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**EVENT-RELATED POTENTIALS REFLECTING THE PROCESSING OF
PHONOLOGICAL CONSTRAINT VIOLATIONS**

Short Title: ERPs and phonological constraint violations

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Abstract

How are violations of phonological constraints processed in word comprehension? The present paper reports the results of an ERP study on a phonological constraint of German that disallows identical segments within a syllable or word (CC_iVC_i). We examined three types of monosyllabic CCVC words: (a) existing words ($\int p\epsilon k$), (b) wellformed novel words ($\int p\epsilon f$), and (c) illformed novel words ($\int p\epsilon p$) as instances of OCP violations. Wellformed and illformed novel words evoked an N400 effect in comparison to existing words. In addition, illformed words produced an enhanced late posterior positivity effect compared to wellformed novel words.

Our findings support the well-known observation that novel words evoke higher costs in lexical integration (reflected by N400 effects). Crucially, modulations of a late positive component (LPC) show that violations of phonotactic constraints influence later stages of cognitive processing even when stimuli have already been detected as non-existing. Thus, the comparison of electrophysiological effects evoked by the two types of non-existing words reveals the stages at which phonologically based structural wellformedness comes into play during word processing.

Keywords: Event-related potentials, OCP, non-word processing, phonological constraints, LPC

Introduction

Models on spoken word recognition have developed different views on the time-course of phonological, lexical, and semantic activation. Serial or modular neuro- and psycholinguistic models of spoken word comprehension (e.g. Patterson & Shewell, 1987; Ellis & Young, 1996; Cutler & Norris, 1979; Norris, McQueen, & Cutler, 2000), for instance, suggest that the acoustic and phonological analysis of words precedes lexical-semantic processing. Phoneme detection is thus assumed to be a prerequisite for the access to lexical entries and semantic information. Parallel and interactive activation models of word recognition on the other hand (e.g. Marslen-Wilson & Tyler, 1980; Marslen-Wilson, 1987; McClelland & Elman, 1986) are based on the assumption that phonological, lexical, and semantic processing are not strictly serial. In this sense, phonological processing does not have to be completed prior to word retrieval in the mental lexicon or to semantic activation, but can also be affected by lexical or semantic knowledge.

However, all models of word recognition agree that phonological processing involves the detection of phonemes and of the rhythmic structure of words. So far, the role of phonemic information for word retrieval has been in the focus of research. However, to date it remains unclear at which level of processing phonological restrictions (e.g. phonotactic rules) are active. Likewise, it is also unknown which types of electrophysiological components are correlated with violations of phonological constraints.

The present study will examine whether violations of phonological constraints evoke early (prelexical) or late (lexical or postlexical) electrophysiological components. Since event-related potentials (ERPs) provide a high temporal resolution with respect to neurophysiological processes, they are especially suited to investigate the stage at which

phonological restrictions operate.¹ If an effect induced by a phonological violation occurs prior to lexical processes, it may be assumed that words are checked according to their phonological shape before lexical look up. If the violation detection appears concurrent with lexical processes or later, this would show that phonological processing is not completed during the retrieval of lexical-semantic information.

In order to investigate the time-course of phonological processing, we performed an EEG study on violations of the so-called *Obligatory Contour Principle*, a phonological constraint banning identical elements in a string of sounds within a specified domain (Goldsmith 1976, Odden 1986, McCarthy 1988).

The Obligatory Contour Principle (OCP)

Many languages restrict the co-occurrence of homorganic or identical consonants within syllables, roots or even words. In Semitic languages like Hebrew and Arabic, for instance, the first two consonants in a tri-consonantal root must not be homorganic, i.e. roots can have shapes like *ktb* ‘write’ or *mdd* ‘stretch’, but not **kxb*, **ttb*, **bmk*, or the like (Greenberg 1950; McCarthy 1986, 1994). English and German, like many other Indo-European languages, disallow roots of the type CC_iVC_i. Thus, English has *speak*, *smell*, and *plate*, but not **speap*, **smemm*, and **plale* (Fudge, 1969; Davis, 1989, 1991). Likewise, *Speck* [ʃpɛk] ‘bacon’, *schmal* [ʃma:l] ‘narrow’, and *platt* [plat] ‘flat’ are attested in German, but **Spep* [ʃpɛp], **schmam* [ʃmam], and **plall* [plal] are not. The few exceptions to this generalization involve

¹ We are aware of the fact that strictly serial models of word recognition have been challenged by parallel or interactive accounts, and that there is some good evidence that lexical information affects prelexical processing. For instance, Cutler, Mehler, Norris, and Segui (1987) found that the lexical status of a sound string might influence the phoneme identification. However, previous ERP studies on phonologically illformed words (e.g. Holcomb & Neville, 1990; Bentin et al., 1999) showed that lexical processes are not initiated if prelexical analyses reveal a stimulus to be non-existing. Therefore, we assume that the processing of words – to some extent – can be divided into prelexical, lexical and postlexical processing steps.

coronal stops, e.g., English *state*, *stout*; German *Stadt* [ʃtat] ‘city’, *Staat* [ʃta:t] ‘state’, *stet* [ʃte:t] ‘steady’.

Phonologists attribute such restrictions to the *Obligatory Contour Principle* (OCP), a family of constraints militating against identical phonological material (Leben, 1978). One specific instance of this family relates to place of articulation: OCP-PLACE rules out sequences of dorsal consonants (**kxb*), coronal consonants (**ttb*), or labial consonants (**bmk*) in Semitic languages (e.g., Greenberg, 1950, McCarthy, 1988, 1994, Frisch, 2001);² while another instance (OCP-SEGMENT) disallows identical consonants in languages like English and German (e.g. Yip, 1988, 1998; Plag, 1998). The whole picture is somewhat more complex because both English and German do tolerate C_iVC_i roots, e.g., English *pipe*, *cake*, *noon*; German *Pepp* [pɛp] ‘liveliness’, *Mumm* [mʊm] ‘courage’ (colloquial), *nun* [nu:n] ‘now’. Thus, the ban on identical consonants crucially hinges on the existence of a preceding root-initial C. This observation constitutes a considerable challenge for phonological theory: while strings of the type CC_iVC_i are illformed, the substrings from such a string are wellformed and often existing words: compare **spiep* to German words *spie*, *piep*, or (non-existing but possible) *iep*. Here, the whole seems to be more than the sum of its parts. However, a formal and comprehensive account of this restriction is beyond the scope of this paper.

Previous psycholinguistic research suggests that the OCP is a psychologically real part of grammar: Native speakers of Arabic judge novel words violating OCP-PLACE (e.g., *tasaba*) as significantly less word-like than well-formed novel words (e.g., *tahafa*) (Frisch & Zawaydeh 2001); and native speakers of Hebrew identify illformed novel words faster than wellformed novel words (Berent et al., 1997; Berent, Shimron, & Vaknin, 2001; Berent, Everett, & Shimron, 2001). As for English, Coetzee (2003) observes that the OCP exerts a bias on the

² Notice, for the sake of completeness, that the class of coronal consonants is further subdivided into (at least) obstruents and sonorants (so that roots like *ndʿr* ‘to dedicate’ are well-formed). Uvular fricatives /χ, ʁ/, on the other hand, belong to two classes, i.e. they neither co-occur with dorsals /k, g, q/ nor with ‘gutturals’ /ħ, ʕ, h, ʔ/ (see McCarthy 1986, 1994; Frisch, Pierrehumbert & Broe 2004 for detailed descriptions).

perception of novel words with phonetically ambiguous final consonants that can either be perceived as *spape* or *spake* and *skake* or *skape*. Such words are preferentially perceived with dissimilar consonants, i.e. *spake* in the former case and *skape* in the latter.

In the present study, the implications of OCP violations for neurophysiological processes, measured either by changes of mean voltage or by latencies of ERP components, will be examined. The investigation of nonsense words that fulfill or violate the OCP is an ideal test case to elucidate at what processing steps violations of phonological constraints become apparent.

ERP studies on pseudo- and non-words

Numerous ERP studies have shown that the processing of non-existing words is typically associated with a negativity effect at about 400 ms after presentation of the critical item (Kutas & Hillyard, 1980, Kutas, Neville, & Holcomb, 1987; Holcomb 1988, 1993, Holcomb and Neville 1990; Bentin, et al. 1999). But even though the psycholinguistic studies cited in section 1 suggest that phonologically illformed novel words (or ‘non-words’) are processed differently from wellformed novel words (‘pseudo-words’), few ERP studies so far have dealt specifically with the processing of phonological violations. Interestingly, they all report that phonologically illformed non-words are already recognized as non-existing at a prelexical level of processing and thus do not initiate processes of lexical retrieval and semantic evaluation. Bentin et al.’s (1999) visual word recognition tasks, for instance, showed that French speakers process wellformed novel words (e.g. *lartuble*) and unpronounceable words (e.g. *rtgdfs*) rather differently: while the former evoke an N400 in a lexical decision task, and an N450 in a semantic task, the latter show a P300 component in both lexical decision task and semantic task. Holcomb and Neville (1990) report a similar distinction from an auditory lexical decision task with English pseudo-words and illformed non-words, the latter created by reverse presentation of existing words.

Finally, Dehaene-Lambertz, Dupoux, and Gout (2000) argue that phonotactic restrictions play a very early role in speech processing. These authors showed that the ban on non-nasal coda consonants in Japanese affects the perception of illformed words in Japanese: when confronted with sequences of the type [ebuzo – ebuzo – ebuzo – ebzo], Japanese speakers were unable to discriminate (behaviorally and in ERPs) between wellformed pseudo-words (*ebuzo*) and illformed words (*ebzo*). Specifically, their ERPs did not show the mismatch negativity effect (MNN) that was apparent in the control group of French speakers.

It is worthwhile to take a brief look at the phonological violations these studies discuss: Bentin et al's 'unpronounceable words' (*rtgdfs*) violate basic universal principles on how phonemes can be combined into wellformed syllables. Since strings like *rtgdfs* cannot be syllabified, they cannot be considered even as *potential* words and are thus rejected prior to lexical analysis.³ Holcomb and Neville's reverse forms of English words are problematic to use in an investigation of truly phonological constraints. The authors do not give a word list, but even reverse forms of simple words like 'stamps' [spmæts] or 'ladder' [r.ræɫ] involve multiple severe violations at the phonotactic level, such as [spm] onsets or initial syllabic [r], let alone violations of accent and intonation patterns. Finally, the ban on coda consonants in Japanese, while clearly a phonological constraint, is a rather absolute and automatic one in that speakers of Japanese did not even perceive the crucial consonants as appearing in syllable-final position (see also Dupoux et al. 1999).

In contrast to this, the aim of the present study is to investigate online phonological processing by means of a less automatic phonological constraint, one that can be violated by perfectly pronounceable words and that even allows for lexical exceptions. The constraint under consideration is the OCP-related ban on CC_iVC_i roots in German (henceforth called *SPEP). Notice that the illformedness of words like [ʃpɛp] does not relate to an illformed

³ In addition, these words were presented visually. We suspect a word like *rtgdfs* to be rejected already by visual inspection, i.e. independent of "phonological processing".

combination of two adjacent segments, but rather to an illformed co-occurrence of identical segments within a global structure, the morpheme according to Davis (1991). Since words violating *SPEP are phonologically illformed *and* non-existing (though with a few lexical exceptions), the potential effects of a phonotactic violation will be obtained by comparing three types of words: (a) existing words ([ʃpɛk], <Speck>), (b) wellformed novel words ([ʃpɛf]), and (c) illformed novel words ([ʃpɛp]).⁴ Note that German speakers have absolutely no problems in perceiving⁵ or pronouncing the words violating the constraint, as witnessed by the few exceptions to the constraint, which do not provide any difficulty; neither is there an observable tendency to adjust the words or non-words in question in order to avoid the violation. The constraint *SPEP can thus be classified as a non-automatic constraint, in contrast to the ban on coda consonants operative in Japanese studied by Dehaene-Lambertz, et al. (2000).

To summarize, the general question of the present investigation is: Are non-words violating *SPEP processed differently from pseudo-words obeying the constraint, and how does the effect of a phonological violation interact with processes of lexical decision in particular? Specifically: Are phonological violations recognized early (as can be inferred from the Hebrew and Japanese data referred to above) or late in comparison to lexical retrieval? Are phonological and lexical aspects of word recognition processed independently or does the early recognition of a phonotactic violation prevent lexical search from being initiated (as suggested for unpronounceable words by Bentin et al. (1999))? In other words, do we find N400 effects for neologisms in comparison to existing words, and how does a contrast between both types of neologisms surface, if the processing systems differentiates between them.

⁴ Wellformed *ʃpɛf* words are termed “pseudo-words” below; illformed *ʃpɛp* words are referred to as “non-words”. Taken together, they are called “neologisms”, in contrast to existing words.

⁵ Recall, however, Coetzee’s 2003 observation that words with synthetically manipulated ambiguous final consonants (acoustically between [p] and [k]) bias the perception of English speakers towards wellformed words.

Method

Participants

36 right-handed native speakers of German (17 women) with normal hearing participated in the experiment. Their mean age was 22 years (ranging from 19 to 29 years). Participants were paid.

Material and design

Each condition (word, pseudo-word, and non-word) was represented by 42 monosyllabic items of the form SC_1VC_2 , where S stands for a sibilant [s, ʃ], and C_1 can be a stop (e.g. *Stall* ‘barn’), a nasal (e.g. *Schmuck* ‘jewellery’), or a lateral (e.g. *Schliff* ‘grinding’). Non-words had identical C_1 and C_2 ([ʃpɛp]); existing words and pseudo-words had different C_1 and C_2 (*Speck*, [ʃpɛf]; see appendix). Note that an unambiguous decision between the three word types can only be made by perceiving information about the final C_2 . In other words, a sequence ʃCV (e.g. [ʃpɛ]) alone does not allow for the discrimination between existing words (e.g. [ʃpɛk]), pseudo-words (e.g. [ʃpɛf]) and non-words (e.g. [ʃpɛp]).

Since comparisons between both groups of neologisms are central to our study, Table 1 provides information about phonetic properties (mean fundamental frequency, mean intensity, and mean duration) as well as lexical properties (bi-, triphone frequency and neighborhood size) together with statistical comparisons between properties of pseudo- and non-words. Table 1 illustrates that, with respect to phonetic parameters, pseudo-words and non-words differ according to mean fundamental frequency. Although the small difference of 5 Hz (mean frequency of 218 vs. 223 Hz) is significant statistically, studies on perceptive phonetics revealed that the human perceptual system is not capable of discriminating between such

differences. For instance, Noteboom (1997, p. 645) reported that stimuli can be reliably discriminated when sound signals exhibit pitch differences of at least three semitones. One semitone corresponds roughly to a frequency difference of 6 per cent, i.e. 12 Hz in stimuli with a mean frequency of 220 Hz. In other words, the difference observed in our stimulus material is considerably smaller than the perceptual threshold in pitch perception. With respect to the neighborhood size, table 1 provides results indicating that our critical conditions differ in terms of type frequency of neighbors: neighbors of SPEP-words are of higher frequency than neighbors of SPEF-words. We will discuss potential effect of such a difference on ERP results in the discussion section.

//Table 1 about here//

In order to balance the number of words ($n = 42$) and neologisms ($n = 84$), another 42 existing words were presented as filler items. The set of filler items consists of (a) the three existing words which violate *SPEP: *Stadt*, *Staat*, and *stet* (presented five times each), and (b) words with $C_1 = [v, r]$ (*Schwall*, *Schreck*). The small number of illformed existing words (the items just mentioned) did not allow for their systematic inclusion in the analysis. Thus, the filler items are merely added to fulfill requirements of a balanced lexical decision task.

Each word was embedded in a carrier sentence: *Er soll nun ([ʃpɛp]) sagen*. 'He is supposed to say ([ʃpɛp])', the carrier sentence always being identical. The sentences were spoken by a female native speaker of German, recorded on a digital audio tape and digitized at 44 kHz with a 16 bit sampling rate (mono). After recording, the stimuli were cut and pasted into a single realization of the carrier sentence using a sound editor (CoolEditPro v. 1.2, ©Syntrillium Software). In order to determine the onsets of the critical items and to avoid different context inferences, a defined pause of 150 ms occurred before and after each critical

item. We consider an auditory presentation of the stimuli as essential in order to receive a real-time picture of phonological processing, i.e. one that excludes effects of visual word perception.

Procedure

Participants were comfortably seated in front of a computer screen in a dimly illuminated room. The experimental stimuli were auditorily presented via loudspeakers, and the participants had to perform a lexical decision task; i.e. they were asked to decide whether the critical word within each sentence was an existing German word. Each trial started with a fixation cross that appeared 500 ms before presentation of a test sentence. The fixation cross remained on screen throughout stimulus presentation to avoid eye blinks. The mean duration of test sentences was approximately 3 s. After the offset of each sentence, a question mark appeared on the screen for 2000 ms. Participants were instructed to press a yes- or no-button with their thumbs as soon as the question mark appeared. The assignment of fingers to the yes- and no-buttons was counterbalanced across participants. The appearance of the question mark also indicated that the participants were allowed to blink and rest their eyes. The next trial started after an inter-trial interval of 3000 ms.

The sentences were presented in four experimental blocks, each preceded by a short practice phase. Words, pseudo-words, and non-words appeared in a pseudo-randomized order. The order of the blocks was systematically varied to avoid sequence effects. The entire duration of each experimental session was approximately 20 minutes.

EEG-recording and data analysis

The EEG was recorded by means of 22 AgAgCl electrodes in the standard 10-20 system via a *Brainvision* amplifier with the C2 electrode serving as ground electrode. The reference electrode during recording was placed at the left mastoid. EEGs were re-referenced off-line to

both mastoids. To control for eye-movement artifacts, vertical eye movements were recorded by electrodes above and below the participant's left eye, and horizontal eye movements by two electrodes fixed to the outer canthus of both eyes. Electrode impedances were kept below 5 k Ω . EEGs and EOGs were recorded continuously with a digitization rate of 250 Hz and filtered off-line with a bandpass filter from 0.5 to 20 Hz.

ERPs were computed for each participant, condition, and electrode. Trials with eye movement artifacts were removed off-line from the data via semi-automatic artifact rejection device (magnitude of voltage changes higher than $\pm 40 \mu\text{V}$ within a time window of 200 ms). Averages were calculated starting at the onset of the critical word up to 1500 ms thereafter. Analyses of variance (ANOVAs; General Linear Model with repeated measures) were calculated for two subsequent time windows determined by visual inspection: (i) from 880 ms to 1150 ms for the negativity effect between neologisms and words, and (ii) from 1130 to 1380 ms for the positivity effect obtained for non-words in comparison to pseudo-words. Three factors were considered: (i) WORDTYPE (word, pseudo-word, non-word) and (ii) REGION (frontal: F3, Fz, F4; parietal: P3, Pz, P4), and (iii) TIME (t1: 880-1130 ms; t2: 1130-1380 ms).

Results

Behavioral Data

In order to avoid interference of motor activities with the ERPs, a two-second delay was introduced for reaction times (see above). For this reason, reaction times are hardly meaningful and were not analyzed. Analyses on error rates, however, were conducted. The error rates for existing words, pseudo-words, and non-words were 4%, 3%, and 1%, respectively. These low rates were mainly due to the fact that responses were given with a delay after the completion of the carrier sentence. An ANOVA revealed a main effect for the factor WORDTYPE in the subjects-analysis ($F(2, 70) = 17.018, p < .001$), but not in the items-

analysis, ($F(2, 82) = 1.823$; $p < .184$ ns). This effect results from a higher error rate for existing words than for neologisms.

ERP Data

Figures 1 and 2 depict the grand average ERPs for the three different conditions, starting at the onset of the critical word. As can be seen from Fig. 1, both pseudo-words and non-words produce a broadly distributed negative deflection in comparison to grand averages of existing words.

//figure 1 about here//

Statistical analyses (see Table 2) revealed that the expected negativity effect between existing and non-existing words did not occur during the typical N400 time-window (between 300 to 500 ms), but between 880 and 1130 ms post onset. This is due to the fact that a decision on the lexical status of the presented words must wait until the acoustic information of the final segment has been processed. Although the extended effect seems to be most pronounced in frontal regions, the post-hoc analysis of the interaction of the factors WORDTYPE and REGION did not reveal a difference between frontal and parietal electrode sites.

//Table 2 about here//

With respect to the interaction between the factors WORDTYPE and TIME, a post hoc analysis exhibit that the process active in the later time-window between 1130 to 1380 ms differs from the process involved in the earlier time-window. Whereas both types of non-words produce a negativity effect in the first time window, this is the case only for pseudo-words in the second time-window. Instead non-words produce a positivity effect in comparison to pseudo-words

and no effect in comparison to existing words (see Table 2). That this positivity effect is most pronounced in parietal regions, is shown by the post-hoc analysis of the interaction WORDTYPE x REGION. Figure 2 compares the grand averages of pseudo-words with those of non-words. The graphs indicate an enhanced parietal positivity for non-words with a maximum at 1230 ms.

//Figure 2 about here//

Discussion

The present study on the processing of existing words ([ʃpɛk]), pseudo-words ([ʃpɛf]) and non-words ([ʃpɛp]) in German revealed a biphasic ERP component, i.e. a negativity followed by a positivity effect. First, both pseudo-words and non-words elicit a negativity effect with a peak at 950 ms after the onset of the critical items. Given that our critical items have a mean duration of about 750 ms, and that lexical retrieval can only be completed successfully towards the end of a word, this negativity effect can be interpreted as an N400 component. The rather late occurrence of this effect is related to the task itself and to the modality of stimulus presentation, since the lexical status (existing word or pseudo-word) of our stimuli could not be identified until information about the final segment was encountered. For most of our pseudo- and non-words, neighbors exist that vary only with respect to the final segment (e.g. [ʃpɛk] vs. [ʃpɛf] and [ʃpɛp]). The other reason for the observed latency shift of the N400 effect is related to the presentation modality. In an auditory ERP-study using bisyllabic words and pseudo-words with a mean length of approximately 680 ms, Friedrich, Eulitz, and Lahiri (2006) reported a comparable component shifted in latency, namely a frontally distributed N400 effect for pseudo-words within a time range of 500 to 1000 ms post stimulus onset. Their finding – like ours – confirms that the expectation that an effect should occur in a

specific time-window is problematic under the premise that studies vary according to presentation modality, availability of information, and input parameters (see Friederici & Meyer, 2004). A fronto-central distribution of the N400 effect due to the modality of stimulus presentation was found in other studies as well: Holcomb and Neville (1990) reported a broader N400 distribution in auditory as compared to visual presentation, and Domalski, Smith, and Halgren (1991) as well as Friedrich, Eulitz, and Lahiri (2006) observed N400 components with the highest amplitude difference in fronto-central regions.

Taking the previous findings into consideration, the present negativity effect can be interpreted as an instance of an N400 component, supporting previous ERP results on the processing of neologisms in comparison to existing words (e.g. Kutas et al., 1980; Kutas et al., 1984; Bentin et al., 1999). In addition, visual inspection of grand averages did not reveal any effects prior to the N400 time window, supporting the claim that the processing system does not differentiate between the non-words and the other stimulus types during earlier phases of processing.

With respect to the distribution of the N400, the topographical maps in Figure 3 show a more frontal distribution of the N400 for non-words (b) than for pseudo-words (a). Although this difference is not statistically meaningful (see table 2), it predicts the subsequent posterior positivity evoked by non-words in comparison to pseudo-words. This observation leads us to the second important result of our experiment: non-words, but not pseudo-words, show an extended positive deflection at posterior electrode sites with a peak at 1230ms (see Figure 2 and Figure 3c). We interpret this late positivity effect (LPC) as resulting from the violation of the phonological constraint *SPEP. Crucially, non-words show this effect in *addition* to the N400 component, even though these words have already been detected as non-existing.

//Figure 3 about here//

How can the positivity for non-words be interpreted in terms of a functionally-oriented perspective? In the ERP literature on different cognitive processes, a positivity preceded by an N400 has been interpreted in various directions. The so called P600 has been associated with a mechanism of reanalysis or evaluation of syntactic complexity or violation in the context of sentence processing (e.g. Osterhout & Holcomb, 1992; Friederici, 1995; Friederici 2002; Frisch & Schlesewsky, 2005). Coulson, King, and Kutas (1998) report diverging results for two different morphosyntactic violations. Violations of pronominal case marking evoked a negativity followed by a late positive deflection, whereas violations of verb-agreement produced a negativity effect only. The authors suggest that the positive component increases with the saliency of a violation. A similar interpretation has been proposed by Frisch and Schlesewsky (2005), who observed graded positivity effects for different degrees of ungrammaticality in syntactic structure building. Even in other cognitive domains like verification tasks of simple multiplication problems (e.g., $3 \times 6 = 18$), related and unrelated errors (e.g., 24 and 19) induce an N400 component, while unrelated errors produce an enhanced late positive shift, which indicates that the specific status of the multiplication error plays a role even after the semantic task has been completed (Niedeggen & Rösler, 1999; Niedeggen, Rösler, & Jost, 1999). The late positive component has been interpreted here as a function of implausibility of a presented solution, since its amplitude is strongly correlated with the distance and unrelatedness of multiplication errors.

With respect to lexical decision tasks and pseudo-word processing, a positivity effect following an N400 effect was observed and classified as an instance of a P300 effect (e.g. Bentin et al., 1999; Roehm, Bornkessel-Schlesewsky, Rösler, & Schlesewsky, 2007). In these studies pseudo-words evoked a positive shift in comparison to words, an effect interpreted to reflect an anticipatory task-dependent process not related to deeper processes of lexical search. According to Bentin and colleagues (1999), latency and amplitude differences between

different tasks do not reflect different levels of processing, but rather the complexity of the process involved and the decision time needed.

With reference to these different interpretations of late positivity effects, the question now is what kind of process is reflected by the positivity observed in the present study. Although the task and material used in our experiment is quite comparable to those used in the studies reported by Bentin et al. (1999) and Roehm et al. (2007), we did not obtain a positivity effect for neologisms in comparison to existing words, but only in contrast to each other (see figure 2). This is a surprising result that should be addressed in more detail. In the lexical decision study performed by Bentin et al. (1999), effects for unpronounceable non-words and pseudo-words diverge in earlier processing steps of the phonological analysis leading to a biphasic N400 / P300 pattern only for the processing of pseudo-words. The lexical decision task reported by Roehm et al. (2007) contrasted word pairs that are either antonyms, unrelated words or consisted of one pseudo-word. Here again, pseudo-words revealed a biphasic N400 / P300 pattern, in which the N400 reflects an increase of costs in lexical retrieval and the P300 the anticipation of a certain type of targets (i.e. pseudo-words). In contrast to previous studies, we presented two types of neologisms that could not be separated by early phonological analysis or by lexical processes. A crucial difference of the present task requirements might be that the participants had only few auditory cues in order to discriminate existing words from neologisms. In most of our monosyllabic stimuli, the final segment provides the crucial information. Due to this rather difficult task of lexical decision, the positivity effect seems to reflect how clearly they can be classified as either an existing word or a neologism. A higher positive amplitude is correlated with the simplicity of a stimulus according to the task-requirements. In this respect, the decision task was easier for words and non-words than for pseudo-words. Words benefit from the existence of lexical entries and non-words from the phonotactic violation. Taking the ERP pattern in the critical conditions into account, the

positivity effect in our experiment show that pseudo-words are less clearly analyzed as non-existing than words are accepted and non-words rejected as lexical items.

Thus, in analogy to observations made in the arithmetic and syntactic domain, we infer that non-words like [spɛp] are less similar to German words than pseudo-words fulfilling the constraint *SPEP. This means that the ease of the task depends on the degree of wellformedness insofar as non-words can be rejected more easily than pseudo-words, as manifested in a more pronounced positivity for non-words. Therefore, amplitude differences indirectly reflect the degree of wellformedness.

The lexical status of existing words can also be evaluated more easily than the status of pseudo-words, yielding a positivity effect that is comparable to that observed for non-words. The logic behind this is that the evaluation of possible words is more costly than the evaluation of existing and illegal forms.

At which processing steps do phonological constraints such as the OCP come into play? The lack of early components suggests that the processing of the OCP violation does not surface prior to the initiation of lexical processes indicated by an N400 effect. Thus, non-words of the type studied here are accepted as possible words in an early step of phonological analysis, since they did not evoke the early positivity effect found for unpronounceable non-words (e.g. Bentin et al., 1999), but showed an N400 effect just like pseudo-words. In a later stage, however, the EEG curves of pseudo-words and non-words diverge in parietal regions, leading us to the conclusion that a violation of the phonological structure of German words (i.e. *SPEP) is relevant here.

Alternatively, the findings could be accounted for by differences in neighborhood size between both types of non-existing words. In an ERP study investigating the modulation of the N400 component by the orthographic neighborhood size, Holcomb, Grainger, and O'Rourke (2002) have shown that words with a large neighborhood size elicited an enhanced N400 effect compared to words with a smaller one. The authors argue that an increase of the

N400 component for high neighborhood density reflects a summation of semantic activation by the target and/or the lexical neighbors. Accordingly, one could argue that the decrease of the N400 component for non-words is due to a smaller size of neighborhood density in comparison to pseudo-words. An analysis of neighborhood density for the pseudo- and non-words (based on CELEX database, Baayen, Piepenbrock, & Gulikers, 1995) – however – revealed no differences of neighborhood size in terms of the number of neighbors (see Table 1; Mann-Whitney U-test: 711,5, $p > .12$). In terms of the frequency of the neighbors, we found even higher frequencies for neighbors of non-words than of pseudo-words (see Table 1; Mann-Whitney U-test: 7939, $p < .004$). If differences in neighborhood size were responsible for the contrast observed between the two types of neologisms, we would expect a larger N400 for non-words than for pseudo-words rather than an enhanced positivity effect. Following the logic of the positivity effect stated above, non-existing words with more frequent neighbors should evoke a less pronounced positivity because they are more likely to be judged as words in lexical decision tasks. This is, however, not the case.

Therefore, we argue that the violation of the constraint *SPEP is responsible for the late positivity effect which separates phonologically wellformed from illformed sound strings. We suggest that the violation of the OCP is a phonotactic violation not detected in early processing steps preceding lexical integration processes, but checked at later processing levels. It is quite possible that violations caused by non-permitted adjacent segments lead to the detection of non-words prior to lexical processing (see Holcomb & Neville, 1990; Bentin, 1987; and Holcomb, 1988 for unpronounceable non-words in which phonotactics is violated by concatenation of two adjacent segments). In contrast, phonotactic violations involving non-adjacent segments apparently become relevant at later processing levels, when the evaluation of the lexical status has already been initiated. However, it cannot be excluded that the lack of vowels rather than the mere illformed combination of two adjacent consonants is responsible for the non-existence of a lexical effect in non-words presented by Bentin et al. (1999).

As for models of spoken word recognition, the present results do not provide evidence for a particular model of word recognition. But this was not the principle aim of our study which focussed on the question whether violations of phonological constraints like the OCP constraint are processed on-line at all, and whether this occurs at earlier or later processing steps of word recognition. In this perspective our conclusion is that electrophysiological effects elicited by non-words like [ʃpɛp] do not precede effects induced by lexical processes. However, we have to leave open the question whether prelexical and lexical processes are operative serially or interactively, since we investigated two types of non-existing stimuli and therefore could not find on-line feedback from the lexicon. Further ERP studies have to be performed in order to find evidence for one or the other model. For instance, such studies may include existing words, which violate the phonotactic principle examined.

Our results contrast with those of Dehaene-Lambertz et al. (2000) who found (inter alia) an *early* negativity for the detection of a change in syllable structure (by French speakers). But the Japanese speakers, for whom the crucial items of the type /ebzo/ are illformed structures, did *not* react (behaviorally and in the EEG) to the violation, while for the French participants those items did not present any phonotactic violation. The present results are compatible with these findings, if it is acknowledged that the nature of the constraint studied here is quite different. In contrast to the constraint used by Dehaene-Lambertz, et al. (2000), the constraint *SPEP is not automatic, spans a larger domain of non-adjacent segments, and is not obviously related to processes of language-specific production and perception. Thus, while the constraint against syllable-final consonants in Japanese “probably goes back to the coding of phonetic properties” (Dehaene-Lambertz et al., 2000, p. 643), this is not the case for the constraint *SPEP.

The fact that even a constraint of the *SPEP type can be part of a psychologically real grammar is all the more remarkable as this constraint banning German words of the type

CC_iVC_i has a few lexical exceptions (as in [ʃta:t] ,state'). Nevertheless, speakers of German are still sensitive to the oddity or markedness of words that violate *SPEP. On this level, our findings are in accordance with results obtained in previous psycholinguistic studies (Berent et al., 1997; Berent et al., 2003; Coetzee, 2003). Moreover, using the ERP technique, the comparison between non-words and pseudo-words enables us to determine at which level of phonological (word) processing such a constraint comes into play.

Conclusion

The aim of the present study was to examine the processing of phonological constraints by means of electrophysiological measurements. Consistent with findings of several behavioral studies on OCP violations, neologisms violating the ban on CC_iVC_i produce an LPC in comparison to neologisms that obey this constraint. Such an effect is interpreted as evidence that the processing system differentiates between legal and illegal neologisms, even after they have been detected as non-existing. This finding suggests that phonological constraints play a role in later (perhaps postlexical) stages of word processing and thus speaks against discrete models which postulate the completion of phonological processing prior to lexical processing.

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Appendix

Test stimuli and their classification. The stimuli are given in IPA transcription

existing words		non-existing words	
wellformed	illformed	wellformed	Illformed
ʃneɪ	ʃte:t	ʃlɪn	ʃnu:n
ʃlap	ʃta:t	ʃpe:k	ʃmø:m
ʃlaf	ʃtat	ʃnax	ʃni:n
ʃlʊk	Filler items	skʊp	ʃpɑp
ʃpu:ə	ʃkɑŋk	ʃpɔ:m	ʃmɔ:m
ʃtɔk	ʃval	ʃpyk	ʃnan
ʃnɪt	ʃvel	ʃlɔ:k	ʃpe:p
ʃpe:t	ʃkɛk	sko:p	ʃny:n
ʃlɔs	ʃki:p	skɛ:ə	ʃlɪl
ʃtɑɜ	ʃka:t	ʃne:p	ʃnʊn
ʃmɪs	ʃvy:l	ʃmaf	ski:k
ʃnu:ə	ʃkɛ:k	ʃpe:f	ʃmɪm
ʃmu:s	ʃvam	ʃmø:m	ʃpa:p
ʃtu:l	ʃvats	ʃlat	ʃti:t
ʃlam	ʃvʊŋ	ʃnet	ʃlœl
ʃpa:n	ʃvæts	ʃmɔt	ske:k
skɑ:t	ʃvu:ə	ʃtɪɜ	ʃmɔm
ʃtiç	ʃkɔf	ʃpo:k	ʃma:m
ʃpu:k	ʃvax	ʃti:n	ʃme:m
ʃmʊk	ʃkɪt	ʃmɪn	ʃly:l
ʃlɪf	ʃkɔt	skim	ʃmɪm
ʃpek	ʃvo:f	ʃnɔl	ʃmam
ʃlus	ʃvan	ʃmi:p	ʃpɔp
ʃtɔf	ʃvʊnt	ʃnʊm	ʃto:t
ʃta:p	ʃkɑɪn	ʃta:n	skɔk
ʃla:k	ʃkɪl	skʊf	skɪk
ʃto:s	ʃvu:l	ʃny:m	ʃtø:t
ʃlɪm	ʃve:ə	ʃme:k	ʃpi:p
ʃpa:s	ʃvɑŋk	ʃla:ə	ʃli:l
ʃpa:t	ʃva:n	ʃto:k	ʃnen
ʃla:f	ʃkɔ:t	ʃli:m	ʃlo:l
ʃma:l		ʃpat	Skak
ʃpi:s		ʃmo:p	ʃpɛp
ʃpe:ə		ʃpa:l	ʃtyt

ʃte:k	ʃni:l	ʃlɔl
ʃtal	skɑ:n	ʃtœt
ʃti:ə	ʃtu:k	ʃpœp
ʃlo:t	ʃtø:p	ʃpo:p
ʃtʊm	ʃlø:p	ʃlɑl

Table 1

Acoustic properties of pseudo-words and non-words (mean fundamental frequency, mean intensity, and mean duration), lexical properties (biphone-, triphone frequency and neighborhood size; based on the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995) and the database for sublexical frequencies (Aichert, Marquart, & Zieger, unpublished)), and comparisons between both groups of non-existing words.

Word type	F₀ (mean)	Intensity (mean)	Duration (mean)
Pseudo-words (n = 42)	218 (± 6 SD) Hz	37 (± 3 SD) dB	758 (± 84 SD) ms
Non-words (n = 42)	223 (± 4 SD) Hz	37 (± 3 SD) dB	759 (± 81 SD) ms
Comparison Pseudo-words vs. Non-words	t(82) = -3.976; p < .001	t(82) = .894; p > .374	t(82) = -.038; p > .969
Word type	Biphone frequency (mean)	Triphone frequency (mean)	Neighborhood size (mean)
Pseudo-words (n = 42)	3990	164	Types: 4.1 Tokens: 194
Non-words (n = 42)	4237	177	Types: 2.8 Tokens: 438
Comparison Pseudo-words vs. Non-words	Mann-Whitney Test: Z = -.024, p > .981	Mann-Whitney Test Z = -.262, p > .793	Mann-Whitney Test Types: Z = -1.6, p > .121 Tokens: Z = -3.01, p < .004

Table 2

Results of statistical analyses of mean voltage changes with the accounted factors WORDTYPE (existing words, pseudo-words, non-words), REGION (frontal region: F3, Fz, F4 and parietal region: P3, Pz, P4) and TIME (880-1130 and 1130-1380).

Contrasts	Results	
WORDTYPE x REGION x TIME	WORDTYPE:	F(2,70) = 38.630; p < .001
	REGION:	F(1,35) = 122.10; p < .001
	TIME:	F(1,35) = 157.27; p < .001
	WORDTYPE x TIME:	F(2,70) = 18.201; p < .001
	WORDTYPE x REG.:	F(2,70) = 6.9130; p < .004
Post-hoc analyses		
WORDTYPE x TIME:		
Time 1 (880-1130ms)		
WORDTYPE	WORDTYPE:	F(2,70) = 53.501; p < .001
Pair-wise contrasts:		
- words vs. pseudo-words	WORDTYPE:	F(1,35) = 82.203; p < .001
- words vs. non-words	WORDTYPE:	F(1,35) = 58.324; p < .001
- pseudo-words vs. non-words	WORDTYPE:	F(1,35) < 1
Time 2 (1130-1380)		
WORDTYPE	WORDTYPE:	F(2,70) = 3.597; p < .041
Pair-wise contrasts:		
- words vs. pseudo-words	WORDTYPE:	F(1,35) = 5.219; p < .03
- words vs. non-words	WORDTYPE:	F(1,35) < 1
- pseudo-words vs. non-words	WORDTYPE:	F(1,35) = 9.215, p < .006
WORDTYPE x REGION:		
Frontal Region		
WORDTYPE	WORDTYPE:	F(2,70) = 34.100; p < .001
Pair-wise contrasts:		
- words vs. pseudo-words	WORDTYPE:	F(1,35) = 52.309; p < .001
- words vs. non-words	WORDTYPE:	F(1,35) = 38.594; p < .001
- pseudo-words vs. non-words	WORDTYPE:	F(1,35) < 1
Parietal Region		
WORDTYPE	WORDTYPE:	F(2,70) = 31.609; p < .001
Pair-wise contrasts:		
- words vs. pseudo-words	WORDTYPE:	F(1,35) = 61.999; p < .001
- words vs. non-words	WORDTYPE:	F(1,35) = 15.308; p < .001
- pseudo-words vs. non-words	WORDTYPE:	F(1,35) = 17.791, p < .001

Fig. 1. Grand averages of event-related brain potentials (ERPs) obtained for words (solid lines), pseudo-words (broken lines), and non-words (dotted lines). The vertical line indicates the onset of the critical words.

Fig. 2. Grand averages of event-related brain potentials (ERPs) obtained for pseudo-words (solid lines) and non-words (broken lines).

Fig. 3. Scalp topography maps showing voltage differences between experimental conditions in the two critical time-windows 880-1130 ms and 1130-1380 ms. The amplitude of mean voltage differences ranges from -2 μV (white) to +2 μV (black). a) and b) indicate that both pseudo-words and non-words evoke a fronto-central negativity in comparison to words, whereas the contrast between pseudo-words and non-words (c) revealed a parietal positivity effect for non-words. Overall, the brain maps calculated in two subsequent time-windows illustrate that the two components can be separated by means of latency. Note that the spatial resolution of the topographic view is rather low, since mean voltage changes were measured by means of 22 scalp electrodes only.

Figure 1

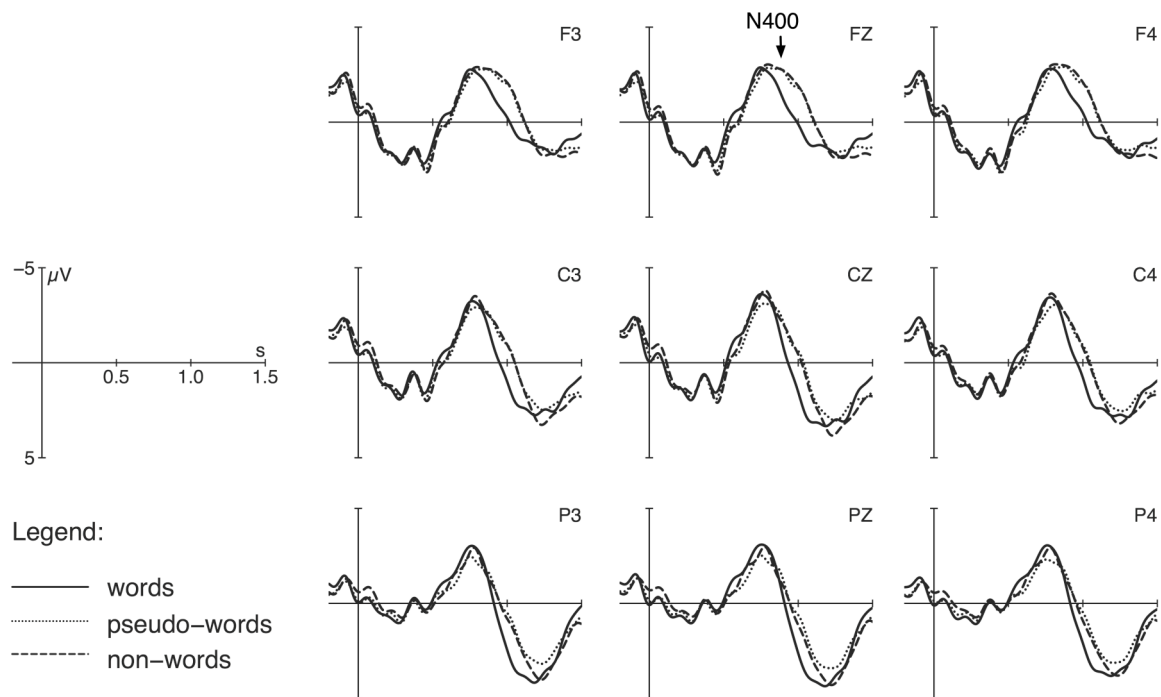


Figure 2

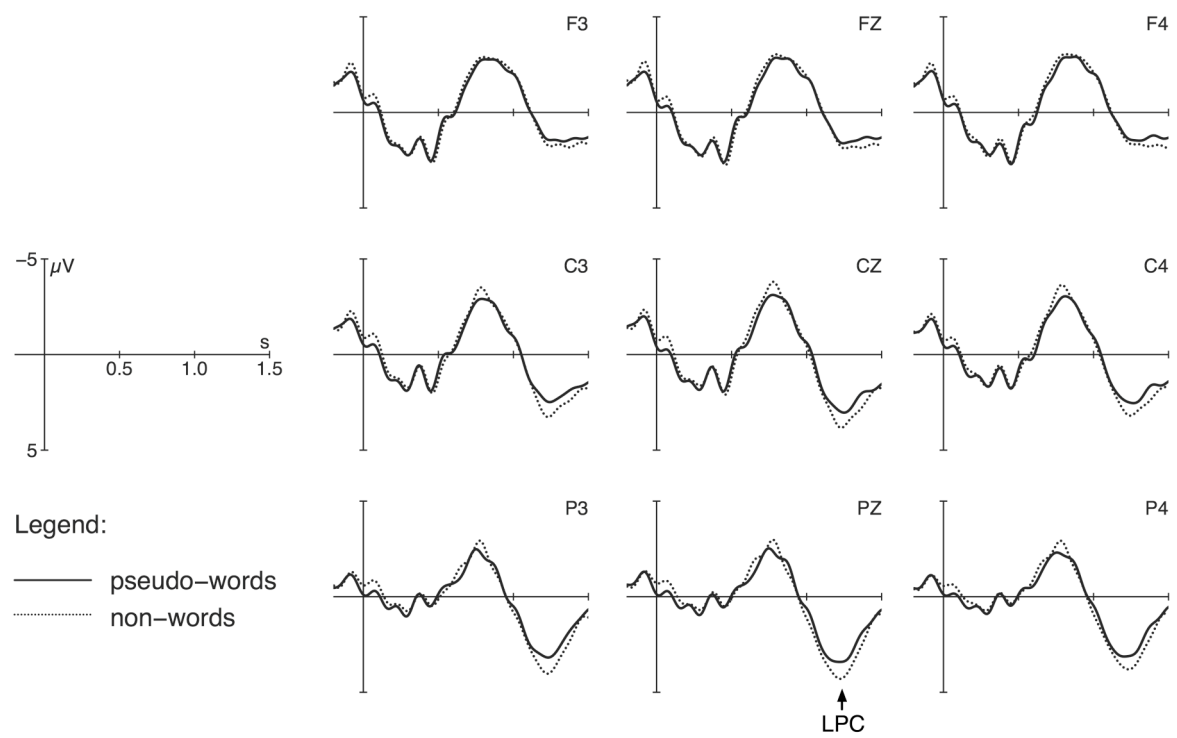


Figure 3

