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Cognitive Brain Research 20 (2004) 529–532

COGNITIVE BRAIN RESEARCH

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Short communication

When does the brain register deviances from standard word spellings?—An ERP study

Paul Sauseng, Jürgen Bergmann, Heinz Wimmer*

Department of Psychology, University of Salzburg, Hellbrunnerstrasse 34, A-5020 Salzburg, Austria

Accepted 19 April 2004
Available online 10 June 2004

Abstract

Event-related potentials (ERPs) in response to the standard form of words (e.g., taxi) were compared with ERPs in response to letter-altered (e.g., taksi) or case-altered forms (e.g., taXi). The altered forms always resulted in the same reading as the standard forms. First divergences between ERPs were found at around 160 ms. At occipital sites, the peak amplitude of the N160 was higher for standard than letter-altered strings. At frontal and central sites, the standard strings diverged from the altered strings persistently by higher positivity from about 160 ms onwards. These early ERP differences between standard and altered visual word forms speak for early contact between the letter input and stored visual–orthographic representations of words.

Theme: Neural basis of behavior
Topic: Cognition

Keywords: Early ERP components; Visual word form processing

As event-related potentials (ERP) provide a continuous ms-by-ms record of electrical changes related to perceptual and cognitive processes, they can provide information on the time course of reading processes. A prime example of the sensitivity of the ERP to cognitive–linguistic processes is the consistent finding of a higher amplitude of the N400 (i.e., the negative wave peaking about 400 ms after stimulus) elicited by an incongruous word at the end of a sentence [3]. Sereno and Rayner [8] pointed out that such late ERP components cannot be informative about perceptual reading processes as the eyes on average rest only about 250 ms on a word before they move on. ERP studies were less successful in providing converging findings on processes within this time constraint. For example, studies concerned with the sensitivity of ERP components to high vs. low frequency words showed quite discrepant results ranging from an early N150 sensitivity [9] to differences occurring after 500 ms [5].

The present study explored the visual orthographic processing of words by contrasting ERPs elicited by the standard form of words with ERPs elicited by case-altered and letter-altered strings. Of main interest were the time-course and the rough localization of the ERP differences between standard and altered visual word forms. Such differences should be informative on visual–orthographic processes as the altered forms resulted in the same readings as the standard forms, so that differences in phonology and meaning cannot account for ERP differences between standard and altered forms. We are not aware of ERP studies, which examined visual–orthographic processes by keeping constant phonology and meaning.

Participants were 20 right-handed German-speaking students (12 females and 8 males; mean age 26.2 years). Stimuli were 120 word triplets, each consisting of the standard letter string of a German noun and a case-altered and a letter-altered alternative. The mean length of all three string types was 6.1 letters and varied between 4 and 11 letters. The mean frequency of the words in written texts according to the Celex data base [2] was 40.8 per million (S.D. = 96.5). The words were chosen in such a way that a homophonic letter-altered version was possible. Examples are Physik (physics) changed to Fysik or Quantität (quantity) changed to Kwantität. As evident from the examples,

* Corresponding author. Tel.: +43-662-8044-5128; fax: +43-662-8044-5126.
E-mail address: Heinz.Wimmer@sbg.ac.at (H. Wimmer).

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doi:10.1016/j.cogbrainres.2004.04.008

German nouns begin with an upper-case letter. The position of the letter for which the case was changed in a specific word, roughly corresponded to the position of the exchanged letter(s) in that word. For example, the case change corresponding to the letter-altered form Taksi was TaXi. When the exchanged letter was in initial position, then the first upper-case letter of the standard form was changed to lower-case and the second letter was changed to upper-case (e.g., Physik changed to pHysik). A case change of the first letter alone (e.g., resulting in physik) was considered a too minor deviation from the standard form.

The same random order of stimuli was used for all participants with the constraint that the distance between members of a triplet was large. The task was to silently read each item. Presentation time was 1000 ms with a 1000-ms interval between presentations. Participants were warned that a question mark might appear immediately after some items in response to which they had to vocalise their reading. Question marks appeared after 30 of the 360 items and in all cases correct responses were given. The average size of the upper- and lower-case letters was 1.15° and 0.72° of visual angle, respectively, and average string length was 3.62°.

The EEG signal was recorded from 13 sites (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, PO1, PO2, O1, O2 according to the International 10–20-system) against a common reference on the nose. The electro-oculogram was recorded from two additional channels. The signals were amplified by a BEST 32-channel system and digitized at 128 Hz. Impedance for all channels was kept under 5 kΩ. Frequency limits were 0.16 and 35 Hz. After EOG-correction and inspection for artefacts, the mean number of trials used for averaging was 87, 85 and 89 for standard, letter-altered and case-altered strings, respectively.

Fig. 1 shows how the ERPs evoked by the altered strings differed from the standard strings. For examining the time course of these differences, point-by-point *t*-test were calculated with each point consisting of 7.8 ms according to the 128 Hz sampling rate. In order not to miss differences in early sharp components, only three *t*-tests ($p < 0.01$, two-sided) in immediate sequence had to be significant for accepting an ERP difference as reliable. The results of the point-by-point *t*-test comparison between the standard and each type of altered strings are shown in Fig. 1 below the ERPs. The length of the line indicates the time for which the reliable differences persisted. The case- and the letter-altered strings did not differ reliably from each other.

As evident from Fig. 1, the most conspicuous deviation of the altered from the standard strings started from about 200 ms onwards. From that time onwards, the standard strings elicited a broad positive deflection, which peaked at around 300 ms post-stimulus and which was much reduced for both types of altered strings. This reduced positivity of the altered strings became reliable at $p < 0.01$ (two-sided) for the majority of sites between 220 and 260 ms post-stimulus. However, at several anterior sites the divergence of the altered from the standard strings began earlier. For example, the letter-altered strings began to differ (by reduced positivity) from the standard strings at 173, 188 and 203 ms at F4, C4 and C3, respectively. Furthermore, a persistently reduced positivity of the altered compared to the standard strings at frontal and central sites is present already before it is marked as reliable at $p < 0.01$ in Fig. 1. Actually, a less conservative criterion of $p < 0.05$ (two-sided) found the difference between standard and letter altered strings to be reliable from about 150 ms onwards at all three frontal sites and at C4. At posterior sites a reliable difference in peak amplitudes between altered and standard strings was observed only for the two occipital leads and only for the difference between letter altered and standard strings. The onset of the reduced negative amplitude of the letter-altered strings was at 156 and 164 ms at O1 and O2, respectively.

Fig. 1 further shows that at the majority of sites—excluding occipital and frontal ones–the difference between standard and altered strings persisted up to 600 and 700 ms and included a negative deflection between 400 to 700 ms, which corresponds to the well-known N400 component.

To examine whether the early effect of the string type variation on ERPs was different for the left and the right hemisphere, separate ANOVAs were run for each pair of left vs. right hemisphere leads (O1/O2, PO1/PO2, P3/P4, C3/C4, F3/F4). The dependent measure was the mean amplitude from 140 to 195 ms, which covered both the posterior N160 and the synchronous anterior P160 peak. The string type effect was reliable only for both the frontal (F3/F4) and the central electrode pair (C3/C4), $Fs(2, 38) > 4.25$, $p < 0.03$. However, no single interaction term was reliable, all $Fs(2, 19) < 3.73$, $p > 0.05$, suggesting that the early string type effect was similar for both the left and the right hemisphere lead of each pair. For the central leads there was a hemisphere effect, $F(1,19) = 10.36$, $p < 0.01$, with a lower (i.e., less positive) mean amplitude at the left than at the right lead.

The present study to our knowledge is the first one, which provided ERP evidence on visual word form perception by contrasting the standard letter strings of words with case-altered and letter-altered strings. Because the altered strings result in exactly the same readings as the standard strings, the ERP differences between the standard and the altered strings are informative about the time course when the letter input makes contact with stored visual orthographic word memories. The most conspicous difference between standard and altered strings was observed for the broad positive deflection which set in at around 200 ms and which peaked around 300 ms. The standard strings elicited a much larger P300 than the altered strings. This effect of the standard strings on the amplitude of the P300 corresponds to the recognition potential of Rudell and Hua [7] who found that recognizable visual stimuli (words, pictures, faces) resulted in a larger potential than meaningless stimuli.

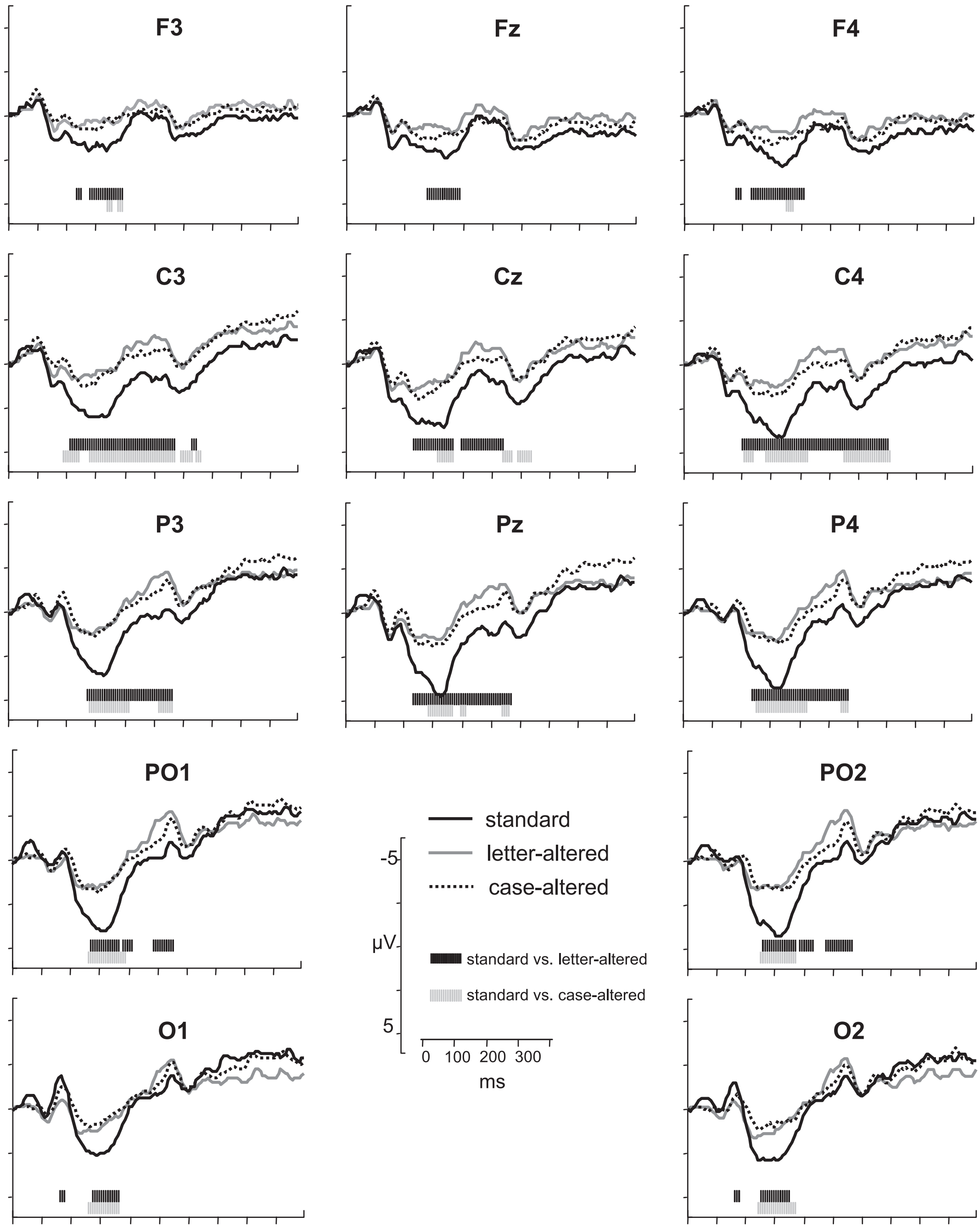

Fig. 1. Grand average ERPs ($N = 20$) for the standard letter strings of words contrasted with letter-altered and case-altered strings. Numbers of contributing trials were 87, 85 and 89, respectively. Bars below ERPs indicate the duration of reliable differences between ERPs.

However, of particular interest is that the ERP divergence between standard and altered strings was already observed in components preceding the onset of the P300. At occipital sites there was a difference between standard and letter altered strings at around 160 ms, when the standard strings elicited a higher negative amplitude around the peak of the N160 component. At around the same latency, the altered strings began to diverge persistently from standard strings at anterior sites by first eliciting a reduced peak of the P160 and then a reduced P300. These ERP differences emerging around 160 ms post-stimulus allow the conclusion that at this time the letter input came in contact with memory representations. The critical point is that these memory representations must have contained the standard letter sequence of the words (including case information). For example, input strings like Taksi must have made contact with memory representations like Taxi. The deviation of the altered input strings from the established memory representation must have led to the reduced peak amplitudes of the P160/N160 component and to the reduced peak amplitude of the subsequent P300 component.

The present finding of early ERP divergence of altered from standard letter strings is in correspondence with time course of visual word perception suggested by eye movement findings. As summarized by Sereno and Rayner [8], the eyes on average fixate a word in text only about 250 ms before they move on, and, already before the saccade, attention has to be shifted to the next word to allow programming of the following saccade. Thus, the visual perception of words in text reading cannot take much longer than 200 ms on average, which nicely corresponds to the presently observed divergence of altered and standard letter strings from about 160 ms onwards.

The early ERP divergence of altered from standard strings suggests a modification of the comprehensive theorizing of McCandliss et al. [4] on the early phase of visual word processing. These authors assume that the first stage of visual word processing from about 150–200 ms consists in the computation of a ''normalized'' letter string representation, which abstracts from superficial input characteristics, such as retinal position, size, or font. An additional assumption is that this stage of letter string normalization is not affected by cognitive characteristics of the input, that is, whether it does or does not correspond to an existing word or whether it is a high- or low-frequency word. The present result suggests that at least visual–orthographic word memories do have an early influence on letter string processing. Actually, one could envisage that letter string normalization and activation of stored visual–orthographic word representation may go hand in hand. The early activation of visual–orthographic word memories may have a helpful top-down effect on letter string processing. The classic word superiority effect [6] on the perception of letter strings which are presented for less than 100 ms is suggestive of this possibility. However, we note that any definitive modification of the visual word form theorizing of Cohen and Dehaene, which is based on a wealth of data, including ERP findings, must await replication of the present findings. We are encouraged by ERP findings of Assadollahi and Pulvermüller [1] and Sereno et al. [9] who found an effect of word frequency in the latency range from 120 to 170 ms in line with our findings.

Acknowledgements

This research was supported by grant P14494-SPR of the Austrian Science Foundation to Heinz Wimmer. We gratefully acknowledge the helpful comments of three reviewers.

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