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Rhythm's gonna get you: Regular meter facilitates semantic sentence processing

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ABSTRACT

Rhythm is a phenomenon that fundamentally affects the perception of events unfolding in time. In language, we define 'rhythm' as the temporal structure that underlies the perception and production of utterances, whereas 'meter' is defined as the regular occurrence of beats (i.e. stressed syllables). In stress-timed languages such as German, this regularity functions as a powerful temporal and structural cue in speech comprehension. Recent evidence shows that it also interacts with higher level linguistic faculties such as syntax (Schmidt-Kassow & Kotz, 2009a). The current ERP experiment investigated the impact of metric structure on lexico-semantic processing, comparing the effects of semantic and metric expectancy in regular and irregular metric sentence contexts. We predicted that (1) semantically unexpected words would result in an increased N400 amplitude and (2) metric context modulates the N400 amplitude. Our results confirm these predictions: semantically unexpected words elicit an N400 that is significantly smaller in a metrically regular than a metrically irregular sentence context. The current findings support the idea that metric regularity enhances the prediction of stress locations in a sentence context, which in turn facilitates lexico-semantic integration.

1. Introduction

The role of rhythm in human behavior has long been subject to elaborate experimentation and theory building. This is not surprising as rhythm is a fundamental phenomenon affecting a range of behaviors such as motor, music, and language. In language, we define *rhythm* as the temporally regular or irregular structure that underlies the perception and production of utterances. Conversely, *meter* is defined as the regular occurrence of *beats* (Lehrdahl & Jackendoff, 1983). In languages such as German or English, beats may be realized as stressed syllables in a sentence (Cummins & Port, 1998; Lee & Todd, 2004; Schmidt-Kassow & Kotz, 2009a; Slowiaczek, 1990). In speech, the alternation of stressed and unstressed syllables may provide a temporal cue that allows to predict when the next stressed syllable is likely to occur ("When next?" see Large & Kolen, 1994).

In speech perception listeners focus their attention on particular points in time at which salient stressed syllables are expected to occur (e.g. Mattys, 1997), thereby allowing the listener to entrain to the speech signal (e.g. Arantes & Barbosa, 2010). This assumption is consistent with the "attentional bounce hypothesis" (Pitt & Samuel, 1990), in which attention is thought to move from one stressed syllable to the next enhancing a listener's perception of strong and weak syllables in the speech. Moreover, it is also well known that the auditory system continuously searches for regularities in the acoustic signal and, once detected, allows the listener to form predictions about upcoming events (Winkler, Denham, & Nelken, 2009). Similarly, linguistic context makes it easier for listeners to predict a likely continuation of a sentence and informs the comprehension system of incoming words (e.g. Groppe et al., 2010). We therefore consider that default metric stress patterns and characteristic accent distributions are used to form predictions about when the next stressed syllable should occur regardless of the fact that speech contains dynamic variations (i.e. pauses, intonation, and loudness) and constantly changes over time.

Such an account is in line with the rapid comprehension and the robust interpretation of ambiguous and noisy input (Pickering & Garrod, 2006). Consequently, we consider that the ongoing speech signal is not completely unpredictable but encompasses perceptual regularities that lead to facilitated information processing. It is therefore no coincidence that metric stress plays a significant role in language acquisition (Jusczyk, 1999), speech segmentation (Mattys & Samuel, 1997), lexical grouping (Dilley & McAuley, 2008), and syntactic processing (Schmidt-Kassow & Kotz, 2009a). Based on this evidence, the question arises whether regular metric structure impacts other higher order linguistic faculties such as semantics.

We address this question by using EEG and are looking more closely at the N400 component which has been associated with lexical information processing and contextual integration (for reviews, see Federmeier, 2007; Kutas & Federmeier, 2000, 2011;

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Lau, Phillips, & Poeppel, 2008). The N400 is a good index of lexico-semantic integration and can provide information about contextual factors that influence lexico-semantic information processing. Furthermore, it has been claimed that the N400 amplitude is modulated by expectancy (Lau et al., 2008), reflects the ease with which meaning is integrated into a sentence context (e.g. Boulenger, Hoen, Jacquier, & Meunier, 2011; van den Brink, Brown, & Hagoort, 2006), and is affected by the extent to which properties of incoming words are pre-activated by the contextual information available (see DeLong, Urbach, & Kutas, 2005; Federmeier, 2007).

At first glance, semantic and metric information processing may not have much in common, but both seem to rely on a form of prediction. However, in semantic processing, the orientation towards future events seems to be based on expectancy rather than prediction as it involves a restricted number of potential word candidates (DeLong et al., 2005). As for metric processing, predictions arise at a more structural, form-dependent level (Dohmas, Wiese, Bornkessel-Schlesewsky, & Schlesewsky, 2008; Magne, Gordon, & Midha, 2010; Rothermich, Schmidt-Kassow, Schwartze, & Kotz, 2010). In particular, stress-timed languages such as English or German allow predictions about the position of stressed syllables in a sentence context based on the perceived rhythmic flow of the preceding sentence context. These predictions may occur even if the distribution of stressed syllables does not include precise temporal information.

It is important to note that in the present study, regularity is not achieved through temporal regularity, i.e. having a constant stimulus onset asynchrony (see for example, Quené & Port, 2005; Schmidt-Kassow & Kotz, 2008), but by the regular distribution of stressed and unstressed syllables. We assume that this regular metric structure may provide a context that leads to prediction and facilitated processing in speech comprehension (Gow & Gordon, 1993). Consequently, lexico-semantic information should be more easily processed in a regular than an irregular metric sentence context. Based on this assumption, we directly compared the effects of metrically regular and irregular sentence context on lexico-semantic processing. We hypothesized that lexico-semantic integration of unexpected words (indexed by an N400 amplitude rise) into the sentence context is facilitated by the precedence of a metrically regular sentence context.

However, the exact nature of the N400 is still unclear: on the one hand, it is thought to reflect ease of access due to priming or pre-activation (Federmeier, 2007; Kutas & Federmeier, 2000). Conversely, it is also considered to reflect the level of integration difficulty of a word into a given sentence context (Brown & Hagoort, 1993; Hagoort, 2008; Osterhout & Holcomb, 1992). While the current study will not ultimately clarify this issue, it aims to more closely examine the nature of the N400 response by investigating a potential modulation as a function of metrically predictable (regular) and irregular sentence context.

In the N400 literature, the idea that the amplitude of the N400 is inversely proportional to the ease of contextual integration is well-established (Bentin & McCarthy, 1994; Chwilla, Brown, & Hagoort, 1995; Kutas, Van Petten, & Kluender, 2005; Rugg & Doyle, 1994). The modulation of the N400 is thought to reflect the semantic processing of a word in relation to its preceding context, whereby a larger N400 amplitude reflects an increased effort in semantic processing (Holcomb, 1993; Kutas & Federmeier, 2000; Kutas & Hillyard, 1980). Thus, the more easily a word can be integrated into a sentence context, the smaller the amplitude of the N400 should be (Kutas & Hillyard, 1984). Findings supporting the influence of a metrically regular sentence context on the N400 would extend previous research which suggests that language comprehension can be highly predictive, as long as linguistic (or non-linguistic) context supports such predictions (Pickering & Garrod, 2006).

The purpose of the present study was to examine the interaction of metric and semantic processing, and in particular, the influence of the metric structure of a sentence on lexico-semantic integration. Previously, Magne et al. (2007) investigated the interaction of meter and semantics in French and reported an N400 in response to semantically unexpected words. Furthermore, they reported a biphasic pattern consisting of a P600 and an early negativity (labeled N400) for metrically incongruous sentence-final words. The authors suggested that this early negativity reflects incorrect stress assignment during lexical access, as the encountered metric structure interferes with lexical access to word meaning. They concluded that the negativity may be considered as a part of the N400 family due to its similar latency and scalp distribution.

However, our previous findings provide an alternative account. We have shown that an early negativity in response to metrically unexpected (pseudo)words occurs independently of semantic content (Rothermich et al., 2010). Therefore, we concluded that it is unlikely that the negativity reflects interference with lexical access, but rather a general error-detection mechanism. The current investigation aims to further illuminate this issue by directly comparing the early 'metric' negativity and the N400. Based on our previous findings, we predict that the negativity in response to metrically unexpected words differs qualitatively from the 'semantic' N400.

A further question concerns the influence of the task setting on metric and semantic processing. Magne et al. (2007) reported a P600 effect only in response to metric manipulations in an explicit metric judgment task, and not in an implicit semantic judgment task. In their study, participants focused on metric aspects in one session and on semantic aspects in another session. Results are in line with data provided by Astésano, Besson, and Alter (2004). The authors presented semantically congruous and semantically incongruous sentences that differed in their pitch contour. Some of the sentences were pronounced with the pitch contour of a question even though the sentence structure indicated a declarative sentence. Similarly to Magne et al. (2007), all sentences were tested with a focus either on the prosodic contour or on the semantic congruity. When participants' attention was directed to incongruent prosodic contours, a positive component (P800) was elicited, while a focus on the semantic structure led to an even larger positivity and a N400. When the focus was on semantics, no positivity was elicited by prosodic incongruities, while semantic incongruities resulted in an N400. In summary, both experiments (Astésano et al., 2004; Magne et al., 2007) indicate that semantic processing is not affected by attentional task demands (on prosody/meter), while prosodic/metric processing seems to be attention-dependent.

The current study investigated the influence of metric predictability on the N400 component and the interaction of metric and semantic information. We predicted that (1) semantically unexpected words would elicit an increased N400 amplitude, (2) metrically unexpected words would elicit a biphasic pattern of an early negativity and a P600, (3) semantic and metric processes would be influenced by task demands, and (4) regular metric sentence context would facilitate semantic processing (i.e. reduce the N400 amplitude).

2. Methods

2.1. Subjects

Twenty healthy native speakers of German (10 females; mean age: 25) participated in the experiment. One participant did not meet the inclusion criteria as he showed very discrepant behavior. His performance was below 75% correct in more than two conditions, indicating problems understanding the task assignment. Based on his discrepant behavior we consider this participant as an outlier and have excluded him from further analysis. All subjects were right-handed as determined by the Edinburgh inventory (Oldfield, 1971). They received a small fee for participating. The experiment was approved by the Ethics Committee of the University of Leipzig.

Table 1
Experimental conditions.

Condition	Metrically regular sentence context
correct	'Norbert 'pflückte 'letzten 'Dienstag 'Ginas '**Rosen** und 'Nelken.
literal translation	*Norbert picked last Tuesday Gina's roses and carnations.*
semantic	Stefan pflückte letzten Dienstag Marens '**Rohre** und Kabel.
literal translation	*Stefan picked last Tuesday Maren's pipes and cables.*
Metric	Philipp pflückte letzten Dienstag Franzis **Ro'SEN** und Nelken.
Double	Moritz pflückte letzten Dienstag Birgits **Roh'RE** und Kabel.
Condition	**Metrically irregular sentence context**
Correct	'Pit 'pflückte 'letzten 'Nachmittag Fran'ziskas '**Rosen** und 'Nelken.
literal translation	*Pit picked last afternoon Franziskas roses and carnations.*
Semantic	Jonathan pflückte letzten Nachmittag Melanies '**Rohre** und Kabel.
literal translation	*Jonathan picked last afternoon Melanies pipes and cables.*
Metric	Tim pflückte letzten Nachmittag Annabels **Ro'SEN** und Nelken.
Double	Alfredo pflückte letzten Nachmittag Jans **Roh'RE** und Kabel.

2.2. Stimulus material

To study the relationship between metric and semantic information, we created 152 metrically regular sentences (38 per condition) consisting of bisyllabic trochaic words (stress on the first syllable) as well as 152 metrically irregular sentences with words varying in syllable number and stress pattern, resulting in a total of 304 stimuli. In the regular sentences, the metric context leading up to the target word (the second noun in a sentence, see Table 1 for examples) consisted of five bi-syllabic trochaic words. Standard German is generally accepted (e.g. Jessen, 1999) as a trochaic language, with the trochee (a metrical foot consisting of a stressed–unstressed syllable alternation) being the default stress pattern in stress-timed languages such as German or English (Eisenberg, 1991). The highly frequent trochaic meter directly influences speech processing by guiding speech segmentation (Cutler & Norris, 1988; Lee & Todd, 2004) and provides a temporal grid for speech comprehension. Although it is clearly not the case that listeners encounter sentences consisting solely of trochaic words, the trochee is a very prominent metric foot.[1] It has been shown that at four months of age, infants already prefer the typical stress structure of their native language (Friederici, Friedrich, & Christophe, 2007); in this case, the trochee in German and the iamb in French. Finally, the trochee, the default metric pattern, also leads to perceptual advantages not only in stress-timed languages but also with respect to other acoustic events, e.g. tone sequences (Abecasis, Brochard, Granot, & Drake, 2005; Smith & Cuddy, 1989).

In the present study, the stress pattern in the irregular sentences consisted of five words with one to three syllables each and with stress on the first, penultimate or ultimate syllable. Besides the preceding metric context, all target words were the same across conditions. Sentences were tested in four conditions: correct, semantic, metric and double. In the semantic condition, the expected noun was exchanged with a grammatically acceptable but semantically unexpected noun. In the metric condition, the expected trochaic stress pattern was replaced by an unexpected iambic pattern – that is an unstressed syllable followed by a stressed syllable. In the double condition, a metrically unexpected word was also semantically unexpected (see Table 1 for examples). In general, it is possible that subjects perceive metrically unexpected words as non-words. According to Raettig and Kotz (2008), non-words contain outright violations of the rules that govern the formation of multi-phoneme structures in a given language. Thus, it is not assumed that a shift in stress pattern should is perceived as an outright violation or a severe change in lexical status. Furthermore, in the present experiment, we hypothesize the exact same pattern (early negativity followed by a P600) in the metric task as seen in a previous jabberwocky experiment (Rothermich et al., 2010). This result would suggest that the ERP pattern

Table 2
Splicing procedure.

Original sentence	'Norbert 'pflückte 'letzten 'Dienstag 'Ginas '**Rosen und 'Nelken**.
	Norbert picked last Tuesday Gina's roses and carnations.
Word sequence	Do'reens **Ro'SEN und Nelken**
Spliced sentence	'Norbert 'pflückte 'letzten 'Dienstag 'Ginas **Ro'SEN und 'Nelken**.

in the current experiment does not result from the occurrence of a non-word. Finally, the metric condition in the semantic task is an adequate test case for the lexical status of the words containing stress shifts. The typical response to a non-word in an otherwise lexically legal context would be a classical N400 effect (Federmeier, Segal, Lombrozo, & Kutas, 2000). Thus, if the words in the metric condition were perceived as non-words, the N400 response should differ in metrically *unexpected* words task from the one in response to the metrically *expected* word in the semantic task.

To avoid sentence-final wrap-up effects (Frisch, 2000), the target word was the antepenultimate word. All verbs and also the preceding adverbs were matched in word frequency (according to the Leipziger Wortschatz Lexikon[2]). Sentences were spoken by a professional female speaker of German at a normal speech rate and digitally recorded with a 16-bit resolution at a sampling rate of 44,100 Hz. We instructed the speaker to avoid overemphasizing the regular stress pattern. An extensive splicing procedure was conducted to avoid co-articulation artifacts with respect to incorrectly stressed words and to familiarize the speaker with the incorrect stress pattern in the metric sentences (see examples in Table 2). We constructed phrases consisting of three words, with the first word adhering to iambic patterns to facilitate the speaker's access to unexpected metrical words. The last two words remained the same as in the original sentence. Afterwards, the two nouns were cut out of the signal and inserted into the original sentence. Note that the same procedure was performed for the correctly pronounced sentences in which the first word of the three-word phrases was trochaic. This ensured equal treatment of correct and incorrect sentences.

2.3. Procedure

Two different tasks were implemented in two sessions. In one session, participants judged the metrical correctness, and in another session they judged semantic coherence. The order of the tasks was counterbalanced across participants. Before the experiment all participants received written instructions informing them about the task and the different conditions. During the experiment, participants sat in a comfortable chair in a soundproof booth. Each sentence was introduced by a visual cue in the center of a computer screen. All 304 stimuli were presented via loudspeakers in a pseudo-randomized order. Each session was divided into four blocks of approximately 8 min. Each block contained either only metrically regular or only metrically irregular sentences. Immediately after the offset of the sentence, two smiley faces cued the participants' response. Participants were instructed to avoid eye movements during sentence presentation.

EEG was recorded from 59 Ag/AgCl electrodes mounted in an elastic cap (Electro-Cap Inc., Eaton, OH, USA). Bipolar vertical and horizontal electro-oculograms were recorded to permit eye artifact rejection. Electrode resistance was kept below 5 kΩ. The EEG recording was online referenced to the left mastoid and offline re-referenced to averaged mastoids. An anti-aliasing filter of 135 Hz was applied during recording, and the EEG signal was digitized at 500 Hz. Eye artifacts were first detected automatically, and after that all single-trial waveforms were screened for eye movements, electrode drifting, amplifier blocking and muscular artifacts. Trials affected by artifacts were excluded. Artifact-free trials were then averaged separately for each participant and condition. All ERPs were time-locked to the onset of the target word and calculated with a baseline of −100 ms to 0 ms. The whole epoch ranged from −100 to 2000 ms. Only correctly answered trials in both tasks were included for data analysis.

2.4. Statistical analysis

For all statistical analyses, the SAS 8.20.20 software package was used. After visual inspection, statistical analyses testing for the effects of semantically and metrically unexpected words were performed in different time windows. To achieve exact onset and duration of the resulting ERP effects, mean amplitudes for non-overlapping short sections over the whole epoch (triggered at the beginning of the target word) were calculated. The length of these short sections was 25 ms. Subsequent to the evaluation of these sections, larger time windows were chosen that covered an effect. Factors in the repeated measurements ANOVA, computed on the mean amplitude in these larger time windows, included the experimental factors

[1] Indeed, a corpus analysis based on the lexical database CELEX (Baayen, Piepenbrock, & van Rijn, 1993) by Féry (1998) confirmed that 73% of bisyllabic German words are trochaic.

[2] The Leipzig Wortschatz Lexikon is a corpus that is permanently updated using publicly available texts. It was developed and is maintained by the Department of Computer Science of the University of Leipzig and can be accessed at http://www.wortschatz.uni-leipzig.de.

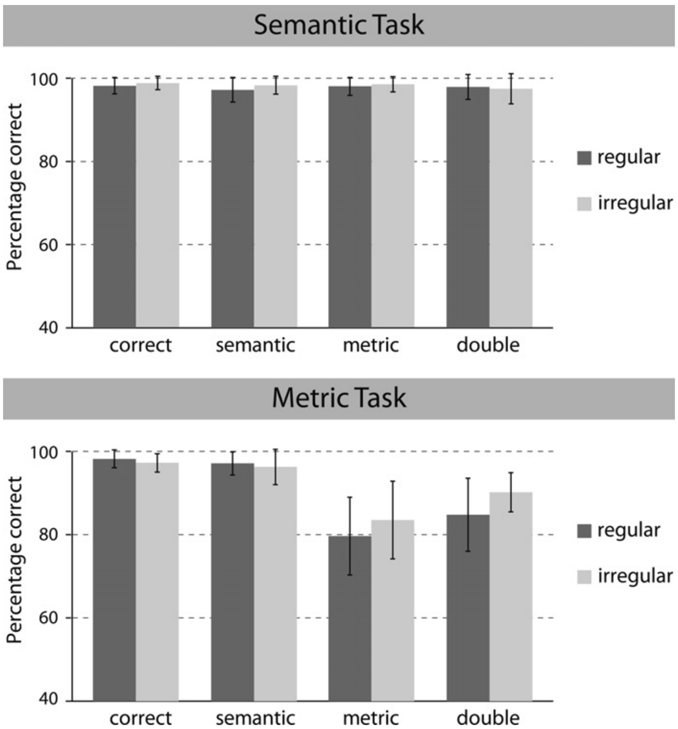

Fig. 1. Percentage correct (%) in the semantic and the metric task.

task (metric and semantic), *condition* (correct, semantic, metric and double), *context* (regular and irregular sentence context), and for EEG data only, the topographical factor *roi* (region of interest; left frontal (LF), left temporal (LT), left parietal (LP), right frontal (RF), right temporal (RT), right parietal (RP) and midline (ML)). For the ERP data, we decided to compute separate ANOVAs for each task as the time-line analysis revealed different brain responses as a function of task. Thus, it was not possible to compute one ANOVA with task as between-subject-factor. Greenhouse and Geisser (1959) correction was applied for effects with more than one degree of freedom. Additionally, to control for multiple comparisons, we adjusted the critical *p*-value in the statistical analysis of the behavioral data by means of Bonferroni correction (Keppel, 1982) wherever the number of pairwise comparisons exceeded the degrees of freedom. In these cases, the Bonferroni-corrected α-level was 0.025.

3. Results

3.1. Behavioral data

Accuracy rates were above 80%, indicating that all participants performed well in both tasks (see Fig. 1). An omnibus ANOVA revealed main effects for the factors *task* ($F(1,18) = 53.67$, $p < .0001$), *condition* ($F(3,54) = 42.27$, $p < .0001$) and *context* ($F(1,18) = 11.20$, $p < 0.01$). Significant interactions were found for *condition* × *task* ($F(3,54) = 37.99$, $p < .0001$), *condition* × *context* ($F(3,54) = 3.83$, $p < 0.05$) and *condition* × *context* × *task* ($F(3,54) = 7.78$, $p < 0.001$). Resolving the interactions by *task* revealed significant effects in the *metric task* for *condition* ($F(3,54) = 45.12$, $p < .0001$) and *context* ($F(1,18) = 7.62$, $p < 0.05$) and an interaction *condition* × *context* ($F(3,54,) = 6.91$, $p < 0.01$). Resolving the latter interaction by *context* revealed significant differences in the metrically regular sentences between the metric (79.63%) and the correct (98.19%) conditions ($F(1,18) = 74.30$, $p < .0001$), the correct and the double (84.76%) condition ($F(1,18) = 35.40$, $p < .0001$), between the semantic (97.09%) and the metric condition ($F(1,18) = 73.58$, $p < .0001$), between the semantic and the double condition ($F(1,18) = 36.41$, $p < .0001$), and between the metric and the double condition ($F(1,18) = 8.83$, $p < 0.01$). Planned comparisons between conditions in the irregular metric context revealed significant differences between the metric (83.51%) and the correct (97.22%) conditions ($F(1,18) = 41.24$, $p < .0001$), the correct and the double (90.16%) condition ($F(1,18) = 37.28$, $p < .001$), between the semantic (96.26%) and the metric conditions ($F(1,18) = 28.79$, $p < .0001$), between the semantic and the double condition ($F(1,18) = 13.48$, $p < .01$), and the metric and the double condition ($F(1,18) = 11.32$, $p < .01$). Directly contrasting performance in the regular and the irregular metric contexts revealed significant differences in the metric condition ($F(1,18) = 7.09$, $p < .0.025$) and in the double condition ($F(1,18) = 10.37$, $p < .001$).

Concerning the *semantic task*, all mean percentages correct were above 97% (correct, regular: 98.19%; semantic, regular: 97.22%; metric, regular: 98.06%; double, regular: 97.92%; correct, irregular: 98.75%; semantic, irregular: 98.19%; metric, irregular: 98.47%; double, irregular: 97.36%). Resolving the overall interaction *condition* × *context* × *task* ($F(3,54) = 7.78$, $p < 0.0001$) revealed no further significant main effects or interactions for the semantic task.

3.2. ERP results

In line with our hypotheses, we report a negativity for semantically unexpected words and a biphasic pattern of an early negativity and a late positivity for metrically unexpected words varying as a function of task setting.

N400 time window (400–750 ms), semantic task (see Figs. 2 and 3): An omnibus ANOVA with the within-subject-factors *condition*, *context* and *roi* yielded a main effect of condition ($F(3,54) = 39.54$, $p < 0.0001$), but no other main effects (all $p > 0.05$). Furthermore, we found a tendency towards an interaction between *condition*, *roi* and *context* ($F(18,324) = 2.26$, $p = 0.0620$). Planned comparisons between the correct condition and each of the incorrect conditions revealed a significant effect for the semantically unexpected word ($F(1,18) = 73.72$, $p < 0.0001$) and the double ($F(1,18) = 60.69$, $p < 0.0001$) condition.

N400 time window (400–750 ms), difference between the metrically regular/irregular, semantic task (see Fig. 4): As it was of special interest whether ERP responses differed in the regular and the irregular sentence contexts and visual inspection suggested such a difference at frontal electrode-sites, a hypothesis-driven analysis of the data was carried out. To assess such N400 difference as a function of metrically regular or irregular sentence context, we computed difference waves of the correct and the semantically incorrect condition and of the correct and the doubly incorrect condition in both metric sentence contexts. Furthermore, as differences between metrically regular and irregular contexts were mostly visible over frontal electrodes, we quantified the following rois: MF (mid-frontal), LF (left-frontal) and RF (right-frontal). There was a significant effect when we compared the N400 effect in metrically regular vs. metric irregular contexts ($F(1,18) = 5.71$, $p < 0.05$). The N400 response to semantically unexpected words was significantly smaller in the metrically regular (μv: −1.54) than the metrically irregular sentence context (μv: −2.73). As for the double violation condition, the analysis revealed a significant effect for the factor *context* ($F(1,18) = 5.00$, $p < 0.05$), indicating a smaller overall N400 in metrically regular (μv: −1.02) than metrically irregular contexts (μv: −2.36). There was no interaction with the factor *roi*. As visual inspection also revealed an onset difference in the N400 latency we included latency as an indicator for facilitation. Results show that the response to semantically unexpected words in the metrically regular context occurs around 50 ms earlier that the response in the metrically irregular context (600 ms vs. 654 ms; ($F(1,18) = 4.84$, $p < 0.05$)). Again, there was no interaction with the factor *roi*.

N400 time window (400–750 ms), metric task: No negativity was evoked by this manipulation.

N400 (400–750 ms) vs. metric negativity (380–480 ms), peak latency and topographical distribution, semantically vs. metrically unexpected words across tasks (see Fig. 5): To assess possible

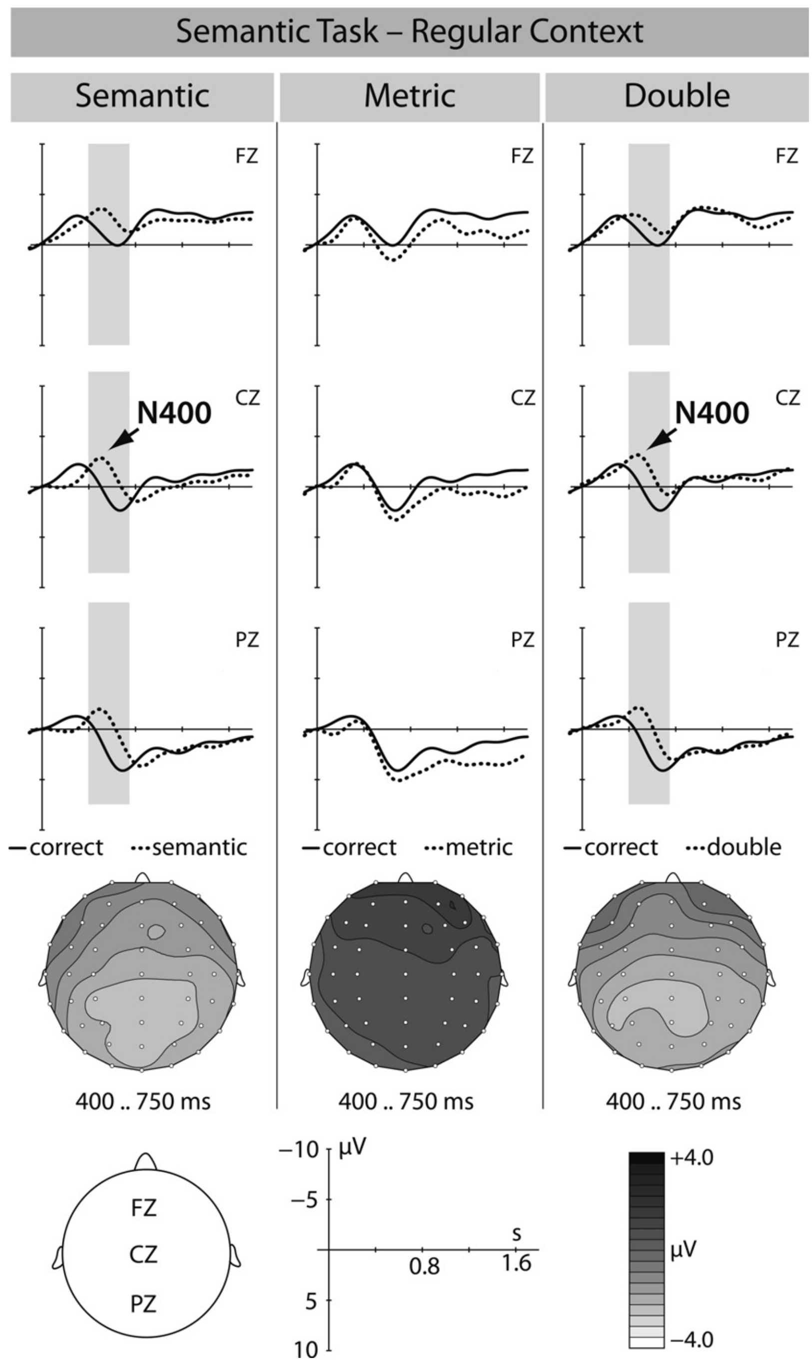

Fig. 2. ERPs for the semantic task, regular context. Waveforms from a subset of electrodes show the average for the correct (solid) and unexpected (dotted) conditions from 100 ms prior to the critical item up to 1800 ms. Gray bars indicate statistically significant time windows. Additionally, difference maps across 59 electrodes are displayed for these time windows.

differences between the N400 effect and the early metric negativity, we computed difference waves of the semantically correct and the incorrect conditions and of the correct and the metrically incorrect conditions in the semantic task (N400) and the metric task (metric negativity). The negativity evoked by metrically unexpected words peaked significantly earlier (382 ms) than in response to semantically unexpected words (462 ms; $F(1,18) = 24.18$, $p < .0001$). Also, both effects differed significantly in topography. An ANOVA with the factors *task* (metric negativity and N400) and *roi* (left frontal (LF), left temporal (LT), left parietal (LP), right frontal (RF), right temporal (RT), right parietal (RP) and midline (ML)) revealed a tendency towards an interaction of *task by roi* ($F(6,108) = 2.80$, $p < 0.07$). The resolution of this interaction showed that the factor *task* reached significance in the *rois* LP ($F(1,18) = 6.28$, $p < 0.05$) and RP ($F(1,18) = 5.37$, $p < 0.05$).

Early negativity time window (380–480 ms), metric task (see Figs. 6 and 7): An omnibus ANOVA revealed a main effect of *condition* ($F(3,54) = 2.96$, $p < 0.05$), but no interaction of the factors *condition*, *context* and *roi*. Planned step-down comparisons revealed significant differences between the correct condition and the double condition ($F(1,18) = 6.99$, $p < 0.05$).

Early negativity time window (380–480 ms), semantic task: No negativity was evoked by this manipulation.

P600 time window (500–1200 ms), metric task (see Figs. 6 and 7): The analysis resulted in a main effect of *condition* ($F(3,54) = 19.37$,

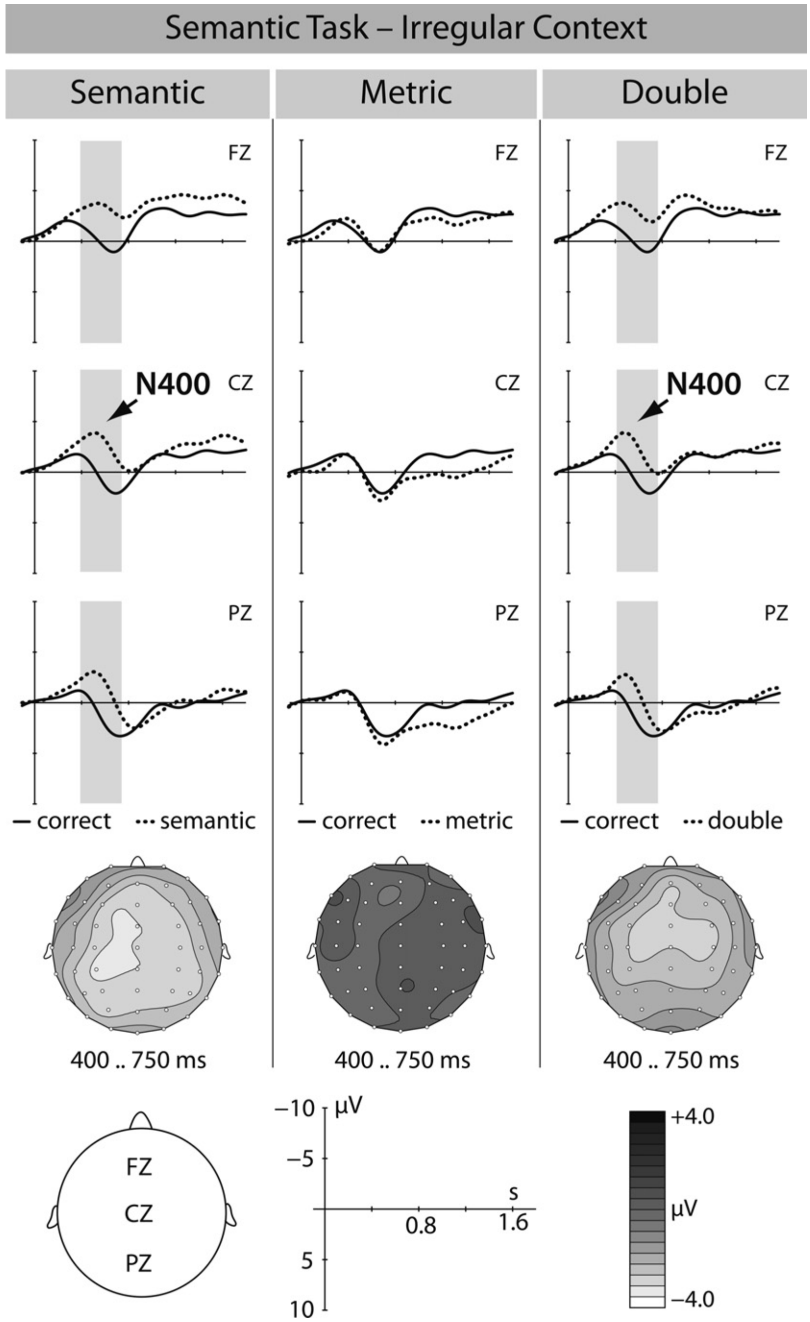

Fig. 3. ERPs for the semantic task, irregular context. Waveforms from a subset of electrodes show the average for the correct (solid) and unexpected (dotted) conditions from 100 ms prior to the critical item up to 1800 ms. Gray bars indicate statistically significant time windows. Additionally, difference maps across 59 electrodes are displayed for these time windows.

$p < 0001$). Planned comparisons showed significant differences between the correct and the metric condition ($F(1,518) = 23.82$, $p < 0.01$) and the correct and the double condition ($F(1,18) = 9.61$, $p < 0.01$). Moreover, the analysis revealed an interaction of the factors *condition* and *roi* ($F(18,324) = 14.79$, $p < .0001$). Resolving the interaction by the factor *roi* led to significant effects of condition in four of the seven rois (LP: $F(3,54) = 32.38$, $p < .0001$; LT: $F(3,54) = 7.59$, $p < 0.01$; ML: $F(3,54) = 30.44$, $p < .0001$; RP: $F(3,54) = 44.27$, $p < .0001$; RT: $F(3,54) = 17.31$, $p < .0001$). Planned comparisons in each roi showed significant differences between the correct and the metric condition (LP: $F(1,18) = 40.33$, $p < .0001$; LT: $F(1,18) = 10.93$, $p < .0001$; ML: $F(1,18) = 45.07$, $p < .0001$; RP: $F(1,18) = 51.05$, $p < .0001$; RT: $F(1,18) = 17.62$, $p < .001$) and the correct and the double condition (LP: $F(1,18) = 28.06$, $p < .0001$; ML: $F(1,18) = 28.28$, $p < .0001$; RP: $F(1,18) = 24.87$, $p < .0001$; RT: $F(1,18) = 7.92$, $p < .05$).

P600 time window (500–1200 ms), difference between metric regular/irregular, metric task: Although a reduced P600 effect for regular sentence contexts compared to irregular sentence context was visible in the metric condition, the statistics (assessment analog to the N400) did not reveal significant differences ($p > 0.05$).

P600 time window (500–1200 ms), semantic task: No positivity was evoked in this task setting.

4. Discussion

Auditory language comprehension involves a series of processes including the structuring of the incoming speech stream

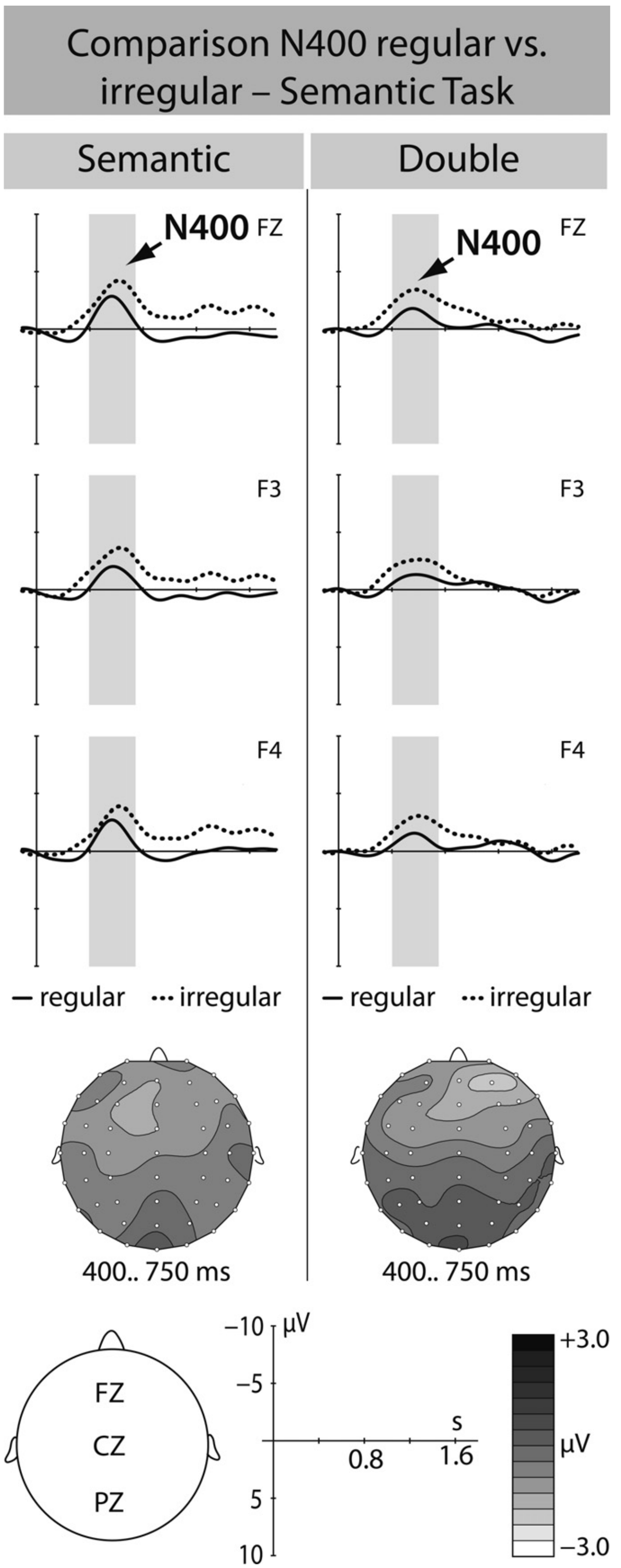

Fig. 4. ERPs for the semantic task, comparison of the N400 in the regular and irregular context. Waveforms from a subset of electrodes show the difference waves between the correct and the semantic condition for the regular (solid) and irregular (dotted) context from 100 ms prior to the critical item up to 1800 ms. Gray bars indicate statistically significant time windows. Additionally, difference maps across 59 electrodes are displayed for these time windows.

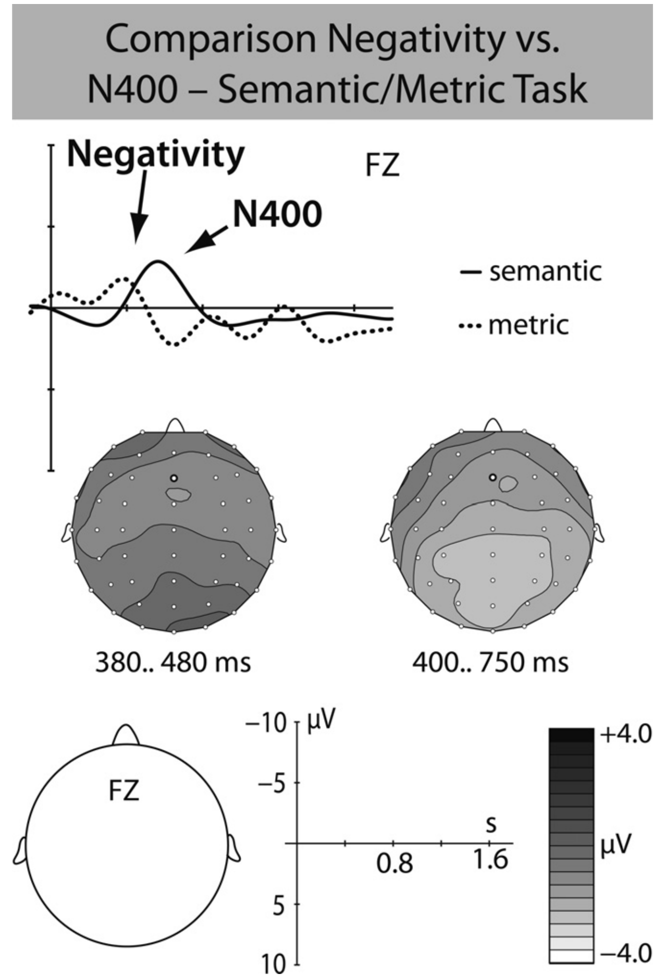

Fig. 5. ERPs for the semantic and the metric task, comparison of the N400 and the negativity. Waveforms from a subset of electrodes show the difference wave between the correct and semantically/metrically unexpected condition for the semantic (solid) and metric (dotted) task from 100 ms prior to the critical item up to 1800 ms. Gray bars indicate statistically significant time windows. Additionally, difference maps across 59 electrodes are displayed for these time windows.

and the accessing of lexico-semantic meaning. A critical issue in language processing is how listeners use information to predict events in the upcoming speech stream and to utilize predictive cues to facilitate language comprehension. The current experiment applied ERPs to investigate the impact of regular meter on language processing, comparing the effects of semantically and metrically unexpected words in regular and irregular rhythmic sentence context.

Behavioral results reveal accuracy rates in the both tasks above 80% on average, indicating that participants performed well. However, participants made more errors in all conditions of the metric task. This is a consistent finding in studies in which participants have to judge metric/rhythmic homogeneity (see for example Geiser, Zaehle, Jancke, & Meyer, 2008; Schmidt-Kassow & Kotz, 2009a; Zhao et al., 2008). It seems that metric inconsistencies are more subtle and thus harder to detect, whereas semantic inconsistencies appear to be more salient. This is likely due to the fact that meter is a more abstract, intrinsic concept than semantics, and participants may not explicitly notice the metric structure of sentences.

We initially expected a facilitation effect of metric regularity in both the behavioral *and* the ERP data based on previous behavioral work (e.g. Gow & Gordon, 1993; Pitt & Samuel, 1990) and ERP patient results (e.g. Kotz, Gunter, & Wonneberger, 2005). However,

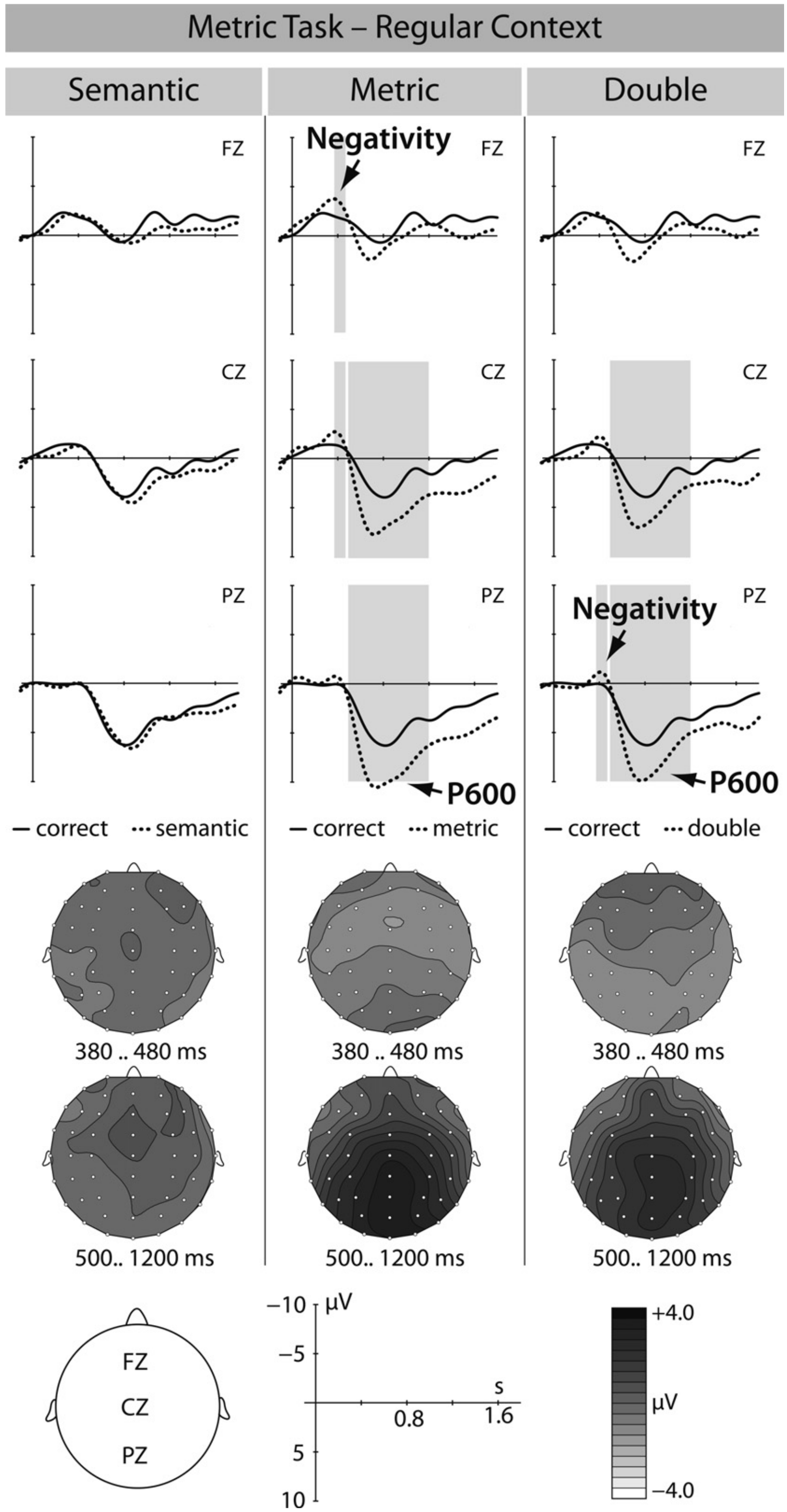

Fig. 6. ERPs for the metric task, regular context. Waveforms from a subset of electrodes show the average for the correct (solid) and unexpected (dotted) conditions from 100 ms prior to the critical item up to 1800 ms. Gray bars indicate statistically significant time windows. Additionally, difference maps across 59 electrodes are displayed for these time windows.

we did not find a significant effect or regularity in the behavioral data in the semantic task. Conversely, we find a significant difference in performance in the *metric* task between the regular and irregular sentence contexts in the metric and the double violation conditions. Subjects performed slightly worse in the regular conditions compared to the irregular condition. Since we do not find a significant effect of metric regularity in the metric task in the ERP results, it is difficult to interpret the effect of regularity in the metric task overall. Future studies with additional measurements (e.g. reaction times and fMRI) should clarify this issue.

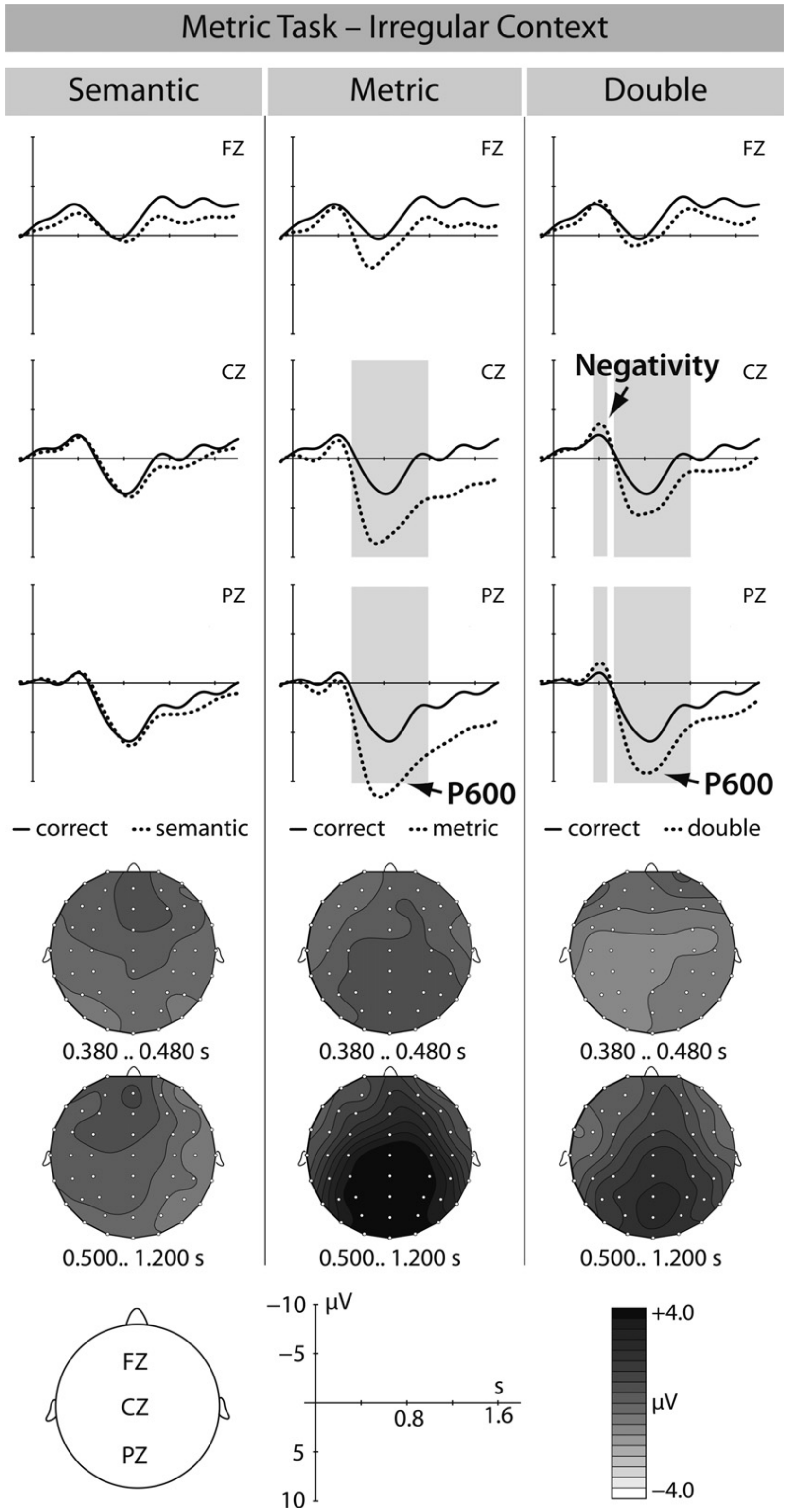

Fig. 7. ERPs for the metric task, irregular context. Waveforms from a subset of electrodes show the average for the correct (solid) and unexpected (dotted) conditions from 100 ms prior to the critical item up to 1800 ms. Gray bars indicate statistically significant time windows. Additionally, difference maps across 59 electrodes are displayed for these time windows.

In general, previous research has shown that the N400 may be a more sensitive index of semantic activation than lexical decision times. This may be due to the high temporal resolution of electrophysiological measures, which are not confounded by response selection, preparation, and executions (e.g. Heil, Rolke, & Pecchinend, 2004; Kuper & Heil, 2009). Thus, ERP indices seem to reveal information about the impact of metric regularity on semantic processing while behavioral measures may not provide such clear-cut effects. Nevertheless, we found an influence of metric context on semantic integration in the ERP data. This shows that ERPs are a useful method to identify even subtle brain responses that may not be observable in behavioral measures (Kotz, 2009).

Furthermore, the current results do not reveal a disadvantage for *metrically* unexpected words in a *semantic* task, which is in contrast to findings of Magne et al. (2007), who showed that semantically congruous but metrically incongruous words produced the highest error rates in a semantic task. Thus, participants often (mistakenly) judged the metrically incongruous words as semantically incongruous even when they were attending to semantics. They concluded that metric incongruities disrupt semantic processing. This seems to not be the case in the present results. While metric context influenced semantic integration in the ERPs, there seems to be no influence in behavioral data.

One plausible explanation for the differences between these studies is the target language; German in the current and French in the former study. It is important to note that the stress systems in French and German differ as French follows a fixed accent pattern. In French stress *always* falls on the ultimate syllable making it inherently metrically regular. Secondly, in Magne et al.'s (2007) study, metric inconsistencies were induced by lengthening the antepenultimate syllable. This pattern never occurs in French, thus making it a very prominent deviation in contrast to German, which carries first and second syllable stress. A more severe metric inconsistency may thus have impacted semantic processing in French, but not in German. Thirdly, the effect of metric regularity may play a lesser role in semantic integration than in for example, segmentation, where the distribution of strong syllables is known to play an important role (e.g. Cutler & Norris, 1988; Mattys & Samuel, 1997). However, this speculation needs to be further tested by comparing different task settings.

The ERP results show that semantically unexpected words elicit an N400 whereas metrically unexpected words elicit a biphasic pattern consisting of an early negativity and a P600. Thus, distinct, process-specific ERP components are attributed to semantic and metric processing, respectively. Since we see the exact same pattern in the metric task as in a previous jabberwocky experiment (early negativity and P600), we assume that the ERP pattern in the current experiment does not result from the occurrence of a potential non-word. Furthermore, when participants were confronted with metrically unexpected words in the semantic task, they do not show a significant ERP response. In other words, even if they focus on the lexical semantics, they do not show a typical response to a non-word in an otherwise lexically legal context, which would be a classical N400 response (Federmeier et al., 2000). In the present experiment, only semantic violations expectancy violations elicit an N400 response. Lastly, stress-shifts such as the ones used in the current experiment do occur in German in different dialectal variants. Needless to say that speakers of different dialects still recognize the word as a word, especially when provided with semantic and situational context. However, we cannot completely rule out the possibility that metrically unexpected words are perceived as non-words. More experiments are needed to clarify how changes in lexical stress are perceived.

Our results are in line with previous findings (Magne et al., 2007), which also show distinct ERP responses to metrically (P600) and semantically (N400) unexpected words. However, in the present results, both late components (N400 and P600) are only evoked when attention is directed to them (via task instructions). It seems that metric and lexico-semantic processes do not have to interact, and the attentional focus to one process may suppress the processing of the other. This is in contrast to earlier findings (e.g. Astésano et al., 2004; Magne et al., 2007), which revealed an N400 in response to semantically unexpected words under explicit *and* implicit task instructions. Both previous experiments (Astésano et al., 2004; Magne et al., 2007) arrived at the conclusion that semantic processing is not affected by an attentional focus on meter, while metric processing is overruled by semantics. This difference between the current study and previous studies may again be based on different target languages and manipulations. For example, Astésano et al. used a mismatch in intonation contours as a prosodic manipulation. This kind of prosodic inconsistency may be more salient and pragmatically relevant than stress shifts, even under implicit task instructions.

The N400 effect in response to semantically unexpected words is smaller in the metrically regular than the metrically irregular sentence context. The amplitude reduction is induced by a phonological phenomenon and shows most prominently at frontal electrode-sites. There are some reports on the nature of frontal N400 effects (Caldara, Jermann, Arango, & Van der Linden, 2004; Holcomb & Mcpherson, 1994), mostly in pitch-based paradigms (Besson, Schön, Schirmer, & Penney, 2004). In general, it seems that the regular distribution of stressed and unstressed syllables may induce a form of metric priming and therefore facilitates lexico-semantic integration. In line with Pitt and Samuel (1990), we suggest that the speech perception system works on the basis of "islands of reliability", consisting of stressed syllables, which lead to processing advantages in predictive contexts.

According to recent reviews on the N400, the *amplitude* of the N400 response is susceptible to predictive manipulations (becoming smaller when information is more expected and thus easier to process, see Kutas & Federmeier, 2011) and is inversely proportional to the goodness of fit between the sentence frame and a target word (Federmeier, 2007; Lau et al., 2008). Furthermore, the latency of ERP components may inform us about facilitated processing. In the present study the response to semantically unexpected words in a metrically regular context occurs around 50 ms earlier than the response in the metrically irregular context. This latency shift is in line with earlier studies showing that cooperating contexts significantly speed up ERP responses (Arnal, Morillon, Kell, & Giraud, 2009; Deacon, Metha, Tinsley, & Nousak, 1995). Additionally, a study focusing on multisensory integration and semantic congruency showed that earlier latencies of the N400 can be attributed to facilitated processing (i.e. Liu, Wu, Wang, & Ji, 2011). Similarly, earlier N400 peak latencies are found for more intelligible compared to noisy speech (Obleser & Kotz, 2011), whereas an acoustically degraded context leads to longer latencies for the N400 component in response to semantically incongruent items (Aydelott, Dick, & Mills, 2006; Holcomb, 1993). Altogether, we consider our results to fit this interpretation of the N400 component: the regular stress pattern allows listeners to entrain to the speech signal and to predict the location of stressed syllables. This leads to faster lexical access and integration and, in turn, decreases the N400 amplitude and reduced the latency onset of the N400.

The current finding also extends behavioral evidence. Gow and Gordon (1993) showed that word-initial stressed syllables facilitate the identification of words in continuous speech comprehension. In a study by Pitt and Samuel (1990), participants performed a phoneme monitoring task, in which the target phoneme occurred in a syllable that was either stressed or unstressed dependent on the context preceding the target word. The results suggest that attention may be preferentially allocated to stressed syllables and lexical stress can be used to improve speech comprehension. Furthermore, it has been shown that regular auditory rhythms can orient attention towards a particular point in time (Jones, Moynihan, MacKenzie, & Puente, 2002). Also, it seems likely that listeners pay more attention to the points in time at which stressed syllables are expected to occur (Quené & Port, 2005). Indeed, recent evidence shows that the brain detects even small deviations from an established metric structure, which supports the idea that listeners perceive regularities in speech comprehension that are guided by regularly distributed stressed syllables (Schmidt-Kassow & Kotz, 2009b). We further assume that the representation of stressed and unstressed syllables consists of a hierarchical organization with regular patterns known as feet (e.g. Selkirk, 1980). These regular patterns do not have to include precise temporal information (i.e. a constant synchronous onset asynchrony, or a strict periodically isochronous pattern) but still entail regularities that might be used during speech comprehension. Thus, even though speech does not support exact temporal predictions, information about temporal structure may be used to align memory representations with a point in time at which an event is maximally salient (i.e. the nucleus of a stressed vowel) to optimize speech processing (Kotz & Schwartze, 2010). By implicitly employing metric cues and expectancies in sentence processing, the listener may use a predictive strategy that leads to more efficient speech comprehension (Kutas & Federmeier, 2000). Consequently, by making perceptual events (i.e. words) in speech predictable via acoustic cues, information processing of successively following events in a sentence is facilitated (Kotz, Schwartze, & Schmidt-Kassow, 2009). This ease of processing would be manifested as a reduction in N400 amplitude due to expectancy-induced priming and a possible entrainment of the listener with the speech signal. Alternatively, if one assumes that the N400 reflects the detection of an unexpected word during sentence processing, the regular context should boost such detection (i.e. making it more salient), leading to a larger N400 effect. This is clearly a very important point, especially when we look at other ERP components such as the P3b, an ERP component usually evoked in oddball-paradigms. Here *larger* amplitudes *are* attributed to facilitated processing (i.e. a larger P3b response to deviants in isochronous compared to a random tone sequences, see e.g. Schwartze, Rothermich, Schmidt-Kassow, & Kotz, 2011). However, our current understanding of the N400 seems to point to the first interpretation, namely, that the regular succession of stressed and unstressed syllables should lessen the cost of lexico-semantic integration.

Nevertheless, we consider that metric regularity does not play a dominant role in everyday speech, but becomes highly relevant in a number of circumstances such as in noisy speech, in hearing-impaired listeners, during language acquisition, in memory formation, in the poetic arts and advertisements, in which metric regularity is used as a rhetoric measure (admittedly additionally through pauses, loudness, etc.). In most of these cases, metric regularity facilitates or compensates for factors disrupting speech comprehension, speech production, music performance, or motor control. Stutterers speak fluently to a metronome (i.e. Brady, 1969), basal ganglia patients profit from regular meter in syntactic integration (Kotz et al., 2005; Schmidt-Kassow, 2007), and walking behavior in individuals with Parkinson's disease is improved by sensory predictable cues (i.e., McIntosh, Brown, Rice, & Thaut, 1997). We believe that all these phenomena point to the critical impact of regularity in a number of domains: Regularity leads to prediction, and prediction impacts the ease of information processing.

As for the interpretation of the N400 results, the present data do not clearly favor the integration or the lexical access hypothesis, since we cannot distinguish both processing steps. We suggest that access and integration may be subsumed in the N400 component. This is in line with the hybrid hypotheses arguing that the N400 actually reflects a summation of several narrower lexical and post-lexical component processes (Pylkkänen & Marantz, 2003; van den Brink, Brown, & Hagoort, 2001). This account would explain why it has been difficult to link a single processing step to the N400.

In addition, we report a metric negativity in an earlier time window that differs from the classical N400 in topographical distribution and latency; the metric negativity peaks earlier and has a more anterior distribution than the N400 effect. We found a similar negativity in an earlier study in which we embedded stress shifts in metrically regular jabberwocky sentences, showing that this negativity occurs independently of lexico-semantic content (Rothermich et al., 2010). In the study by Magne et al. (2007), a comparable negativity was found in response to metrically unexpected words in the metric task and was interpreted as structurally, acoustic-phonological phenomenon. This fits our earlier findings which suggest that the metrically induced negativity is not directly linked to lexical access or semantic integration, even in an overall semantic context like in the present experiment. Given that similar negativities in latency and topography have been found in other domains (e.g. musical chord processing, mathematical operations and non-linguistic sequence processing), we propose that the 'metric' negativity is not language-specific, but rather, reflects a general error-detection mechanism. The current result extends previous findings on the rule-based nature of this negativity (Schmidt-Kassow & Kotz, 2009a). Speech processing cannot be studied in isolation – there are several cognitive mechanisms that underlie and influence it, for example, working memory, attention or timing. More specifically, speech processing is tightly coupled with temporal processing (Kotz & Schwartze, 2010). Here, the role of meter is especially interesting as meter relates to sequencing and timing. In speech perception, temporal structure complements formal predictions about upcoming events in a sequence (Kotz et al., 2009). Thus, we believe that the current experiment provides insight into the role of predictable cues (such as regular meter) in speech processing.

Taken together, our data imply that while semantically and metrically unexpected words elicit different ERP components, metric structure affects lexico-semantic integration. The latter result confirms the idea that regular metric patterns facilitate information processing. The current data provide new evidence in ongoing attempts to verify that word stress has an impact on lexico-semantic processes. In the light of the present result, we suggest that stress information is important for lexico-semantic integration and that syllables with primary stress are very important units in speech perception (Colombo, 1991).

5. Conclusion

Using ERPs recorded during metric and semantic sentence processing, we show that metric and semantic processing can be separated by means of distinct neurophysiological responses. Dependent on the attentional focus induced by the task demands, semantically unexpected words elicit N400 responses whereas metrically unexpected words elicit an early negativity followed by a P600. While these results speak for the independence of form and meaning in speech comprehension, we provide evidence of the influence of metric structure on lexico-semantic integration. It appears that speech comprises predictable cues (such as linguistic meter) that influence higher linguistic faculties such as semantic comprehension, and metrical stress seems to be available to facilitate lexico-semantic integration. Future studies should clarify what this influence is and how it extends to other languages that are not stress-timed (i.e. tone or syllable-timed languages). Another important point of consideration is the immediate effect of stress shifts on the lexical status of a word. For example, it should be interesting to explore the difference between unexpected stress patterns that are correct (for example an iambic word in a trochaic sentence) and stress shifts that create a violation (as in the present experiment). Also, it should be further addressed whether such facilitation can be employed to re-establish lexico-semantic processing in patient populations or to boost language learning.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.neuropsychologia.2011.10.025.

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