àbsagen*. Since this stress shift is an optional process (as mentioned in the Introduction), stress clashes can potentially occur. To detect how the brain reacts to these different options, 30 phonological phrases consisting of a disyllabic noun and a trisyllabic phrasal verb (stress shift target) were created. To receive a condition with a (theoretically) necessary stress shift and one without, two noun groups with different stress patterns were chosen for the disyllabic nouns. Since the phrasal verbs, i.e., the stress shift targets, are stressed on the initial syllable in isolation (e.g., *ábsagen* 'cancel'), the group of disyllabic nouns with initial stress (e.g., *Féi.er* 'party') was chosen for the condition NO SHIFT. If the verbs are on the contrary preceded by a finally stressed noun, stress clash is avoided by stress shift on the phrasal verb. Hence, nouns with final stress were used for the condition SHIFT (e.g., *Ter.mín* 'appointment').

These two kinds of nouns were combined with one adequate phrasal verb to evoke both possible stress patterns in the phrasal verb (Féi.er àbsagen vs. Ter.mín absàgen). Thus, all shifted and unshifted forms of phrasal verbs were produced naturally by the preceding trigger noun without artificially manipulating phonetic parameters. Each noun pair was controlled and matched for frequency, according to the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995) in order to minimize lexical frequency effects on the processing of the different conditions. The thirty phonological phrases of each condition were embedded into an invariant carrier sentence to ensure that the target phrases were located at identical prosodic phrase positions and not influenced differently by intonational properties. A further crucial criterion was that the critical phrases did not occur at the end of the sentence. In such positions, downstep phenomena usually occur which lower the pitch of the final word or syllable. For illustration of the stimuli constructed and their embedding, see Table 1.

Stimuli were spoken by a linguistically trained female speaker of German at a normal speech rate and were digitally recorded with a sampling rate of 44.1 kHz and a 16 bit (mono) sample size, using the sound recording and analysis software Amadeus Pro (version 1.5.3, HairerSoft) and an electret microphone (Beyerdynamic MC 930C) in an anechoic room.

In order to obtain the critical conditions CLASH and LAPSE without manipulating phonetic parameters, the sentences of the two naturally spoken and recorded conditions SHIFT and NO SHIFT were cut between noun and the verb's onset. The final part of each sentence of one condition was spliced with the first part of the same sentence of the other condition and vice versa to obtain 30 sentences with ill-formed rhythmical structures, i.e., stress clashes and stress lapses. Hence, the finally stressed nouns of the condition SHIFT (e.g., *Ter.mín*) were combined with the initially stressed phrasal verbs of the condition NO SHIFT (e.g., *àbsagen*) in order to create the stimuli for the deviation condition CLASH. For the condition LAPSE, the nouns bearing initial stress (e.g., *Féi.er*) of the condition NO SHIFT were combined with the shifted forms of phrasal verbs (e.g., *absàgen*) of the condition SHIFT in order to obtain two adjacent unstressed syllables, see Table 2. The sentences of the well-formed conditions SHIFT and NO SHIFT were also spliced between noun and verb in order to avoid a splicing effect in the critical conditions. For these conditions, each sentence of the two control conditions was recorded twice and the first sentence part of recording 1 was spliced with the final sentence part of recording 2. The same procedure was applied to the filler sentences. All stimuli were controlled for and normalized in loudness, i.e., the volume of all sentences was adjusted to a uniform level of volume throughout all used stimuli. This loudness adjustment was carried out via auditory inspection by the first author using the sound recording and analysis software Amadeus Pro (version 1.5.3, HairerSoft).

A phonetic analysis of the phrasal verbs of the two distinct conditions showed that the speaker had produced real stress shifts in the condition SHIFT and no shifts in the condition NO SHIFT. The analysis revealed syllable duration to be the decisive factor for stress shifts: In order to obtain a perceptible shift, the initial syllable of the phrasal verb was significantly shortened, whereas the second syllable, i.e., the first syllable within the verb stem, was lengthened. Hence, the speaker produced real prominence reversals within the phrasal verbs. The cross-splicing of both conditions thus ensured that the participants heard clear stress clashes of two adjacent stressed syllables in the sentences of the CLASH condition and two adjacent unstressed syllables in the LAPSE condition. Additionally, 60 filler sentences, 30 with correct and 30 with incorrect stress patterns of an included quadrisyllabic verb were recorded. The filler items were embedded in similar sentences and spliced as well.

2.3. Procedure

180 stimuli (30 per condition and 60 fillers) were distributed over four blocks of 45 sentences, each taking approximately five minutes. Experimental and filler sentences were presented in a pseudo-randomized order, and each phrasal verb appeared only once per condition within each block. In order to avoid sequence effects, the blocks' order varied between the participants as well. Participants were seated in front of a computer screen in a dimly lit, sound-attenuating room during the experiment. After a short practice phase, the first experimental block started with the request to click any key to begin the experiment. This ensured the participant's attention when an experimental block started. Each trial was introduced by a fixation cross that appeared for 500 ms. It was followed by the auditory presentation of a stimulus embedded in a carrier sentence. The sentences were presented auditorily via two loudspeakers. After the offset of the heard stimulus, the fixation cross disappeared from the screen and a question mark came up which gave the signal for the participants to perform the respective evaluation within 2000 ms and to blink. The participants' task was to decide whether the heard sentences sounded prosodically natural or not as accurately and as fast as possible by pressing one of four buttons. The assignment of buttons to four possible answers (natural, rather natural, rather unnatural, unnatural) was counterbalanced across participants. This task directed the participants' attention consciously to the rhythmic and metrical features of each sentence. This was important, given that rather small irregularities in rhythm are only detectable and assessable if the focus is on the metrical structure (e.g., Knaus et al., 2007; Schmidt-Kassow & Kotz, 2009b). Moreover, this ensured a certain amount of comparability between the conscious behavioral data and the unconscious ERP data. The next trial started after 2000 ms with a new fixation cross. Between separate blocks, participants were offered a short break of approximately one minute to rest their eyes. All procedures were performed in compliance with relevant laws and institutional guidelines.

2.4. ERP recordings

An electroencephalogram (EEG) was recorded from overall 23 Ag/AgCl electrodes with a BrainVision (Brain Products GmbH) amplifier. Four electrodes measured the electrooculogram, i.e., horizontal and vertical eye movements. Two auricle electrodes served as references and were placed at the left and right mastoids. The C2 electrode served as ground. EEG and EOG were recorded with a sampling rate of 500 Hz and filtered offline with a 0.3 to 20 Hz bandpass filter. All electrode impedances were kept below 5 kΩ. Prior to data analysis, all individual EEG recordings were automatically and manually scanned for artifacts from eye or body movements and muscle artifacts. Artifacts with an amplitude above 40 μV were excluded automatically, a subsequent visual screening excluded any further artifacts. In total, 2.9% of the critical stimuli and 2.6% of the filler items had to be excluded from analysis.

2.5. Data analyses

For the behavioral data analysis, the arithmetical mean of all responses for each condition was used. Therefore, each of the four possible response levels was allocated to a numerical value: 1 ≙ natural, 2 ≙ rather natural, 3 ≙ rather unnatural, and 4 ≙ unnatural. The arithmetical means were analyzed with an ANOVA with the factors rhythm condition and well-formedness. As mentioned before, this evaluation response was given with a delay after the offset of the sentence, due to the prevention of movement artifacts. Based on this temporal distance between the perception of each critical item and the response, the measured reaction times were not meaningful. Therefore, an independent reaction time study was undertaken with the identical set of stimuli. Its results will be reported in the next section.

For the EEG data, the following regions of interest (ROIs) were statistically analyzed with a multifactorial repeated-measures ANOVA: frontal (F3, FZ, F4), central (C3, CZ, C4), parietal (P3, PZ, P4) as well as left anterior (F3, F7, FC5), right anterior (F4, F8, FC6), left posterior (P3, P7, PC5), and right posterior (P4, P8, CP6). Averages were calculated from the particle verb's onset up to 1500 ms thereafter with a baseline of 200 ms preceding the onset. Time windows for each paired comparison were chosen based on hypotheses taken from the literature on rhythmical processing (Magne et al., 2007; Knaus et al., 2007; Domahs et al., 2008; Domahs, Kehrein, Knaus, Wiese, & Schlesewsky, 2009; Schmidt-Kassow & Kotz, 2009a; Rothermich et al., 2010) and were adjusted on the basis of visual inspection of the grand average curves. Reported results will refer mainly to the quadrant ROIs. For effects with more than one degree of freedom, Huynh-Feldt (1976) corrections were applied to the *p*-values.

3. Results

3.1. Behavioral data

The ANOVA for judgment data revealed main effects for the factors rhythm condition and well-formedness (words stressed correctly in SHIFT and NO SHIFT or incorrectly in LAPSE and CLASH) [rhythm condition: $F(1,25)=89.56$, $p=.000$; well-formedness: $F(1,25)=44.78$, $p=.000$], as well as an interaction of the two factors [$F(1,25)=66.11$, $p=.000$]. A further analysis of the two pairs CLASH and SHIFT and LAPSE and NO SHIFT showed that the experimental violation conditions CLASH and LAPSE were evaluated as less natural than the control conditions (on a scale from 1=natural to 4=unnatural). The stimuli of LAPSE were classified as significantly less natural than the stimuli of the control condition NO SHIFT [mean 2.23 (SD.34) vs. mean 1.89 (SD.28); $F(1,25)=74.95$, $p=.000$], the difference between CLASH and SHIFT narrowly failed to demonstrate statistical significance [mean 1.74 (SD.26) vs. mean 1.68 (SD.24); $F(1,25)=3.36$, $p=.079$] but here also the rhythmically well-formed structure was evaluated as more natural than the stimuli including a stress clash. The behavioral data from the additional reaction time study support these results. In this study, the response possibilities were limited to only two: natural (≙ 2) vs. unnatural (≙ 1). Here, the difference between CLASH and SHIFT did not become significant neither [$T(19)=-0.54$, $p>.05$] but there was a clear difference between LAPSE and NO SHIFT [$T(19)=4.71$, $p=.000$]. Thus, in both experiments LAPSE was evaluated as less natural than all other conditions, even CLASH. The *t*-tests conducted for reaction times reveal an additional important difference between the two ill-formed rhythmical structures. While no differences were found for the responses for LAPSE and its control condition NO SHIFT [$T(19)=-0.91$, $p>.05$], participants needed significantly more time to evaluate structures containing stress clashes than stress shifts [$T(19)=-3.35$, $p=.003$] (see Fig. 1). Note here that due to lexical differences, caused by the different preceding noun types (Féier vs. Termín), only these stated pairs (CLASH and SHIFT, LAPSE and NO SHIFT) can be tested and statistically compared with each other, as they share the same preceding noun group.

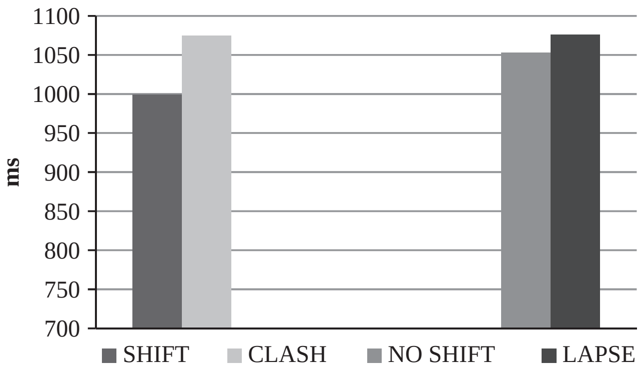

Fig. 1. Reaction times for each condition in ms.

3.2. ERP data

As can be seen in Figs. 2–5, biphasic patterns were found for both rhythmically marked structures CLASH and LAPSE in comparison to each control condition. The first two comparisons are between CLASH & SHIFT and LAPSE & NO SHIFT, respectively. In

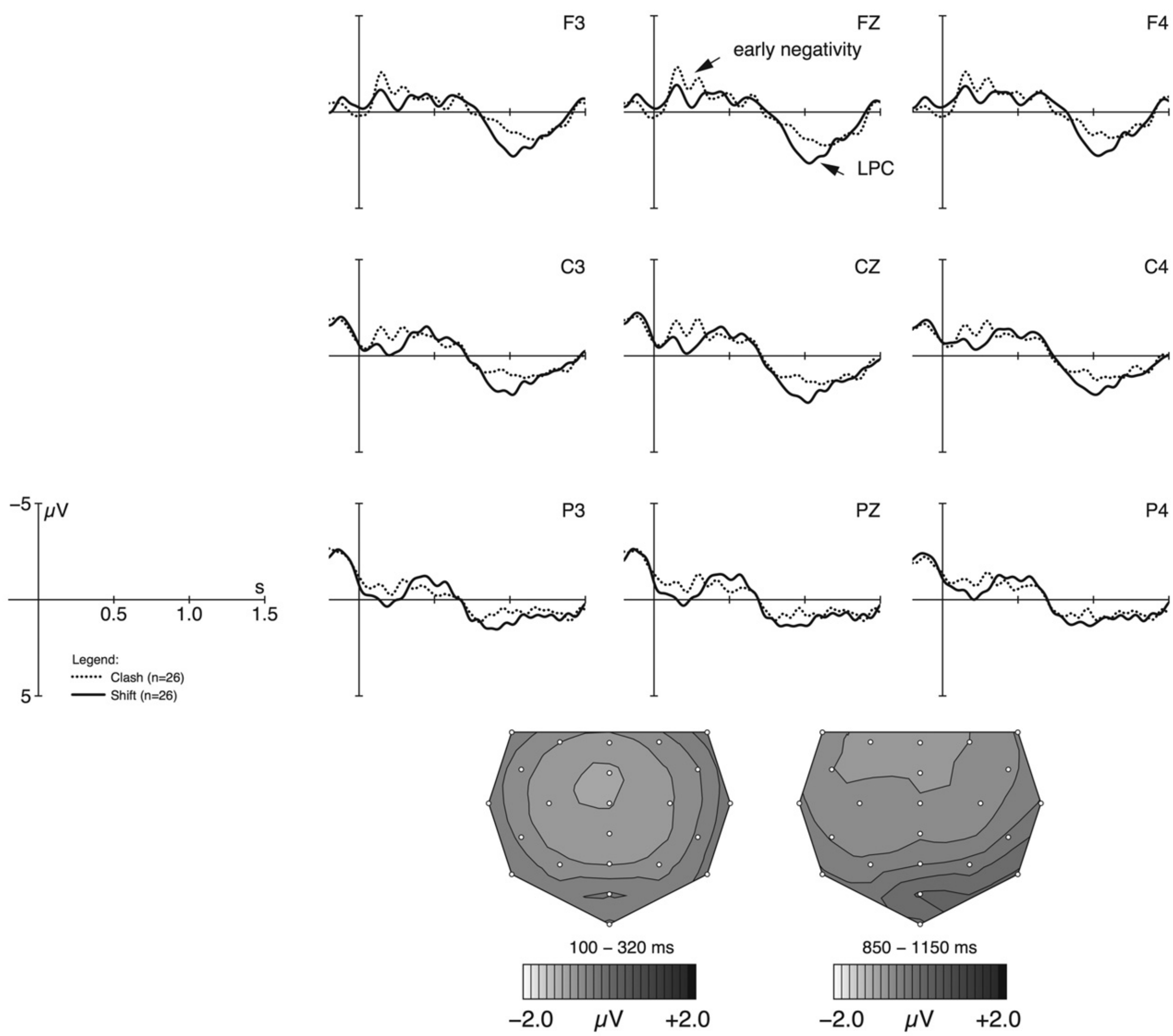

Fig. 2. Grand averages of event-related potentials obtained for the conditions CLASH and control condition SHIFT measured from 200 ms prior the verb onset up to 1500 ms. Topographic difference maps across 23 electrodes show differences between the conditions CLASH and SHIFT in the two critical time windows 100–320 ms and 850–1150 ms.

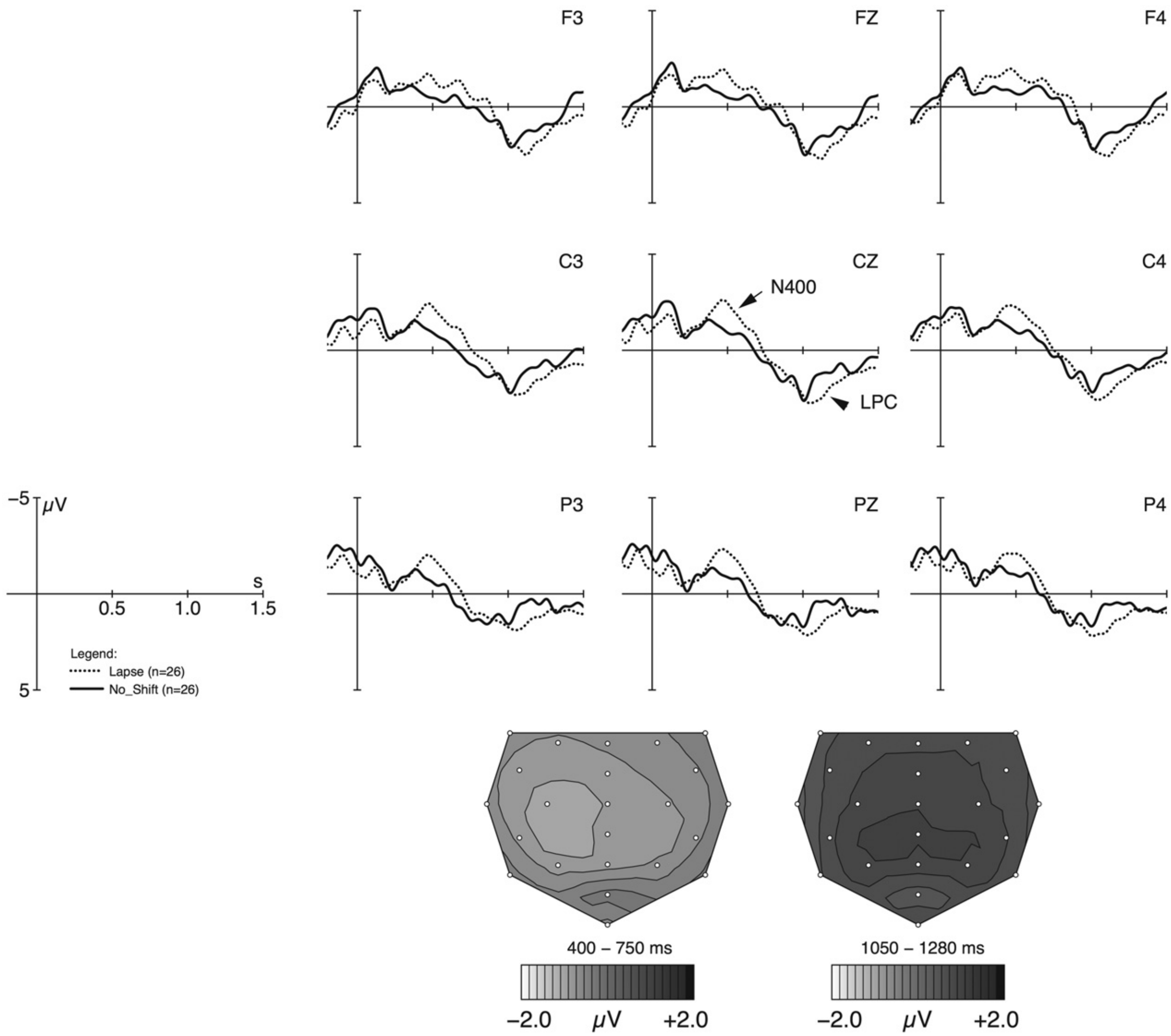

Fig. 3. Grand averages of event-related potentials obtained for the conditions LAPSE and control condition NO SHIFT measured from 200 ms prior the verb onset up to 1500 ms. Topographic difference maps show differences between the conditions LAPSE and NO SHIFT in the two critical time windows 400–750 ms and 1050–1280 ms.

these comparisons, the preceding trigger noun is identical whereas the following phrasal verb either fulfills the rhythmic demands of this noun (control conditions SHIFT and NO SHIFT) or deviates this demand (CLASH and LAPSE). The further two comparisons (CLASH and NO SHIFT, LAPSE and SHIFT) should reveal whether any difference between the first two main comparisons are merely due to the different stress positions in the phrasal verbs that were compared with each other, or whether possible effects are in fact evoked by the rhythmic deviations. Moreover, in order to compare potential differences between the effects elicited by the critical conditions CLASH and LAPSE, difference waves of the two main comparisons were computed by subtracting control conditions from deviant conditions (see Fig. 6). Additionally, difference brain maps across the 23 measured electrodes for all statistically significant time windows were created. Detailed results will be discussed separately for the two rhythmically ill-formed structures and their control conditions.

The comparison of the filler conditions revealed a similar biphasic effect pattern consisting of a negativity (250 to 470 ms) [F(1,25)=21.10, p=.000] and a following positivity between 600 and 1200 ms [F(1,25)=191.93, $p<$.000]. The negativity effect found is interpreted as an instance of an N400 effect which reflects the increased costs in lexical retrieval due to the stress violation in the verbs included in these sentences. Thus, these findings show that all participants were able to detect clear deviations of word stress.

3.2.1. *Comparison between CLASH and SHIFT*

The comparison of the conditions CLASH and SHIFT elicited an early negativity in an early time window (100–320 ms) followed by a late positive component (850–1150 ms). The calculation of a repeated measures ANOVA showed a main effect for rhythm condition [F(1,25)=10.67, p=.003] but no interaction between region and rhythm condition. However, an analysis of the separate regions was calculated in order to clarify the nature of this negativity effect and was guided by the hypothesis that this negativity is a subcomponent of the LAN, as found in previous related studies. In line with our hypothesis, this analysis revealed indeed a more pronounced effect in the left hemisphere [F(1,25)=15.40, $p<$.001]. Statistical analyses of the second time window showed that stress clashes lead to a reduced positivity effect [F(1,25)=14.10, $p<$.001]. Moreover, it revealed a significant interaction between the factors region and rhythm condition [F(3,75)=3.73, p=.027]. The post-hoc analyses of this interaction by region displayed a stronger occurrence of this effect in the left

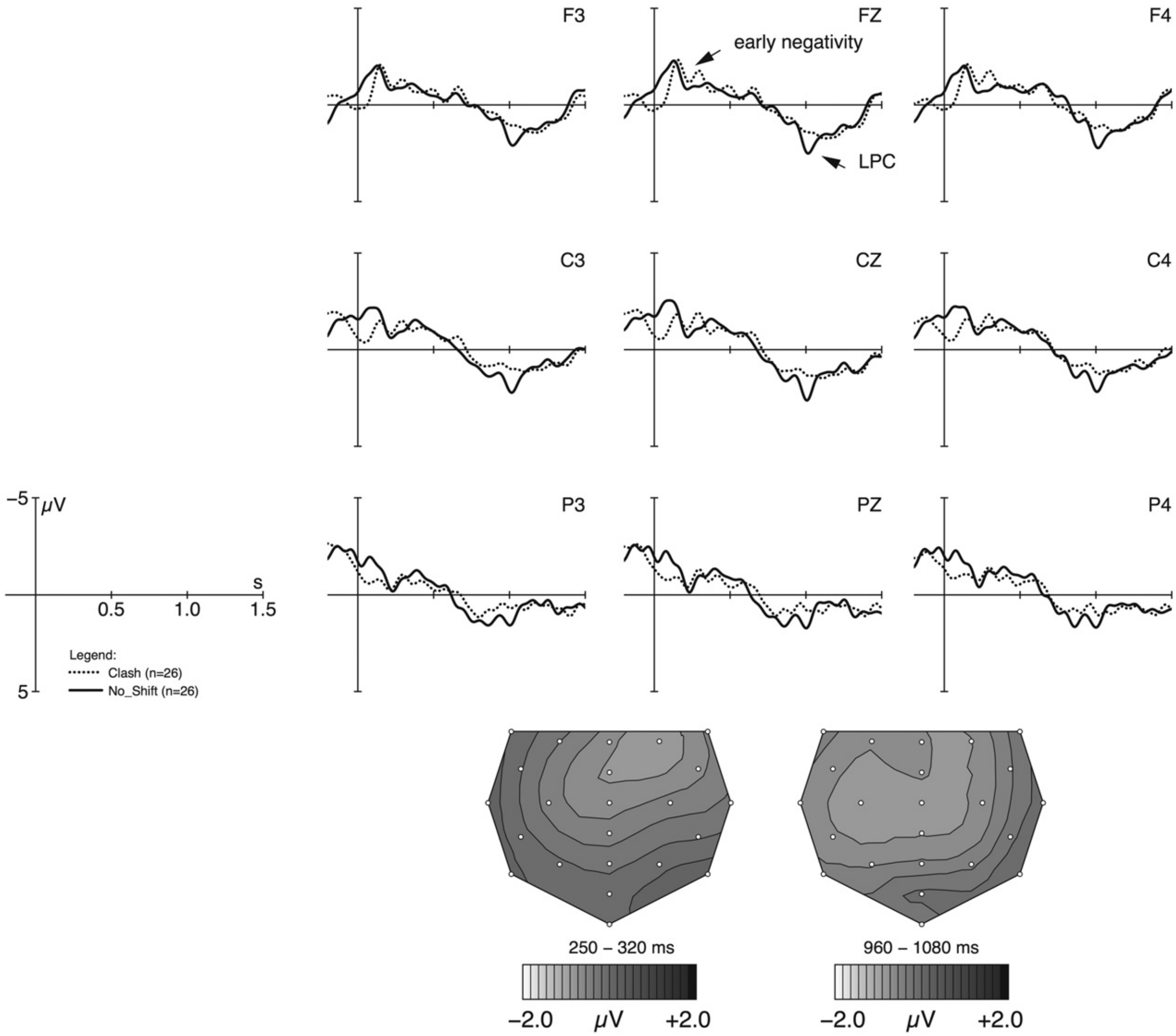

Fig. 4. Grand averages of event-related potentials obtained for the conditions CLASH and control condition NO SHIFT measured from 200 ms prior the verb onset up to 1500 ms. Topographic difference maps show differences between the conditions CLASH and NO SHIFT in the two critical time windows 250–320 ms and 960–1080 ms.

anterior region [$F(1,25)=17.14$, $p<.001$], although all separate regions – aside from right posterior – manifest a significant difference as well.

3.2.2. Comparison between LAPSE and NO SHIFT

For the comparison of LAPSE and NO SHIFT, effects occurred later than in the first comparison. Therefore a later time window was investigated. Note that the position of the stressed syllable in the critical condition LAPSE is the second syllable and not the first as in CLASH. Since a rhythmical deviation can only be detected from this point onwards (Cutler & Norris, 1988: Metrical Segmentation Strategy), the dependent effects occur with the beginning of the stressed syllable and not with the verb's onset. Therefore, the following time windows were chosen: from 400 to 750 ms and from 1050 to 1280 ms. Comparing the condition LAPSE and its control condition NO SHIFT showed a strongly significant negativity effect for the condition LAPSE but no interaction between the factors region and rhythm condition [$F(1,25)=25.12$, $p<.000$]. However, the effect seems to be stronger in the centro-parietal region. This negativity effect is followed by a late positive component, which is more pronounced for LAPSE than for NO SHIFT. Here, this positive component is not reduced in its amplitude like for stress clashes but is very pronounced in its shape, especially in the posterior region. There was only a main effect for the factor rhythm condition but no significant interaction between this factor and region [$F(1,25)=10.96$, $p=.003$].

3.2.3. Comparison between CLASH and NO SHIFT

In order to test whether the effects were evoked by manipulations of lexical stress, two further comparisons were calculated. In the comparison of CLASH and NO SHIFT both conditions maintain the default stress pattern on the first syllable of the included phrasal verb. Hence, this comparison should show whether the rhythmic deviation in CLASH is exclusively responsible for the negativity obtained in the comparison of CLASH and SHIFT as reported in Section 3.2.1. If this is the case, this comparison should reveal a negative component for CLASH, too. As can be seen in Fig. 4, we obtained a biphasic pattern also in the comparison of conditions with identical stress position. The first time window (250–320 ms) shows a stronger negativity for CLASH than for NO SHIFT. However, this effect did not reach a significant status but a significant interaction between the factors region and rhythm condition [$F(3,75)=3.23$, $p=.036$]. Resolving this interaction, a significant right anterior negativity was revealed [$F(1,25)=5.36$, $p=.030$]. In the second time window (960–1080 ms),

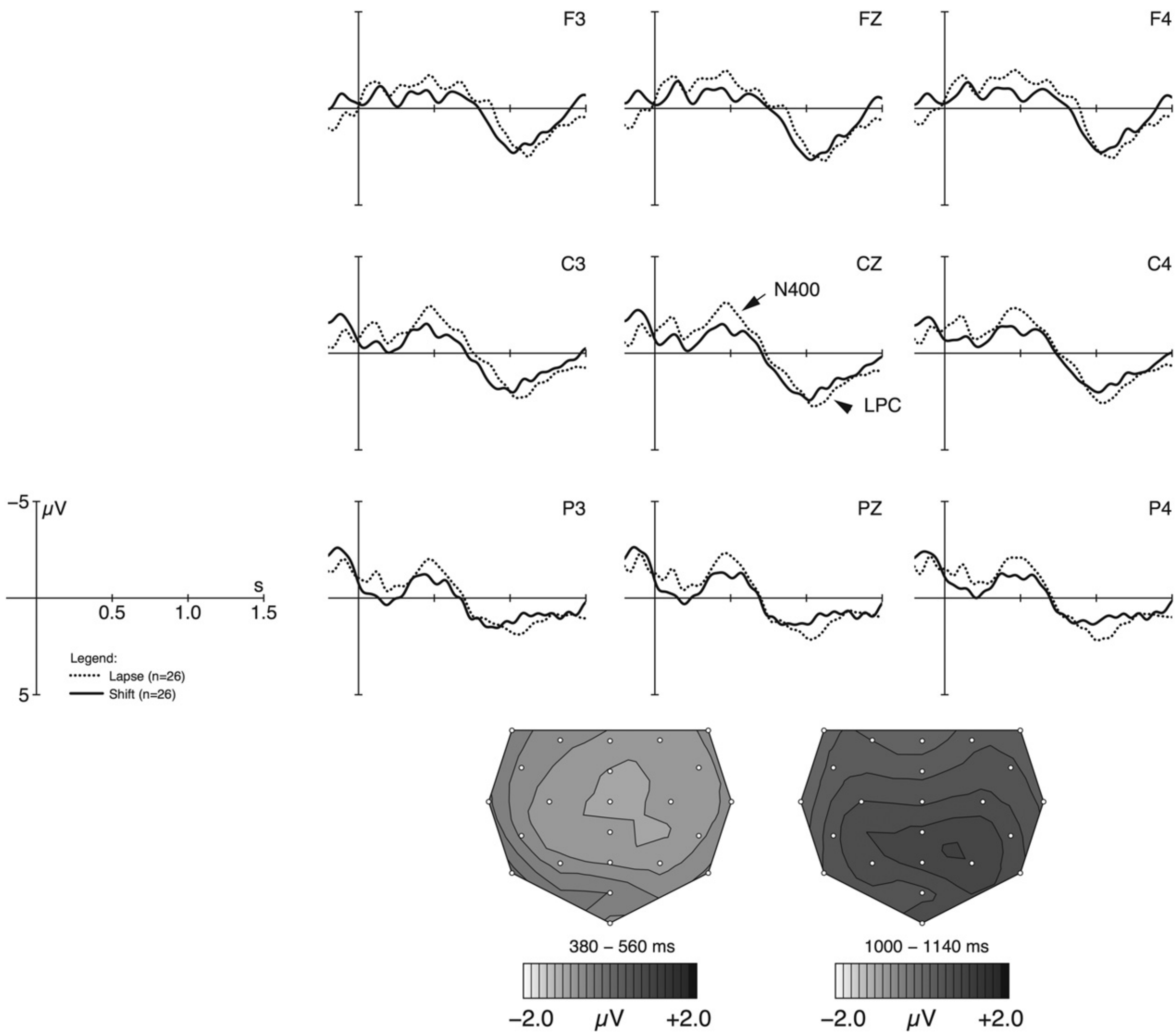

Fig. 5. Grand averages of event-related potentials obtained for the conditions LAPSE and control condition SHIFT measured from 200 ms prior the verb onset up to 1500 ms. Topographic difference maps show differences between the conditions LAPSE and SHIFT in the two critical time windows 380–560 ms and 1000–1140 ms.

a reduced positivity effect is obtained for stress clashes [$F(1,25)=4.34$, $p=.048$]. These results support our hypothesis that the rhythmic deviation in CLASH is mainly responsible for the effects in the first reported comparison of CLASH and SHIFT and not the differences in stress position between CLASH and SHIFT.

3.2.4. Comparison between LAPSE and SHIFT

The two conditions which both include a violation against the default lexical stress pattern were also compared with each other (Table 3). While this lexical deviation is rhythmically motivated in SHIFT, this is not the case in LAPSE. If the lexical deviation of the condition LAPSE is exclusively responsible for the effects obtained in the comparison of LAPSE and NO SHIFT, the comparison between LAPSE and SHIFT should not show any differences, as the phrasal verbs in SHIFT and LAPSE bear the identical stress pattern. The analysis of two time windows showed that LAPSE leads to a strong negativity effect in comparison to SHIFT [$F(1,25)=11.27$, $p=.002$] in the first time window (380–560 ms). In the second time window from 1000 to 1140 ms, LAPSE evoked a moderate positive component [$F(1,25)=3.65$, $p=.067$]. Moreover, a significant interaction between the factors region and rhythm condition [$F(2,50)=4.89$, $p=.030$] was revealed. Post-hoc analyses of this interaction by region displayed that this positivity is most pronounced in the parietal region [$F(1,25)=6.60$, $p=.016$]. These effects are in line with our hypothesis that the interplay of lexical and rhythmical deviations in LAPSE evoked the effects for LAPSE in the comparison of LAPSE and NO SHIFT.

Finally, the two control conditions were tested against each other in order to control for effects purely elicited by lexical deviations. This comparison showed no significant differences in the grand averages. The impression of a negative component at the onset is most likely conditioned by the processing of preliminary lexically and rhythmically different noun groups.

4. Discussion

The present paper explored the importance and influence of rhythmic regularities in speech processing by using the method of ERPs. The aim of the study was to show that metrical deviations can even be detected in a natural, not strictly rhythmically regular environment, in contrast to the material used in the studies of Schmidt-Kassow and Kotz (2009a) and Rothermich et al. (2010, 2012). Furthermore, we tried to clarify whether rhythmic deviations evoke a similar biphasic pattern as in the studies mentioned earlier and how these effects can be explained in terms of cognitive processing.

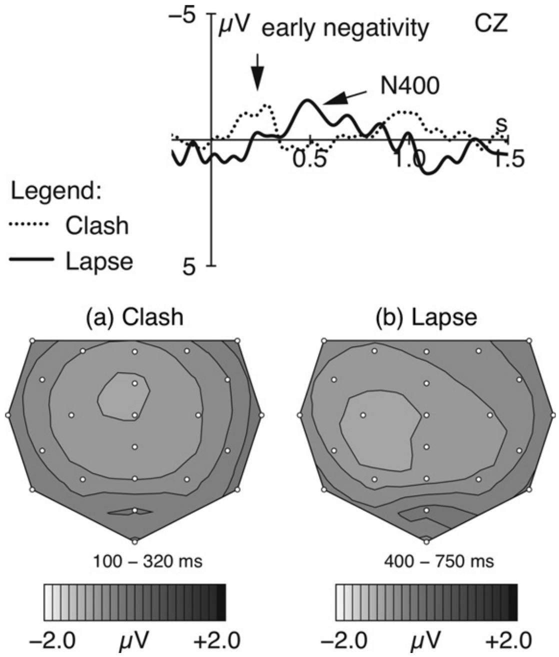

Fig. 6. ERP difference waves contrast the different negativity effects found for CLASH and control condition SHIFT (dotted) and LAPSE and control condition NO SHIFT (solid). Topographic difference maps for the time windows including the negativity effect: (a) CLASH–SHIFT (100–320 ms) and (b) LAPSE–NO SHIFT (400–750 ms).

Our results reveal a biphasic pattern for all tested comparisons. In the following, possible explanations for negativities and positivities found will be discussed in turn together with the behavioral data.

4.1. Negativity effects

The negativity found for CLASH in comparison to (i) SHIFT and (ii) NO SHIFT most likely reflects the error detection in the rhythmical structure of these sentences, i.e., the violation of the Principle of Rhythmic Alternation (see Section 1). The preservation of the lexical stress pattern in the CLASH condition and the early occurrence between 100 and 320 ms cast some doubt on an explanation as a lexical retrieval effect. Hence, we rather interpret this early negativity effect as an instance of a general rule-governed error detection mechanism activated by a rhythmic irregularity. This interpretation is supported by similar results of previous studies focusing on rhythmic deviations (e.g., Schmidt-Kassow & Kotz, 2009a; Rothermich et al., 2010, 2012). Similar to results reported by Rothermich et al. (2010, 2012) for metric deviations, we also found a fronto-central early negativity which might be a subcomponent of an LAN (cf. Hoen & Dominey, 2000). Interestingly, besides other negativity effects found, Rothermich et al. (2012) reported an early negativity elicited by metrically unexpected words. It appears when such words were presented in a metrically controlled, regular context, with task-required focus on the metric structure. In the present study, the context sentence is only controlled for the trigger noun but otherwise not metrically regular. Still, a similar negativity is elicited by the rhythmic deviation of CLASH. Note that a similar component does not only occur in the context of language processing but was also observed in different areas outside of linguistic processes, e.g., in deviations in tone sequences (Brochard et al., 2003; Abecasis et al., 2005; Geiser et al., 2009) and in musical sequences (Patel, Gibson, Ratner, Besson, & Holcomb, 1998; Koelsch et al., 2000), as well as in violations of arithmetic rules (Jost, Beinhoff, Henninghausen, & Rösler, 2004; Núñez-Peña & Honrubia-Serrano, 2004). Functionally, this negativity may be interpreted – comparable to the LAN – as the reflection of recognizing deviations and violations in regular structures. The topography of this negativity also supports this interpretation, since the elicited early negativity has a mainly frontal distribution (see difference brain maps in Figs. 2 and 6). A similar component has also been found in related studies reported earlier (Koelsch et al., 2000; Schmidt-Kassow & Kotz, 2009a; Rothermich et al., 2010, 2012).

Moreover, as the early negativity seems to reflect rather a general than language-specific error detection mechanism, related studies were able to show that this negativity is elicited for rhythmic irregularities irrespective of a matching rhythmic task, i.e., independent of attentional focus towards the rhythmic structure (Schmidt-Kassow & Kotz, 2009a; Rothermich et al., 2010). These findings confirm the independent processing of metrical and rhythmic structures during speech processing and suggest that the negativity found in the present study for CLASH sentences would also be elicited if attentional focus was not on the metrical structure of the sentences heard. This hypothesis is supported by the fact that the present task did not explicitly lead the participants' attention towards the critical structures, but rather in a more general direction of rhythm and meter. We therefore postulate that the early negativity reflects the detection of rhythmic deviations irrespective of task requirements. Since the task was to evaluate the sentences' naturalness rather than to judge rhythmic conditions as correct or incorrect, this task setting was not as explicit as in related studies with clearly explicit and implicit task settings.

The negative component found for LAPSE in comparison to (i) NO SHIFT and (ii) SHIFT might also be explained by the violation of the PRA. The rhythm type of the preceding disyllabic noun (*Féi.er*) allows for a following strong syllable. Hence, stress shift in the following phrasal verb is not only rhythmically unmotivated but also leads to a violation of the PRA and thus an unfulfilled expectation. Furthermore, due to the shifted stress, LAPSE exhibits deviations from the lexical stress pattern, opposed to the verbs in the condition NO SHIFT. Therefore, another interpretation for the negativity found for LAPSE is conceivable, namely that it is an instance of the N400. Previous experiments showed that the deviation from lexical stress patterns increases costs in lexical retrieval, independent from explicit or implicit task settings (Friedrich et al., 2004; van Donselaar, Koster, & Cutler, 2005; Knaus et al., 2007; Magne et al., 2007). This interpretation is supported by the latency of the negativity found for LAPSE in comparison to NO SHIFT at 400 ms post onset and its rather centro-parietal distribution (see Figs. 3 and 6).

Comparing LAPSE with SHIFT, it is important to keep in mind that SHIFT deviates from the lexical stress pattern in the same way as LAPSE does. Nonetheless, the comparison revealed a more pronounced negativity for LAPSE. The lack of a similar negativity effect for the condition SHIFT suggests that the rhythmic irregularity in LAPSE leads to the detection of the lexical deviation in LAPSE and thus that the lexical deviations in SHIFT are rhythmically licensed. Due to the preceding finally stressed noun in SHIFT, a stress shift within the following verb is rhythmically preferred. Further support for this interpretation comes from a study by Rothermich et al. (2012) who showed that the amplitude of an N400 effect evoked by semantically unlicensed words decreases if their stress pattern is in accordance with the surrounding metrically regular pattern in opposition to semantically and metrically deviant forms. This finding is in line with our hypothesis that rhythmic regularity strongly influences the processing of speech. Violations of lexical stress seem hence to be licensed by rhythmic demands. Since stress shift is not rhythmically licensed in LAPSE sentences, it is very likely that the negativity effect induced by LAPSE belongs to the N400 family. This is reinforced by the fact that this effect evolves around 400 ms post onset in both

Table 2
Cross splicing procedure for the critical conditions CLASH and LAPSE.

Condition	Sentence part 1	Sentence part 2
Correct SHIFT	[Sie soll den **Ter'min**]$_{\text{SHIFT}}$	[**ab'sagen**, wie besprochen.]$_{\text{SHIFT}}$
Correct NO SHIFT	[Sie soll die **'Feier**]$_{\text{NO SHIFT}}$	[**'absagen**, wie besprochen.]$_{\text{NO SHIFT}}$
CLASH	[Sie soll den **Ter'min**]$_{\text{SHIFT}}$	[**'absagen**, wie besprochen.]$_{\text{NO SHIFT}}$
Correct NO SHIFT	[Sie soll die **'Feier**]$_{\text{NO SHIFT}}$	[**'absagen**, wie besprochen.]$_{\text{NO SHIFT}}$
Correct SHIFT	[Sie soll den **Ter'min**]$_{\text{SHIFT}}$	[**ab'sagen**, wie besprochen.]$_{\text{SHIFT}}$
LAPSE	[Sie soll die **'Feier**]$_{\text{NO SHIFT}}$	[**ab'sagen**, wie besprochen.]$_{\text{SHIFT}}$

Table 3
Different types of ERP effects in different time windows for all comparisons.

Comparison	Negativity	Positivity	Critical phrases
CLASH and SHIFT	100–320 ms **	850–1150 ms ***	Termín *àbsagen* vs. Termín *absàgen*
LAPSE and NO SHIFT	400–750 ms ***	1050–1280 ms **	Féier *absàgen* vs. Féier *àbsagen*
CLASH and NO SHIFT	250–320 ms * (right anterior)	960–1080 ms *	Termín *àbsagen* vs. Féier *àbsagen*
LAPSE and SHIFT	380–560 ms **	1000–1140 ms * (parietal)	Féier *absàgen* vs. Termín *absàgen*

Statistical significance is indicated by * ($p<.05$); ** ($p<.01$); *** ($p<.001$). Underlined words (*àbsagen*) indicate the critical word's onset for average calculation.

comparisons of LAPSE with NO SHIFT and SHIFT. Hence, the accumulation of lexical and rhythmical violations seems to be responsible for the strong effect for LAPSE, i.e., the hindered lexical retrieval combined with the rhythmic deviation results in a larger N400 effect. This possibility is further supported by the results of the behavioral data and the additional reaction time study, in which the condition LAPSE was evaluated as least natural, even in comparison to CLASH.

The results demonstrate that the brain is sensitive to rhythmic deviations, although some results of previous production and perception studies describe them as possible and unproblematic structures in the use of German (Wagner & Fischenbeck, 2002). What is even more important is the fact that the rhythmic error detection mechanism is also detectable in a rhythmically natural context which does not consist of a repeating trochaic structure, as in the studies by Schmidt-Kassow and Kotz (2009a,b) and Rothermich et al. (2010, 2012). This shows that the brain builds up certain rhythmic expectations along the PRA and is thus able to detect deviations like clash and lapse even in contexts that do not contain strong cues about the rhythmic structure of the incoming speech signal.

4.2. Positivity effects

In most comparisons we observed not only negativities but biphasic ERP patterns. Concerning positivity effects, we observed differences between the two deviation types, as the amplitude of the positivity is very pronounced for LAPSE but reduced for CLASH. Related studies (cf. Knaus et al., 2007; Domahs et al., 2008) assume that a late positive component is a member of the P300 family reflecting the detection and evaluation of the metrical violations in comparison with the correct control conditions. Hence, the component found here is interpreted to reflect the evaluation process which is related to the task requirements. Recall that the participants were asked to evaluate the naturalness of the sentences heard. As stated earlier, this task setting which directed the participants' attention consciously to the rhythmic and metrical features of the sentences heard was responsible for the occurrence of late positive components. This is important, given that related previous studies showed that the reflection of irregularities in rhythm and meter in form of late positive components are only detectable and assessable if the focus lies on the metrical structure (e.g., Knaus et al., 2007; Magne et al., 2007; Schmidt-Kassow & Kotz, 2009b; Rothermich et al., 2010, 2012; Marie et al., 2011). Thus, the positivities elicited here by using a rather explicit task would probably not occur with an implicit task as the late positive components reflect processes related with the evaluation of stimuli. Support for the task-relatedness of this component comes from various studies which interpret the late positive component as a reflection of task-specificity and task-sensitivity (cf. Picton, 1992; Coulson, King, & Kutas, 1998; Knaus et al., 2007; Magne et al., 2007; Domahs et al., 2008, 2009; Domahs, Genc, Knaus, Wiese, & Kabak, 2012; Schmidt-Kassow & Kotz, 2009a,b; Marie et al., 2011). However, although the component seems to be related to the explicit evaluation task, the asymmetrical amplitude patterns of the two critical conditions suggest that the effect found here does not, as in the studies reported earlier, show the comparison of the incorrect stimulus with the built-up expectation. If the positivity purely reflected the detection of a mismatch, both deviant conditions should show more pronounced amplitudes. Therefore, this interpretation cannot explain the present results. The effect rather reflects the degree of complexity and difficulty, i.e., the resolvability of the given task: The easier the evaluation, the stronger the positivity effect. Since LAPSE includes rhythmical and lexical violations, its structure deviates even stronger from expectancy than CLASH, which includes solely a rhythmic deviation. Hence, the sentences including two violations seem to be easier to evaluate as unnatural while the rhythmic deviation in the CLASH sentences seems to be harder to detect and thus to categorize. In comparison with stress clash structures, rhythmically regular structures are therefore easier to evaluate as correct. The particular difficulty of stress clash structures might arise from the fact that the verbs contain a correct lexical stress pattern, but violate the demands of a regular rhythmic structure. Therefore, it may be the case that sentences containing stress clashes are not directly and consciously recognized as deviations. The difficulty to judge sentences including CLASH may lead to higher processing costs, i.e., sentences are retained longer in the auditory working memory for inspection and evaluation as natural or unnatural. Such an explanation is supported by the component's position in the fronto-central area, where auditory working memory is supposed to be located (e.g., Kaiser & Lutzenberger, 2004; Eulitz & Obleser, 2007). However, the connection between a pronounced effect in the fronto-central area measured by an EEG and working memory regions is very speculative, since the spatial resolution of ERPs is poor. Therefore, this locality hypothesis needs to be further tested with a method that offers higher spatial resolution, for example fMRI.

The results of the reaction time study complement the interpretation of decelerated evaluation: The comparison of CLASH and SHIFT showed that significantly more time was needed for the evaluation of sentences including a stress clash, whereas no significant reaction time difference was found for LAPSE and its control condition NO SHIFT. Moreover, the behavioral data revealed that only LAPSE was judged as unnatural. The behavioral data support the idea that the deviations in CLASH are perceived more unconsciously and are therefore harder to detect. Additional support for our interpretation of the reduced positivity found for CLASH comes from a study by Domahs et al. (2009). In this study, the comparison of existing words with well-formed pseudo-words and phonotactically deviant non-words showed clearly that correct evaluation of existing as well as non-words is easier and hence faster than the evaluation of well-formed pseudo-words, as these pseudo-words can neither be rejected as easily as non-words, nor be accepted as correct like existing words. The amplitude of the positive component for this word type was also less pronounced in comparison to the amplitudes of the other two word types.

A recent study on the processing of Turkish word stress (Domahs et al., 2012) illustrates the relation between task resolvability and the occurrence of a late positive component, as well: Words with violations of the default pattern elicited strong positivity effects while no pronounced positivity could be found for words incorrectly stressed with the default pattern. Turkish participants had difficulties to judge the default as incorrect. This process is reflected by a largely reduced positive curve progression. Further, in a study by Schwartze, Rothermich, Schmidt-Kassow, and Kotz (2011), smaller P3b effects were elicited for deviations in temporally irregular structures, whereas the embedding of deviant tones in an isochronous structure led to a more pronounced positivity effect. The authors interpreted the stronger amplitude as a reflection of facilitated processing due to facilitation of the given task via temporal regularity. Hence, also these results endorse our interpretation of the late positive component reflecting the degree of task-resolvability. Note that while a pronounced amplitude for this late positive component reflects processing facilitation, the opposite is true for the negativities reported in this study, where larger amplitudes reflect enhanced processing costs. Thus, amplitude strength cannot be interpreted consistently as a reflection of processing costs (cf. Domahs et al., 2009, 2012; Rothermich et al., 2012).

The late positive components reflect the characteristic features of the P3b component found in previous related studies (e.g., Knaus et al., 2007; Magne et al., 2007; Domahs et al., 2008, 2009, 2012; Schwartze et al., 2011). Interestingly, all these effects labeled as a "P300" developed in time windows with an onset at around 500 or 800 ms (Magne et al., 2007), 500–1100 ms (Knaus et al., 2007), and 500–900 ms (Domahs et al., 2008), i.e., these effects show similar latencies as the positive components in the present study. The variability of latency of the P300 across studies can be explained by the nature of the stimuli used: In the processing of auditory stimuli, the effect's latency depends on the acoustic signal and the position of the stressed syllable in the speech signal. For instance, Domahs et al. (2008) observed that the evaluation positivity was time-locked with the occurrence of stressed syllables, i.e., stress shifts from final to initial syllables (e.g., *ˈVitamin instead of Vitaˈmin) elicit an earlier positivity effect than shifts from initial to final syllables (e.g., *Anaˈnas, ˈAnanas) (Domahs et al., 2008). This is line with the latency onsets of the positivity effects in the present study: The reduced late positive component found for CLASH structures has an earlier occurrence than the enhanced positive component found for LAPSE whose onset is 200 ms later.

The amplitude differences of CLASH and LAPSE as well as the behavioral data and the reaction time data show that unlicensed stress shifts are less acceptable than stress clashes, since they not only disrupt rhythmic alternation but also complicate lexical retrieval due to the violated lexical stress pattern. This is reflected by the N400 effect found for LAPSE. This violation enhances the evaluation of lapses as unnatural, shown by a pronounced following positive component. On the contrary, stress clashes require more complex processing due to their structure: They maintain the lexical stress pattern, but the compliance with lexical stress rules violates the demands of a regular rhythmic structure, leading to an early negativity effect and a reduced positivity for CLASH. Finally, the lack of ERP differences between the two control conditions NO SHIFT and SHIFT further supports the assumption that the observed effects are purely induced by metrical irregularities in the critical conditions. These results support the assumption that such effects may also be generalizable to other stress-timed languages such as English, for which even stronger rhythmical adjustments on stress positions can be observed in comparison to German (Liberman & Prince, 1977; Grabe & Warren, 1995; Vogel et al., 1995; see Section 1). Future work has to show how rhythmical regularities generally influence the production and perception of word stress.

5. Conclusion

The present results show that the phenomenon of rhythmically induced stress shifts plays an important role in the processing of German. The data confirm that rhythmic irregularities are perceived and processed differently from well-formed structures, even in natural contexts. This can be seen not only from the results for the explicit judgment of naturalness but also, and more importantly, from the detected ERP and reaction time data which reflect more implicit processes. These findings contradict the proposition that constant rhythmic patterns are a purely perceptual repair phenomenon. Our data suggest that alternating structures are indeed distinguished from rhythmically deviating structures, as our results illustrate the brain's sensitivity to even small rhythmic deviations which can be produced and perceived by Germans.

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