

Research Report

Welcome to the real world: Validating fixation-related brain potentials for ecologically valid settings

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ABSTRACT

Exploration of the real world usually expresses itself through a perceptual behaviour that is complex and adaptive — an interplay between external visual and internal cognitive states. However, up to now, the measurement of electrophysiological correlates of cognitive processes has been limited to situations, in which the experimental setting confined visual exploration to the mere reception of a strict serial order of events. Here we show — exemplified by the well known old/new effect in the domain of visual word recognition — that an alternative approach that utilizes brain potentials corresponding to eye fixations during free exploration reveals effects as reliable as conventional event-related brain potentials.

Keywords:

Event-related potential

ERP

FRP

Eye-movement

Brain potential

Word recognition

1. Introduction

The most prominent advantage of event-related potentials (ERPs) is that the time course of cognitive processes can be measured at a very high temporal resolution (Hillyard and Kutas, 1983). A critical cornerstone for the analysis of brain potentials is determining the onset of the theoretically relevant cognitive process the electrophysiological correlates of which are supposed to be recorded. In conventional ERP paradigms, a cognitive process and the recording of its electrophysiological correlate are synchronized by linking them to a single external event — most often an experimentally presented stimulus. This approach is based on the implicit assumption that a specific cognitive process (e.g., the recognition of a word) can not start until the relevant information (e.g., the word) — on which the specific cognitive process is dependent — is provided. By having knowledge

about the point in time at which the relevant bit of information was provided researchers know where in the recorded data-stream to look for the electrophysiological correlates of the cognitive process of interest. Although this approach is suitable for the synchronization of cognitive processes with the recording of electrophysiological data, it also bears important limitations with respect to the ecological validity of the resulting experimental settings: Experience and behaviour is broken down into a serial sequence of externally triggered events. For example, in the domain of research on reading and dyslexia, the presentation of a sentence is segmented into an artificial sequence of isolated words, with each word being presented individually, one after the other, separated by relatively long time intervals (usually about 500 ms). Although being useful for research on single word recognition, the experimental paradigms used within the ERP framework are far from natural reading of meaningful text.

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1.1. Fixation-related potentials

Here we present the validation of an alternative approach that allows synchronizing cognitive processes and the recording of its electrophysiological correlates by relating a natural sequence of perceptual events to a series of eye movements and fixations: the fixation-related potentials (FRP) approach. Contrary to the ERP paradigm, in the FRP approach synchronization is not realized by the externally triggered presentation of a stimulus. Rather, an eye tracker is used to assess a subject's eye movements in order to determine when a subject is looking at what (e.g., a word) in a complex, visual pattern (e.g., a sentence).

By doing so, the exact point in time at which certain visual information (that is crucial for triggering a specific cognitive process) is taken in can be assessed — allowing to synchronize the recording of electrophysiological data to the start of a specific cognitive process. Monitoring a person's eye movements during the recording of electrophysiological data therefore provides a self-paced but externally observable indicator for the beginning of a cognitive process (that relied upon the perception of that very specific visual matter).

For a wide applicability of the FRP technique, the exact determination of a subject's gaze position by means of an eye tracker is inevitable. Prior to the broad availability of eye

trackers, electro-oculographic (EOG) recordings were used to assess the on- and offset as well as the direction of saccades. Utilizing EOGs, Marton et al. (1985) could show that brain potentials corresponding to saccades were comparable to visual-evoked potentials in their late components. However, because determining a subject's absolute gaze position by means of EOG is difficult, experimental implementations of this approach bare severe restrictions. For example, during sentence reading only brain potentials corresponding to the last word in a sentence could be assessed (e.g., Marton and Szirtes, 1986, 1988a,b).

With the rise of easy-to-use eye trackers it is now unproblematic to determine a subject's gaze position with high spatial resolution while recording electrophysiological data. Although already utilized for the assessment of cognitive processes (Baccino and Manunta, 2005; Dimigen et al., 2006) a validation of the FRP is necessary in order to prove that the electrophysiological correlates of cognitive processes as reflected in conventional ERPs are also evident in FRPs.

1.2. The rationale

The aim of the present paper is to validate the FRP approach. For that purpose, the underlying rationale was to cross validate an effect that is well documented in conventional ERP

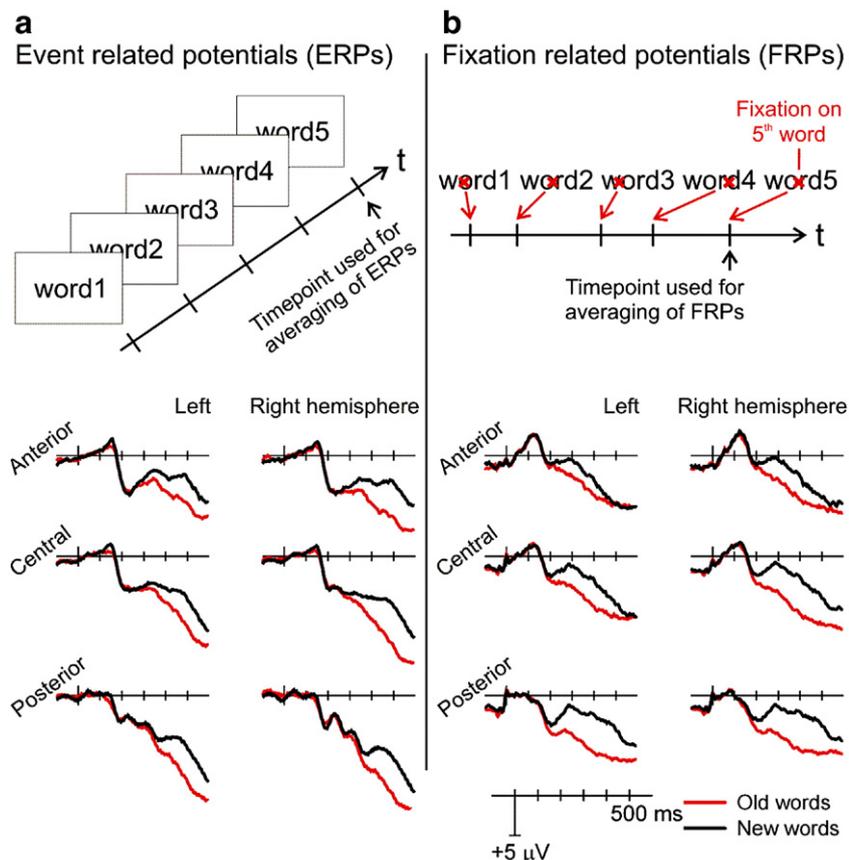


Fig. 1 – Experimental design and results for the old/new effect for event-related potentials (ERPs) and fixation-related potentials (FRPs), plotted for representative locations with red lines representing old and black lines representing new words, (a) ERPs, averaged upon the time-point at which the 5th word was presented, (b) FRPs, averaged upon the time-point at which the 5th word was fixated, with exemplary fixations indicated by red crosses.

research: the old/new effect in visual word recognition, characterized by a positivation for correctly recognized old words from around 250 ms (Rugg and Nagy, 1989; Rugg et al., 2000). This way we can directly compare findings from FRPs with the ERP marker, which in turn is established by state-of-the-art literature. Specifically, a continuous recognition task (Friedman, 1990) was realized in both, the conventional ERP paradigm (with five words being presented one at a time) and in the FRP paradigm, in which the same participants were presented with five words all at once in a row while their eye movements were recorded. Finding the old/new effect in FRPs with a spatial distribution comparable to that found in the ERPs would argue for the validity of the FRP approach.

2. Results

2.1. Analysis

For ERPs, continuous EEG data was segmented according to the standard procedure: Upon the point in time of appearance of the theoretically relevant target word, segments from 100 ms pre-stimulus to 600 ms post-stimulus were extracted for analysis. For segmentation of EEG data in the FRP setting, the point in time of a participant's first fixation on the target word was determined. Based upon the synchronization of the EEG and eye-movement recording, the onset time of the respective fixation could reliably be used to extract segments from 100 ms pre-fixation to 600 ms post-fixation (see upper half of Fig. 1).

Trials with incorrect responses were excluded from analysis (6% and 9% for ERPs and FRPs, respectively). After segmentation of ERP and FRP data, trials corrupted by eye-blinks or EEG-artifacts were rejected by visual inspection (3% and 1% for ERPs and FRPs, respectively). Subsequently, independent component analysis was used for removal of EOG artifacts (Vigario, 1997, see Fig. 2 for illustration).

For baseline correction a non-standard interval from 0 to 100 ms post-stimulus (post-fixation, respectively) was chosen, because for some (posterior) channels in the FRP setting ocular artifacts in the pre-fixation interval could not fully be removed (see Discussion).

For both, ERPs and FRPs, brain potentials in response to old words are more positive-going in the time window from 250–600 ms (Fig. 1). The statistical analysis of the old/new effect was performed on the basis of collapsed values of clusters of electrodes in the left anterior (F3,FC1,FC5), right anterior (F4,FC2,FC6), left central (C3,CP1,CP5), right central (C4,CP2,CP6), left posterior (P3,P7,T7) and right posterior (P4,P8,T8) regions. Mean



Fig. 2 – FRP (recorded at F4) contaminated with ocular artifacts (black line) compared to FRP corrected for eye-movements by independent component analysis (red line). The difference curve (gray) resembles artifacts corresponding to saccadic eye movements prior to the onset of the fixation.

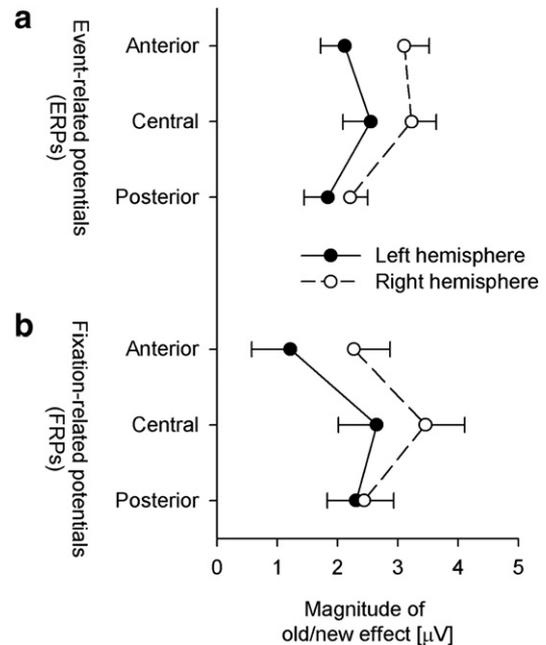


Fig. 3 – Magnitude of the old/new effect (mean amplitude of old items minus mean amplitude of new items) for event-related potentials (a) and fixation-related potentials (b) plotted separately for region (anterior, central and posterior) and hemisphere (left vs. right).

amplitudes for old and new words in the time window from 300–600 ms were submitted separately for ERPs and FRPs to $2 \times 2 \times 3$ repeated measures ANOVAs with old vs. new words, hemisphere (left vs. right) and electrode region (anterior, central and posterior) as within-subject factors. Where appropriate, *dfs* were adjusted using Greenhouse–Geisser correction for the violation of sphericity. In the following we only report the effects and interactions involving the theoretically relevant old/new effect. For illustration, the magnitude of the old/new effect (mean amplitude of old items minus mean amplitude of new items) is depicted for hemisphere and electrode region, separately for ERPs in Fig. 3a and FRPs in Fig. 3b.

For ERPs, an old/new by hemisphere by electrode region interaction, $F(1.87,35.66)=6.71$; $p<.01$, restricts an old/new by electrode region interaction, $F(1.36,25.93)=7.45$; $p<.01$, an old/new by hemisphere interaction, $F(1,19)=6.20$; $p<.05$, and an old/new main effect, $F(1,19)=53.63$; $p<.001$. As can be seen in Fig. 3a, the old/new effect is larger in the right than in the left hemisphere and – as indicated by the three-way interaction – this hemispheric difference is reliable in anterior, $F(1,19)=12.45$; $p<.01$, and central, $F(1,19)=4.38$; $p=.05$, but not in posterior regions, $F<2.04$, as post-hoc tests reveal. Although the magnitude of the old/new effect is smallest in left-hemispheric parietal regions, post-hoc tests reveal that it is still highly reliable, $F(1,19)=22.66$; $p<.001$. For FRPs, again an old/new by hemisphere by electrode region interaction, $F(1.77,33.63)=7.53$; $p<.01$, confined an old/new by electrode region interaction, $F(1.81,34.33)=20.64$; $p<.001$, an old/new by hemisphere interaction, $F(1,19)=8.99$; $p<.01$, and an old/new main effect, $F(1,19)=18.48$; $p<.001$. Again – as evident from Fig. 3b – the old/new effect is larger in the right than in the left hemisphere, the reliable three-way interaction indicates that

this hemispheric difference is reliable in anterior, $F(1,19)=11.42$; $p<.01$, and central, $F(1,19)=11.32$; $p<.01$, but not in posterior regions, $F<1$, as post-hoc tests reveal. Furthermore, post-hoc tests reveal that the old/new effect is only of borderline reliability in left-hemispheric frontal regions, $F(1,19)=3.64$; $p=.072$, but is reliable in all other regions, all $F_s>14.40$.

3. Discussion

The aim of the present paper was the validation of the FRP approach. The important finding is that the chosen marker effect – i.e., the old/new effect – was observed in FRPs as well as in ERPs. Moreover, the spatial distribution of the old/new effect was the same in FRPs and ERPs: In both paradigms, the magnitude of the old/new effect was greater in the right than in the left hemisphere (in accordance with evidence for shallow encoding reported by Rugg et al., 2000). Furthermore, for FRPs and ERPs, these hemispheric differences were found in anterior and central, but not in posterior regions. The similar results for both paradigms strongly suggests the validity of the FRP approach – indicating that brain potentials related to eye-fixations (FRPs) are as reliable as ERPs.

3.1. Remaining challenges

A challenge in using FRPs is the correction of the artifacts of the (inevitable) saccadic eye-movements that precede and follow a fixation. Whereas the follow-up saccades are unsystematic with respect to their temporal onset, the preceding saccades are time-locked to the onset of the FRPs. Due to this temporal synchrony even slight shortcomings of the applied EOG correction algorithms can become evident since systematic correction errors accumulate through averaging. In the present study, EOG correction by means of a standard regression based algorithm (Gratton et al., 1983) turned out to be unfeasible, resulting in large correction errors on all recording sites. In contrast, with independent component analysis (Vigario, 1997) satisfactory results could be achieved even though an inspection of the FRPs in Fig. 1 still reveals slight residual ocular artifacts from preceding saccades in posterior regions. In the present study this problem was circumvented by a non-standard post-stimulus baseline correction, which was unproblematic because the effect of interest was known to have the earliest onset at 250 ms. However, further work is necessary to systematically investigate which of the different available EOG correction approaches meets the affordances of the FRP framework best.

3.2. Conclusion

The important conclusion of the present study is that FRPs seem to be a complement (but no substitute) to ERPs – broadening the spectrum of experimental settings during which electrophysiological correlates of cognitive processes can be recorded. For example, experimental settings with increased ecological validity can be realized in research domains that rely on the processing of complex visual stimuli

such as text reading, scene-perception or visual search. The integration of eye-movements and EEG in the FRP approach might bring us an important step closer in the aim of observing behaviour and experience in its natural context – as a human's interaction with the real world.

4. Experimental procedures

4.1. Subjects

Twenty students (12 female) of the Freie Universität Berlin (mean age 24;6 [years;month]) participated in the study, all were native German speakers with normal or corrected to normal vision, and all except one were right handed.

4.2. Experimental procedure

To obtain the electrophysiological correlates of the old/new effect, a continuous recognition paradigm (Friedman, 1990) was applied: A series of five words was presented and participants had to indicate via button press, whether the fifth word – the target word – was already present among the preceding four words (old-condition) or not (new-condition). Of theoretical relevance were the brain potentials during the processing of the target words in the fifth position. In the present study, the continuous recognition paradigm was realized in both, an ERP and a FRP setting: In each setting every participant attended 100 trials in the old-condition and 100 trials in the new-condition, resulting in 400 experimental trials in total. In both settings, words were presented in uppercase Courier font on a gray background (RGB: 170,170,170) with the first words of a series in black color and the target word in dark gray color (RGB: 136,136,136). To familiarize the participants with the task demands, in both settings 10 practice trials preceded the experimental trials.

In the ERP setting, the five words of a trial were presented serially, word by word, centered on the screen. Every trial started with “xxxxxx” indicating allowance for eye-blinks, presented for a variable duration between 1500 and 3000 ms (in order to prevent phase lock on trial timing), which was followed by a 2000 ms blank screen. Subsequently, the five words were presented for 800 ms, one after another with a 500 ms blank screen in-between; the fifth word remained on the screen until button press. The trial finalized with a 2000 ms blank screen.

For FRP recording, the five words of a trial were presented all at once, horizontally in a row, which was vertically centered on the screen. As in the ERP setting, trials again started with an indicator for eye-blinks, followed by a 2000 ms blank screen. Subsequently, a fixation cross was presented that remained until fixated by the participant (or up to 5000 ms in case of poor eye-tracking calibration, resulting in an automatic calibration verification and, if necessary, a recalibration). The fixation cross was followed by a 200 ms blank screen. Subsequently, the row of five words was presented (with the first letter of the first word in the position of the preceding fixation cross) remaining on the screen until button press. To prevent regressive saccades from the target word back to the preceding four words, a boundary technique was applied: after already having fixated the target word, all letters

Table 1 – Target words were matched upon 11 parameters relevant in visual word recognition

	Event-related potentials (ERPs)		Fixation-related potentials (FRPs)		F
	New	Old	New	Old	
	M (S.D.)	M (S.D.)	M (S.D.)	M (S.D.)	
Frequency ^a	32 (50)	32 (36)	32 (43)	33 (41)	<1
Bigram count [N]	568 (493)	568 (533)	570 (526)	562 (502)	<1
Bigram frequency	8142 (8786)	7778 (12548)	8031 (13562)	8053 (13001)	<1
Syllables [N]	1.82 (0.39)	1.81 (0.39)	1.81 (0.39)	1.79 (0.41)	<1
Letters [N]	5.69 (1.19)	5.71 (1.19)	5.73 (1.19)	5.75 (1.19)	<1
Neighbors [N]	1.96 (2.54)	1.97 (2.28)	2 (2.3)	1.94 (2.27)	<1
Frequency of neighbors	171 (646)	171 (1005)	178 (997)	180 (863)	<1
Higher frequency neighbors [N]	0.59 (1.27)	0.6 (1.2)	0.57 (1.21)	0.57 (1.21)	<1
Frequency of higher frequency neighbors	165 (642)	161 (999)	170 (995)	170 (854)	<1
Emotional valence ^b	0.22 (1.43)	0.22 (1.45)	0.22 (1.5)	0.22 (1.54)	<1
Imaginability ^b	4.41 (1.37)	4.35 (1.33)	4.36 (1.39)	4.27 (1.35)	<1

Statistical analysis did not reveal reliable differences between the four categories (all $F_s < 1$). Means (M) and standard deviations (S.D.). ^aBaayen et al. (1993). ^bVö et al. (2006).

of the first four words were replaced by '#’s in case participants tried to look back on them.

4.3. Stimulus material

To implement a continuous recognition paradigm, an old- and a new-condition were realized. Trials were made up of series of five words. Trials in the old-condition consisted of three filler and two target words (with the first occurrence of the target word in the first, second or third position and the second occurrence in the fifth position). Trials in the new-condition consisted of four filler words and a target word in the fifth position. The continuous recognition paradigm was realized with different stimulus material for the ERP and FRP setting, with a condition consisting of 100 trials, resulting in a total of 400 different trials. Therefore, 400 target words (2 [FRP vs. ERP] × 2 [old vs. new] × 100) and 1400 filler words (2 [FRP vs. ERP] × 3 [positions] × 100 filler words in the old-condition and 2 [FRP vs. ERP] × 4 [positions] × 100 filler words in the new-condition) were selected. The target words of the four different

categories were matched upon 11 parameters that are known to be relevant in visual word recognition (see Table 1).

Furthermore, to prevent spillover effects, the filler words that immediately preceded the target words of the four different categories were matched upon 9 parameters (see Table 2).

4.4. Apparatus

Multichannel EEG was recorded in the ERP and the FRP setting from 27 Ag/AgCl electrodes mounted on standard positions according to the 10–20 system with a modular elastic cap (Easy Cap, Falk-Minow Systems, Germany). Signals were amplified by a Brainamp (Brainproducts, Germany) 32-channel amplifier system with a band-pass of .01–70 Hz and a 50 Hz notch-filter. All electrodes were recorded against a common reference (linked earlobes), the signal was digitized with a sampling rate of 250 Hz. To monitor horizontal and vertical eye-movements, EOG was recorded bipolar from the outer canthus of each eye and above and below the right eye,

Table 2 – Filler words in the fourth position preceding the target words were matched upon 9 parameters relevant in visual word recognition

	Event-related potentials (ERPs)		Fixation-related potentials (FRPs)		F
	New	Old	New	Old	
	M (S.D.)	M (S.D.)	M (S.D.)	M (S.D.)	
Frequency ^a	10 (34)	10 (28)	10 (27)	10 (25)	<1
Bigram count [N]	256 (299)	260 (301)	266 (287)	258 (310)	<1
Bigram frequency	4949 (6509)	4942 (6292)	4911 (7358)	4840 (5801)	<1
Syllables [N]	1.86 (0.35)	1.84 (0.37)	1.83 (0.38)	1.85 (0.36)	<1
Letters [N]	6.16 (1.43)	6.12 (1.42)	6.12 (1.41)	6.16 (1.41)	<1
Neighbors [N]	1.50 (2.07)	1.41 (2.11)	1.45 (2.04)	1.45 (1.98)	<1
Frequency of neighbors	208 (1661)	209 (1057)	216 (1941)	207 (944)	<1
Higher frequency neighbors [N]	0.77 (1.39)	0.80 (1.27)	0.79 (1.33)	0.79 (1.39)	<1
Frequency of higher frequency neighbors	206 (1661)	207 (1056)	213 (1941)	204 (945)	<1

Statistical analysis did not reveal reliable differences between the four categories (all $F_s < 1$). Means (M) and standard deviations (S.D.). ^aBaayen et al. (1993).

respectively. Impedances for scalp electrodes were kept below 5 k Ω . In the FRP setting eye movements were recorded from the left eye using a video-based IView X Hi-Speed eye tracker (SensoMotoric Instruments, Germany) with a sampling rate of 250 Hz. Participants were seated in a distance of 50 cm to a 17" CRT monitor connected to an IBM compatible desktop computer; stimulus presentation was controlled by Presentation (Neurobehavioral Systems, Canada). Uppercase letters of the stimulus material were 11 mm high and therefore corresponded to a vertical visual angle of 1.3°. In the ERP setting, the time-point of stimulus presentation was registered by the EEG recording equipment via standard communication. In the FRP setting, the point in time of presentation of the five words (that were presented all at once) was simultaneously registered by the EEG- and the eye-movement recording equipment, thereby guaranteeing synchronization of EEG and eye-movement recording and allowing later off-line analysis.

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