CHAPTER 47

Eye movements and concurrent event-related potentials': eye fixation-related potential investigations in reading

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Abstract

The eye-fixation related potential (EFRP) technique is based on electroencephalogram (EEG) measurements of electrical brain activity in response to eye fixations. EFRPs are extracted from the EEG by means of signal averaging but in contrast to conventional event-related potential (ERP) technique the averaged waveforms are time-locked to the onset and offset of eye fixation, not to the onset of stimulus events. EFRPs have shown to be a useful technique, in addition to eye movement recordings, to investigate early lexical processes and for establishing a timeline of these processes during reading. Moreover, the technique permits one to analyse the EEGs in a natural condition allowing the investigation of complex visual stimuli such as visual scenes or three-dimensional images. However, some challenges remain to be solved. Among them, we discuss the saccadic contamination and the overlap effects that may distort the findings and we propose some suggestions that might improve these issues. EFRPs may also represent a point of interest for many applications involving tools for disabled people, video games, or brain–computer interfaces.

Introduction

In the last 20 years computers and other electronic equipment have become remarkably important for vision research and cognitive psychology in general. While offline techniques such as questionnaires and recall tests were primarily used in experimental psychology during the 1960s and 1970s, the progress in computer science and electronics has allowed development of very accurate equipment for tracking cognitive processes online. Among these techniques, two methods, eye tracking and event-related potentials (ERPs), have become very popular and widely used in laboratories. Both of these techniques hold the potential to give a precise timeline description of processes over time and this temporal accuracy helps to refine the cognitive modelling. However, both techniques also have severe limitations. In this chapter, we start by reviewing the advantages and limitations of these techniques in order to show how their combination can provide a better understanding of cognitive operations. Indeed, seeking a convergence between different techniques has become an actual challenge for many laboratories in brain research and cognitive psychology. There are several attempts to combine EEG and functional magnetic resonance imaging (fMRI) (Rossell et al., 2003), magnetoencephalography (MEG) and fMRI (Sato et al., 2008), and fMRI and eye tracking (Brown et al., 2008) with the aim to find the best cognitive measurement. We will describe here how it is possible and relevant to combine ERP and eye tracking recordings (the so-called eye fixation-related potential (EFRP) technique) and how this EFRP technique can provide valuable information about cognitive processes underlying reading. Finally, we will review a number of challenges to be addressed in the future for improving this technique and to succeed in establishing a reliable technique for investigating cognition.

ERPs and eye movements are complementary techniques

ERPs are widely used in cognitive neuroscience to capture cognitive processes and their time-course with a high temporal resolution (Hillyard and Kutas, 1983). ERPs reflect electrical brain activity (primarily summed postsynaptic potentials of pyramidal cells in the neocortex) that is associated with sensory or cognitive events. ERPs emerge after averaging continuous electroencephalogram (EEG) recorded during many presentations of stimuli. These time-locked average waveforms show several positive (such as P1, P300, etc.) or negative (such as N1, N400, Contingent Negative Variation, etc.) components within a certain latency range after an event onset. Each component has a characteristic scalp distribution, some differences in polarity (positivity or negativity), amplitude, or latency that permit us to correlate them to particular cognitive processes (for a review, see Rugg and Coles, 1995). This technique has been used to investigate mechanisms of sensory memory (for review, see Näätänen, 1990 and Näätänen et al., 1978), semantics of language (for review see, Kutas and Federmeier, 2000; Kutas and Hillyard, 1980), and visual perception (for a review, see Hegdé, 2008).

However, the ERP signal is contaminated by saccades and cannot be recorded with cognitive activities requiring a free visual inspection (i.e. with sequences of saccades). This limitation strongly constrains the use of this technique in a natural environment. Although several techniques such as multisource component analysis (Berg and Scherg, 1994) and regression-based methods (Wallstrom et al., 2004) have been developed to cope with these ocular artefacts, researchers usually reject the contaminated EEG segments resulting in data loss (Junget al., 2000). In order to avoid such ocular artefacts caused by excessive saccadic eye movements (blinks, saccades), stimuli are therefore presented in isolation and subjects are asked to maintain their eyes fixated on the display and instructed to avoid any eye movements. This, however, creates, difficulties, especially when reading, visual scene perception, or object recognition are under investigation.

Another serious difficulty with the ERP paradigm is that these isolated stimuli are displayed with unnaturally long intervals between them (>500 ms or 1000 ms). These long delays serve to prevent the overlap between cognitive processes (Dambacher and Kliegl, 2007). They might also explain why rather late components such P300 and N400 have been investigated for studying cognition. For example, in reading studies, the presentation of words isolated with long interstimulus interval (ISIs) (as in Hillyard et al., 1983) prevents the study of any anticipatory or overlapping processes (spillover effects) which occur normally during text comprehension. This situation is far from a natural reading process and the ecological validity of the experimental results is questionable. In real life, most cognitive activities which involve a sequence of visual fixations to inspect the environment have a great majority of fixations lasting less than 300 ms In reading once again, typical fixation lasts around 200 or 250 ms and during this time period all perceptual and cognitive operations are realized. In reality, studying the typical late ERP components in reading, such as P300 and N400, means that the eyes have already moved to the next word when the peak of these components appears.

Eye movement measurements provide a complementary method to capture cognitive processes with a high resolution. The eye tracking technique provides data about the positions and timing of eye fixations with a high spatial (<0.5° visual angle) and temporal accuracy (>1 kHz). It also allows one to distinguish between early and late processing by comparing first-pass fixations (fixations occurring in a certain region of interest for the first time) with second-pass fixations in the same region in order to capture the processes associated with reprocessing or verification. The eye tracking technique has been used widely during reading, scene viewing, and visual search tasks but also to investigate attentional effects during spoken language comprehension (Tanenhaus et al., 1995). Eye movement variables (such as fixation duration, timing, and saccadic path) provide a robust measure of underlying cognitive processes. In reading studies, for example, it has been shown that fixation duration to a lexically frequent word is shorter than to a non-frequent word (Rayner 1998) or that the length of scan path can provide a good index of ergonomic difficulty on an interface (Goldberg and Kotval, 1998).

One of the major difficulties in interpreting the eye movements is to determine whether a fixation represents rather deep processing (i.e. semantic processing) or more superficial processing. The researcher can only rely on temporal variables (gaze duration, 1st pass fixation duration, etc.) obtained in certain experimental conditions for interpreting the meaning of these fixations. However, even in this case, the interpretation is not still ensured due to the large variability (between and within-subjects, tasks, etc.) on fixation durations and it would be beneficial to have other indices that might confirm or invalidate it.

Combining measures of ERPs and eye movements: EFRP technique

In our view, ERPs and eye movements provide complementary measures to capture cognitive processes providing the possibility to find out precisely when and in which order (in a text or visual scene) different cognitive operations occur. This approach has been used by measuring ERPs and electro-oculogram (EOG) simultaneously (Yagi et al., 1998; see also the literature on saccade-related potentials), or by measuring eye movements with an eye tracker and ERPs in separate sessions (Sereno et al., 1998), or by measuring ERPs and eye movements by an eye tracker simultaneously (Baccino and Manunta, 2005; Hutzler et al., 2007). Each of these approaches has, however, some limitations and further development is needed to understand the underlying cognitive processes during single eye fixations. In the following section these approaches are briefly described and the synchronized measuring technique is explained in detail.

EOG-based EFRPs

As early as 1964, the analysis of eye movements recorded concurrently with ERPs was used to investigate the neural processes associated with saccades (Gaarder et al., 1964). The so-called saccade-related potentials used EOGs that were measured simultaneously with EEG by electrodes placed on the scalp and around the eyes—horizontal and vertical EOGs, respectively. The EEG signals were time-locked to the onset of the saccades. These neurophysiological investigations were not focused on cognitive processes occurring during a fixation (on a meaningful stimulus) but rather by the topography (frontal or parietal areas) and temporality of human brain potentials *preceding* saccades (visually triggered or self-initiated). In particular, they widely used the well-known pro- and antisaccade task (Brickett et al., 1984; Evdokimidis et al., 1991, 1996; Everling and Fischer, 1998; Everling et al., 1997; Kurtzberg and Vaughan, 1982; Moster and Goldberg, 1990). The pro- and antisaccade terms refer to saccades that are performed towards a target (Pro-) or to the opposite side (Anti-). The overall scope was to determine whether a reflexive response (prosaccade) might be suppressed by a voluntary motor act (antisaccade). In particular, the task served to investigate pathophysiological mechanisms of several disorders of the central nervous system and has been used as a diagnostic tool.

The term EFRP was first introduced by Yagi and colleagues (Joyce et al., 2002; Yagi and Ogata, 1995; Yagi et al., 1998). EFRPs consisted of time-locking the EEG signals to the offset of saccadic eye movements and not at the onset of stimulus events, as in the conventional ERP studies and averaged them to obtain EFRPs for single eye fixations. The most prominent component of the EFRP is called the lambda response, which is a positive component with a latency of about 80 ms from the offset of saccades (Kazai and Yagi, 2003). The lambda response has been shown to exhibit changes with properties of the visual stimulus (e.g. Kazai and Yagi, 1999) and attention (Yagi, 1981). The purpose of these EFRP experiments has been to focus the interest on early ERP components showing that even at these short latencies cognitive signals might be extracted (and not only visual-evoked potentials). However, EFRP technique based on measuring EOG does not provide an accurate measurement of fixation location since the eye position is not tracked directly but recalculated from calibrated positions. Furthermore, the EOG method is sensitive to changes in luminance and the ability to accurately identify the amplitudes for small saccades is not very precise. EOG literature is replete with examples showing the limits of such a practice to determine the spatial accuracy of a fixation (Marton and Szirtes, 1988a, 1988b). For a wide applicability of the EFRP technique, the exact determination of a subject's gaze position by means of an eye tracker is inevitable.

Infrared eye tracking-based EFRPs in two separate sessions

In some other studies, the analyses of eye movements concurrently to ERPs have been made by running two experiments in parallel: one using eye tracking and the other ERPs, but with *different* subjects (Dambacher et al., 2007; Sereno and Rayner, 2003; Sereno et al., 1998). Trying to establish a timeline of lexical processing, Sereno et al. (2003) showed interesting findings on early components (P1, N1, P2) appearing during a single fixation. ERPs appeared to be sensitive to lexical processing as early as 100 ms and to context effects as early as 132 ms (132–192 ms) after stimulus presentation. However, due to parallel and not simultaneous measures of ERPs and eye movements, the results are not confirmative because they come from different experiments increasing the variability of data.

Infrared eye tracking-based EFRPs

The EFRP technique has been recently improved by synchronizing the measures from an infrared eye tracker with an EEG permitting the recording of data simultaneously (Baccino et al., 2005; Hutzler et al., 2007; Simola et al., 2009). The setup of an EFRP experimental platform is based on two computers generally connected through their parallel ports (Fig. 47.1).

While one computer (A) is devoted to stimulus presentation and eye movement (EM) acquisition, the other one (B) collects the EEG signals. The coupling of the two systems is achieved by sending a synchronization signal (TTL Trigger) as soon as the stimulus (words, images, etc.) is presented on the display (stimulus onset). The synchronization signal enables the EM and EEG data to be recorded simultaneously and to get an accurate timestamp for offline data matching. Therefore, one important thing is to ensure that both signals are sampled at the same rate. A sampling rate around 1 KHz is, at present, possible with many EEG and eye trackers and this frequency appears preferable to detect fine processes occurring within a fixation. EFRPs will emerge with segmentation of the continuous EEG signal with reference markers such as fixation onset and offset detected during eye movement analysis. As in ERP studies, EFRPs are obtained by averaging the EEG epochs for every fixation on a specific stimulus but are shorter in time than ERPs.

The EFRP technique has several advantages when compared with previously techniques using EOG or recording eye movements and ERPs in separate sessions.

- *Same subject, same stimulus:* one of the most important advantages is to directly correlate the eye fixations with the EEGs for the same subject, the same stimulus, and within the same region of interest. This procedure decreases the data variability observed in comparing eye movements and ERPs in separate sessions and ensures better interpretation of the underlying cognitive processes.

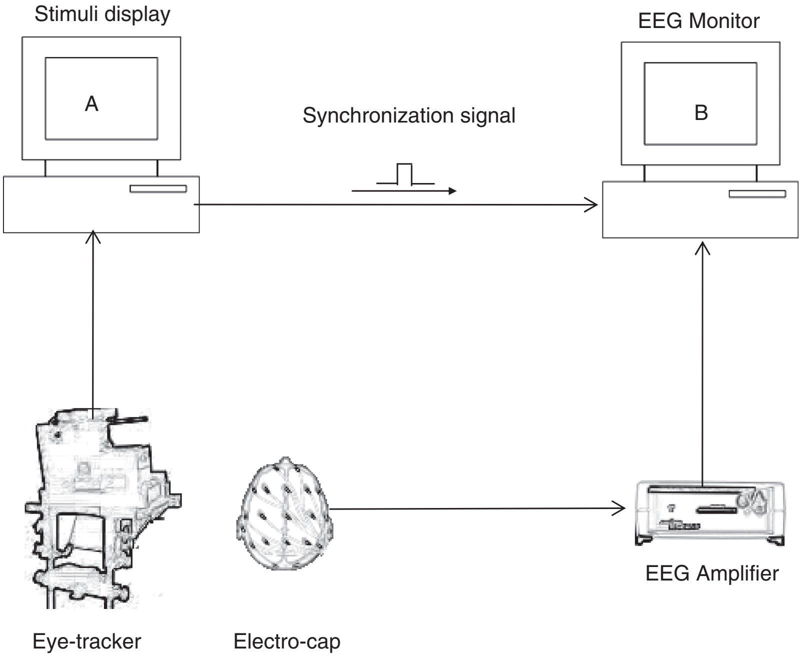

Fig. 47.1 Experimental set-up for recording EFRPs. A TTL trigger synchronizes two computers, one (A) dedicated to presentation of stimuli and eye tracking, and the other one (B) monitoring and recording the EEG.

- *Precise time line:* combined with an eye tracker at high temporal resolution (≥1 KHz) and high accuracy (<1° visual angle), EFRP technique allows one to establish a precise time course of the activation/inhibition sequence of EEG waveforms underlying any fixation. Thus, it is possible to know what EEG components are correlated to a fixation on a specific stimulus and this can be fruitful for cognitive interpretation and modelling. In this sense, the EFRP technique acts as a zoom into a fixation and permits to investigate the role of early components in cognitive activity rather than late components which have been extensively studied by the conventional ERP paradigm. However, some challenges have to be solved as the overlap problem associated to short stimuli presentation (Dambacher et al., 2007) and some suggestions will be given in the next section.
- *Natural context:* another major advantage of the EFRP technique is the ability to capture ERPs in a natural context. As we have seen, the artificial presentation of stimuli during a conventional ERP paradigm requiring a steady gaze during one or more seconds is no longer employed with EFRPs. This artificial presentation could sometimes be the cause of severe restrictions especially for studying spillover effects[1] or integrative processes (as in text comprehension). With the EFRP technique, experimental settings allowing for a strong ecological validity can be used since the technique allows one to move the gaze freely onto any complex stimuli (text, visual scenes, etc.).
- *Categorizing fixations:* recently, Unema et al. (2005) have shown by crossing fixation duration with the amplitude of the following saccade that fixations, at least during free viewing, can be categorized as ambient or focal fixations. EFRP analyses should be able to improve this categorization process by analysing the corresponding EEGs components and detect whether some attentional component can be associated to the fixation. Separating these components with statistical procedures (see next section) but also the localization of the activation (on which electrode) may

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[1] Effects coming from the previous word and spread out on the next word.

be highly informative for labelling fixations. These findings will contribute greatly to interpreting scanpaths and fixations on some region of interests in real life activities.

EFRPs during reading tasks

One of the most well-studied ERP components associated with reading is the N400 component which occurs several hundreds of milliseconds after word presentation. There is extensive evidence that the occurrence of the N400 component is related to semantic priming that indicates a semantic relationship between a word and the context in which it occurs (e.g. Kutas et al., 1980, 2000). In a typical N400 experiment, a subject reads a sentence having either a semantically incongruent or congruent sentence ending (Federmeier and Kutas, 1999). The amplitude of the N400 component is smaller for congruent compared with incongruent sentence endings suggesting that more lexical search is required during the incongruent condition. However, during the natural reading process the eye fixations are short (around 200 to 250 ms) which constrains the amount of time for lexical processing and oculomotor operations (Rayner, 1998). As a consequence, ERP components occurring later than 250 ms overlap with those in response to the next word (Dambacher et al., 2007). It seems therefore important to examine the early components and to find out about their role in lexical processing. Only a few studies have examined early components by comparing eye movements and early ERPs (e.g. Sereno et al., 1998, 2003). In both of these studies, ERPs and eye movements were recorded in two separate sessions with different subjects.

In Sereno et al. (1998), eye movements and the ERPs were recorded while the subjects were reading single-line sentences and performing a lexical decision task for words presented in isolation, whereas in the other study, the subjects were reading sentences. However, the words were presented word-by-word, and the target word was always at the end of the sentence (Sereno et al., 2003). High- and low-frequency regular words were compared with high- and low-frequency non-regular words. ERP outcomes showed that a lexical effect emerges around 100 ms post-stimulus as reflected by P1 component, followed by N1 and P2 components associated with word frequency and regularity, respectively (Sereno et al., 1998). On the other hand, Raney and Rayner (1993) studied mechanisms of rereading by recording eye movements and ERPs also in two separate sessions. Eye movement recordings showed that reading speed increased during the second reading, that is, forward fixation durations were shorter, the number of forward fixations decreased, and forward saccade lengths increased. The ERP results showed that the amplitude of N1–P2 complex increased during the second reading, suggesting that during the second reading 'lower level' demands such as initial perceptual and comprehension processes decreased and this facilitation is reflected in the magnitude of N1–P2 responses. As mentioned previously, all of these comparative studies between ERPs and eye movements did not use real EFRPs since both measures have been made with different subjects in separate sessions.

In a first study on reading using a real EFRPs technique, Baccino et al. (2005) recorded EEGs and eye movements simultaneously during a priming task. The prime and the target words were presented simultaneously and subjects were asked to make a judgement about semantic relatedness after reading the two words. The aim of the work was to study parafoveal-on-foveal effect, that is, whether the processing of the next word (word on the right) affects the processing of the fixated word in order to test whether parallel or sequential processing occurs during reading and whether semantic processing occurs in the parafoveal field during early lexical processing. The results showed that even first-pass fixation duration (summed fixation duration before the eyes moved to the second word) did not show any evidence for semantic processing during parafoveal processing, the early EFRPs in response to prime words were sensitive to lexical processing of the target word, especially at occipital O1 electrode (Fig. 47.2). A marginally stronger effect was found for the amplitude of N1 component at around 120 ms post-stimulus. Similarly, a stronger effect was found for non-associated than for non-words for a positive component appearing around at 140 ms post-stimulus at the central and frontal recording sites. These results suggest that these early ERP effects are due to sensitivity to word form in parafoveal area and preventing semantic access of illegal form for further processing. Semantic effects were observed in the P2 component (peaking around 215 ms) which was more pronounced

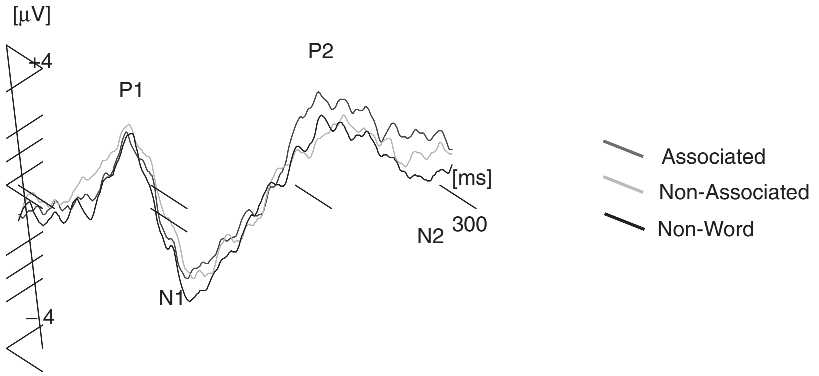

Fig. 47.2 Grand-averaged EFRP waveforms recorded at the left occipital electrode (O1) during three conditions: associated, non-associated and non-word prime-target word pairs.

during processing of prime words followed by associated other than non-associated target words suggesting that semantic processing occurs parafoveally during early lexical processing.

However, in all previous ERP studies, the reading process was mimicked by presenting the words in isolation (Sereno et al., 1998), word-by-word (Sereno et al., 2003), or presenting only two words simultaneously (Baccino et al., 2005). It is questionable whether these paradigms are suitable enough to study the mechanisms of reading or whether they instead capture processes related to single word processing. As a consequence further investigations are needed in order to understand the mechanisms underlying reading sentences but also to find out whether the EFRP technique brings added value in comparison to conventional ERP studies in this area.

In a recent study, Hutzler et al. (2007) attempted to validate the EFRP technique by comparing it with the conventional ERP technique on a very known effect in visual word recognition: the old/new effect (Rugg and Nagy, 1989). This effect is characterized by a positive component peaking around 250 ms for correctly recognized old words. Subjects were instructed to read a sentence with five words presented concomitantly in a row. After correcting the EOG artefacts with an independent component analysis (ICA), similar results were acquired using both techniques. Brain potentials associated with old words were more positive at the right than the left recording sites and in anterior and central regions as reported earlier by Rugg et al. (1989). This positivity occurred in a time window from 250 to 600 ms after reading the last word in a sentence. With this striking similarity of effects, the authors conclude that EFRPs are as reliable indicators of word processing as conventional ERPs.

Challenges in EFRP research

While the EFRPs seem to have a promising future in the cognitive toolbox, some challenges remain to be solved for rendering this technique efficient and reliable. In particular, further investigations are needed to understand which factors have a prominent contribution to EFRP waveforms by removing the effects of previous saccadic amplitude and microsaccades within the fixation and by analysing the effects of overlap processes. These questions cannot be only processed by psychologists but require the contribution of more formal sciences such as mathematics, statistics and signal processing. This renders this technique highly interdisciplinary and very challenging.

EEG source separation: overlap responses, saccade and microsaccade artefacts

During a conventional ERP paradigm, the EEG signal is contaminated by saccadic eye movements. While in the EFRP paradigm, theoretically only the EEG segments occurring during a visual fixation are analysed (and so eye movements are filtered out), it is still possible that these EEG segments are contaminated by saccadic eye movements that precede or follow fixations. A number of ocular corrections algorithms (Schwind and Dormann, 1986; Vigário, 1997; Wallstrom et al., 2004) have been applied to EEG analyses and one challenge would be to test whether they can also be applied to EFRP data.

Furthermore, since the eye is always in motion even during a fixation, miniature saccades (microsaccades, drifts, tremors) are actively generated involuntarily and unconsciously. It is still possible that this microsaccadic[2] activity represents an artefact which complicates the interpretation of EFRPs. A real challenge in EFRP technique is therefore the correction of these artefacts caused by saccades and microsaccades.

Finally, since EFRPs have very short duration (corresponding to duration of a given fixation) neural responses elicited by successive fixations can temporally coincide and produce a strong overlap of cognitive components. Many potential pitfalls can result from this adjacent-response overlap and it can distort the EFRPs averages. A challenge would be to solve this overlap problem.

All these potentials problems (saccades, microsaccades, and overlap) are related to the fact that the EFRP waveforms are complex and difficult to interpret. So, the question for the future, which is also the case for classical ERP studies, would be to dissociate this complex signal into a set of simpler signals in order to determine more clearly the underlying cognitive processes correlated with them. This question has received a lot of consideration in the past mainly by using several decomposition methods.

Saccades artefacts and ocular corrections

As stated above, the EEG signals are contaminated by extracerebral artefacts of biological origin, originating outside the brain, but still recordable from the scalp (Gratton, 1998; Schwind et al., 1986; Vigário, 1997). These extracerebral signals come mainly from tongue, facial, jaw, and neck muscles which generate a persistent low-voltage high-frequency signals (>20 Hz) with focused spatial distribution and rapidly decaying autocorrelation function (Whitham et al., 2007). Since, these artefacts have characteristic signatures in space, time, and frequency, definitely distinct from EEG spontaneous activity (Picton et al., 2000), a number of valuable statistical techniques have been developed to handle these ocular artefacts in the EEG signals and to remove them. The best known methodology for doing this is blind source separation (BSS) based on second-order statistics (such as autocorrelation) or based on higher-order statistics such as principal component analysis (PCA) or independent component analysis (ICA) (Congedo et al., 2008). The principle of BSS is the separation of a set of signals from a set of mixed signals, without the aid of any information (or with little information) about the source signals or the mixing process. BSS can be applied only if source signals does not correlate with each other and thus the separation is realized such that the regularity of each resulting signal is maximized, and the regularity between the signals is minimized (i.e. statistical independence is maximized). BSS methods have proven their usefulness in the removal of eye blinks from the EEG signals because of their high energy (Jung et al., 1998, 2000) and recently to identify the signal of cognitive load in pupillary responses (Jainta and Baccino, 2010). But eye movements, both volitional movements, saccades and microsaccades, generate smaller brain potentials than do blinks and the question is whether these BSS methods can also be applied here. This has been suggested in a comparative study testing different BSS methods (Wallstrom et al., 2004). Other approaches have been introduced using Bayesian techniques (Roberts, 1998) or incorporating a model of brain activity to detect already known brain components (Berg et al., 1994). The research on EEG source separation is still in constant evolution and the challenge for EFRP studies will be to investigate which of the different ocular correction algorithms have to be chosen or developed for having the most reliable EFRPs possible.

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[2] Here, the term microsaccade will be used generically.

Microsaccades artefacts

Microsaccades (Engbert 2006; Martinez-Conde et al., 2004, see also Martinez-Conde and Macknick, Chapter 6, this volume) are small saccades (mostly <0.5°) occurring involuntarily during fixation. Their role seems to neutralize the natural perceptual fading caused by retinal adaptation during fixation. Even under stabilized conditions of visual stimulus presentation as used with a conventional ERP paradigm, the micro-saccadic activity can be a source of artefacts, specifically an induced enhancement of power in the gamma band (30–70 Hz) around 200–300 ms following stimulus onset. Usually, this gamma-band activity is widely assumed to reflect synchronous neural oscillation associated with perceptual binding (i.e. binding of visual elements into unitary percepts) (Tallon-Baudry et al., 1996), recognition of object category and familiarity (Tallon-Baudry et al., 1997), attention (Kaiser and Lutzenberger, 2005), and consciousness (Summerfield et al., 2002). Recently, it has been suggested that this synchronization reflects rather the outcome of ocular muscle spike potentials generated by microsaccades (Yuval-Greenberg et al., 2008). Most of the classical ERP studies do not control microsaccades although they can represent a serious source of artefacts and consequently for EFRPs analyses. However, due to their weak electrical activity generated, microsaccades cannot be removed automatically by BSS techniques as for saccades previously. Consequently, one challenge is to devise new methods capable of identifying the electrical signature of microsaccades in EFRPs signal according to their characteristics.

Overlap processes occurring during short EFRPs

EFRPs are obtained by signal-averaging EEG epochs which are time-locked to eye fixations. However, as EFRPs are especially short in time around 200–300 ms—which is the delay for fixation duration on average in reading—they can overlap in time because of successive fixations. This overlap can distort the EFRPs averages mostly in the earliest components (P1, N1). A future challenge in EFRP research will be to analyse the distortion of these EFRP averages provoked by the adjacent-response overlap in order to isolate the different components and permit their interpretation. Various methods may be employed to deal with this overlap.

A promising approach seems to be those employed by Woldorff (1993) with a set of algorithms (ADJAR for Adjacent Response Technique) that might be applied to dissociate the effects coming from successive fixations (Talsma and Woldorff, 2005). At the origin, this method has been devised to cope with the overlap problem occurring in the ERPs recorded at high stimulus presentation rates (i.e. short ISIs). Indeed, at short ISIs, the ERP responses to successive stimuli may overlap and distort the ERP averages. The case is similar for eye fixations. The procedure works in two steps: first, by subtracting out the differential distortion from previous fixation overlap and secondly by using an iterative algorithm trying to converge toward the best estimates of the waveform (i.e. by removing distortions resulting from overlap by both previous and subsequent fixation). The method has been employed successfully for dissociating attentional components (Fu et al., 2005) or removing overlap from scalp-recorded activity (Hopfinger and Maxwell, 2005).

Another approach would be to employ a statistical decomposition method already known for removing ocular artefacts and which also may be used to dissociate the different subcomponents which occur during EFRPs data. PCA and ICA are of course popular methods that can be used for this purpose (see also the description of BSS methods given earlier) and are used to create space/time decompositions of the EEG signal. All of them attempt to decompose an array of data into sets of component scores and loadings (Shaw, 2003) using eigenvalue decomposition to derive the components of EEG signals. While PCA supposes that EEG sources are spatially orthogonal to one another (i.e. independent of each other), ICA segregates these EEG sources using non-orthogonal (oblique) factors. A priori, there is no reason to believe that distinct EEG sources are spatially orthogonal and this explains why ICA is generally preferred to PCA (Jung et al., 1998, 2000) for this objective. The ICA approach is better for the study of cortical sources of ERP because ICA components tend to result in single components that are a result of single cortical sources, whereas PCA components often result in single components that are linear combinations of multiple underlying sources and must be modelled with multiple-dipole source models (Richards, 2004). Actually, the problem with these statistical techniques lies in the interpretation of the different isolated components, namely how to associate components to cognitive processes–attention, semantic. . . . One way would be to go beyond the two-way data used in PCA/ICA and overcome the typical time-frequency decomposition of single channels. Such methods are called multi-way methods (Miwakeichi et al., 2004; Mørup et al., 2006) and permit to add more variables into the analysis such as channels, subjects, conditions, etc. One of these multiway methods is the Parallel Factor Analysis (PARAFAC) used in several papers for separating multiple potential components in the EEGs (Mørup et al., 2006, 2007). We assume that PARAFAC may be also well adapted to separate different components elicited by successive fixations (as EFRPs) in entering them into the analysis. This operation should cope with the overlap difficulty inherent to EFRPs and this type of work should be carrying out in the future.

Categorizing fixations and ecological impact

One of the most difficult exercises for any scientific experimenter is to interpret different measures recorded during an experiment. Measurement is usually very variable according to subject variability or task characteristics. As we seen in previous sections, the problem is also obvious for both eye tracking and ERP techniques. For example, how is it possible to compare two fixations apart from their duration or from the orientation of the previous saccade (backward vs. forward saccade) and to be able to interpret the underlying processes occurring during this fixation? One of the major advances of the EFRPs should be to succeed in categorizing or describing more accurately eye movements (fixations and saccades) as a function of the concurrent EEG measures. However, as in any fixation several components overlap, a challenge in the development of the technique would be to index some specific brainwaves that might correlate closely to some cognitive processes (attention, perception, etc.) as the N400 is an index of semantic incongruity. This challenge certainly needs the development of appropriate signal processing analyses as shown above and also to test on simple tasks dedicated to one component the characteristics of the associated EFRPs. Once these questions are addressed, it would be possible to improve the interpretation process by generating some interpretation maps which consists of visualizing the attentional/perceptual/semantic components coupled with gaze positions. Until now, these maps can only represent the position or duration of fixations but with the adjunct of EFRP analyses, it would be possible to categorize fixations from their principal component. For example, in the Unemà experiment (2005) which aims to disentangle between ambient or focal fixations by crossing two different variables (saccade extent and fixation duration), EFRPs will surely bring better information about the characteristics of EFRPs associated with each fixation and would facilitate the cognitive labelling of these fixations. Furthermore, the activation/inhibition phases can be spatially localized on the scalp and this spatial information can provide some information about the type of processing involved. Let's take an illustration from the distinction between ambient/focal fixations during the perception of visual scenes (Velichkovsky, 2002). As the author pointed out, there is a possibility that during the ambient processing (preattentive mode) the neural substrates in the 'dorsal visual pathway' guide the eye movements and locate the regions of interest for further examination. In contrast, during focal processing (attentive mode), the neuronal network in the 'ventral visual pathway' is thought to be recruited for further analysis of object shape, colour, and texture. If these claims are true, electrodes attached to the dorsal region should be more activated during ambient fixations and electrodes attached to ventral region more activated during focal fixations. In both cases, EFRPs should reflect these two modes of visual processing and may help in classifying fixations as ambient or focal.

An applied perspective of EFRPs: brain–computer interfaces

BCIs is an emergent field of human–computer interfaces (HCIs) which aims to utilize neurophysiological signals (such as EEG or any brain imagery techniques) originating in the brain to control external devices or computers. Of course, the application of BCIs is obvious for impaired people but can have also many other applications in video-game, remote system control (robot, camera, etc.) and any adaptive interfaces in real or virtual environments. However, nowadays, BCI control capabilities are still not comparable to other HCI peripherals such as joysticks or a computer mouse and the technique remains focused on impairments. Most investigated paradigms include motor commands that are either real or imaginary; virtual spellers or object selectors based on the monitoring of the subject's oriented attention, either auditory or visual (Birbaumer et al., 2006). EFRPs and BCI techniques are very close in essence, they represent the two sides of a same principle: how to interpret an EEG signal either to understand cognitive processes in context (EFRPs) or to work out an action by controlling a device in real-time (BCIs). As a consequence, the same questions need to be solved: how to process the EEG (EFRP) signal, what waves patterns can be picked up as detectable cognitive activity and for BCI how to translate them into control devices.

Conclusion and future studies

The EFRP technique has proven to be a useful approach to investigate cognitive processes during reading by simultaneously measuring eye movements and concurrent ERPs. In comparison with conventional ERP technique, it provides a better tool to investigate these processes in a more natural experimental setting, allowing eye movements to occur naturally during reading or viewing. Moreover, EFRP can have a large number of applications with BCIS in adding the eye position information to the recorded continuous EEGs and allowing a more precise knowledge of the underlying cognitive activity. These applicative forms may be useful for the development of assistive technologies for disabled people. However, as with every new methodology, some challenges need to be resolved, particularly the problem of overlapping processes. Decomposition methods seem to be suitable for disentangling the complex brain waves into simpler and interpretable components. Furthermore, more experimental studies are needed to ascertain the role of factors that influence the EFRP components. Despite some methodological drawbacks, coupling of eye movement and ERP recording techniques (that might be called augmented eye movements) provides a valuable tool to explore the neural, cognitive and behavioural mechanisms and their time course during reading or any other cognitive tasks involving visual inputs such as object recognition (Rämä and Baccino, 2010).

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References

Baccino, T. and Manunta, Y. (2005). Eye-fixation-related potentials: insight into parafoveal processing. *Journal of Psychophysiology*, **19**(3), 204–215.

Berg, P. and Scherg, M. (1994). A multiple source approach to the correction of eye artifacts. *Electroencephalography and Clinical Neurophysiology*, **90**(3), 229–241.

Birbaumer, N., Weber, C., Neuper, C., Buch, E., Haapen, K., and Cohen, L. (2006). Physiological regulation of thinking: brain-computer interface (BCI) research. *Progress in Brain Research*, **159**: 369–391.

Brickett, P.A., Weinberg, H., and Davis, C.M. (1984). Cerebral potentials preceding visually triggered saccades. *Annals of the New York Academy of Sciences*, **425**: 429–433.

Brown, M.R.G., Vilis, T., and Everling, S. (2008). Isolation of saccade inhibition processes: Rapid event-related fMRI of saccades and nogo trials. *NeuroImage*, **39**(2), 793–804.

Congedo, M., Gouy-Pailler, C., and Jutten, C. (2008). On the blind source separation of human electroencephalogram by approximate joint diagonalization of second order statistics. *Clinical Neurophysiology*, **119**(12), 2677–2686.

Dambacher, M., and Kliegl, R. (2007). Synchronizing timelines: Relations between fixation durations and N400 amplitudes during sentence reading. *Brain Research*, **1155**, 147–162.

Engbert, R. (2006). Microsaccades: a microcosm for research on oculomotor control, attention, and visual perception. In Martinez-Conde, S., Macknik, S.L., Martinez, L.M., Alonso, J.-M., and Tse, P.U. (eds.) *Progress in Brain Research* (pp. 177–192). Amsterdam: Elsevier.

Evdokimidis, I., Liakopoulos, D., and Papageorgiou, C. (1991). Cortical potentials preceding centrifugal and centripetal self-paced horizontal saccades. *Electroencephalography and Clinical Neurophysiology*, **79**, 503–505.

Evdokimidis, I., Liakopoulos, D., Constantinidis, T.S., and Papageorgiou, C. (1996). Cortical potentials with antisaccades. *Electroencephalography and Clinical Neurophysiology*, **98**, 377–384.

Everling, S. and Fischer, B. (1998). The antisaccade: a review of basic research and clinical studies. *Neuropsychologia*, **36**(9), 885–899.

Everling, S., Krappmann, P., and Flohr, H. (1997). Cortical potentials preceding pro- and antisaccades in man. *Electroencephalography and Clinical Neurophysiology*, **102**(4), 356–362.

Federmeier, K.D. and Kutas, M. (1999). A rose by any other name: Long-term memory structure and sentence processing. *Journal of Memory & Language*, **41**(4), 469–495.

Fu, S., Caggiano, D.M., Greenwood, P.M., and Parasuraman, R. (2005). Event-related potentials reveal dissociable mechanisms for orienting and focusing visuospatial attention. *Brain research. Cognitive Brain Research*, **23**(2–3), 341–353.

Gaarder, K., Krauskopf, J., Graf, V., Kropfl, W., and Armington, J.C. (1964). Averaged brain activity following saccadic eye movement. *Science*, **146**, 1481–1483.

Goldberg, J. and Kotval, X.P. (1998). Computer interface evaluation using eye movements: methods and constructs. *International Journal of Industrial Ergonomics*, **24**, 631–645.

Gratton, G. (1998). Dealing with artifacts: The EOG contamination of the event-related brain potential. *Behavior Research Methods, Instruments & Computers*, **30**(1), 44–53.

Hegdé, J. (2008). Time course of visual perception: coarse-to-fine processing and beyond. *Progress in Neurobiology*, **84**(4), 405–439.

Hillyard, S.A., and Kutas, M. (1983). Electrophysiology of cognitive processing. *Annual Review of Psychology* **34**, 33–61.

Hopfinger, J.B., and Maxwell, J.S. (2005). Appearing and disappearing stimuli trigger a reflexive modulation of visual cortical activity. *Cognitive Brain Research*, **25**(1), 48–56.

Hutzler, F., Braun, M., Võ, M.L.-H., Engl, V., Hofmann, M., Dambacher, M., *et al.* (2007). Welcome to the real world: Validating fixation-related brain potentials for ecologically valid settings. *Brain Research*, **1172**: 124–129.

Jainta, S. and Baccino, T. (2010). Analyzing the pupil response due to increased cognitive demand: An independent component analysis study. *International Journal of Psychophysiology*, **77**, 1–7.

Joyce, C., Gorodnitsky, I., King, J., and Kutas, M. (2002). Tracking eye fixations with electroocular and electroencephalographic recordings. *Psychophysiology*, **39**(5), 607–618.

Jung, T.P., Humphries, C., Lee, T.W., Makeig, S., McKeown, M.J., Iragui, V., *et al.* (1998)**.** Removing Electroencephalographic Artifacts : Comparison between ICA and PCA. *Neural Networks for Signal Processing*, **VIII**, 63–72.

Jung, T.P., Makeig, S., Humphries, C., Lee, T.W., McKeown, M.J., Iragui, V., *et al.* (2000). Removing electroencephalographic artifacts by blind source separation**.** *Psychophysiology*, **37**(2), 163–178.

Kaiser, J. and Lutzenberger, W. (2005). Human gamma-band activity: a window to cognitive processing. *Neuroreport*, **16**(3), 207–211.

Kazai, K. and Yagi, A. (1999). Integrated effect of stimulation at fixation points on EFRP (Eye-fixation related brain potentials). *International Journal of Psychophysiology*, **32**, 193–203.

Kazai, K. and Yagi, A. (2003). Comparison between the lambda response of eye-fixation-related potentials and the P100 component of pattern-reversal visual evoked potentials. *Cognitive, Affective & Behavioral Neuroscience*, **3**(1), 46–56.

Kurtzberg, D. and Vaughan, J.H.G. (1982). Topographic analysis of human cortical potentials preceding self-initiated and visually triggered saccades. *Brain Research*, **243**(1), 1–9.

Kutas, M. and Hillyard, S.A. (1980). Reading senseless sentences: brain potentials reflect semantic incongruity. *Science*, **207**, 203–205.

Kutas, M. and Federmeier, K.D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Science*, **4**, 463–470.

Martinez-Conde, S., Macknik, S.L., and Hubel, D.H. (2004). The role of fixational eye movements in visual perception. *Nature Reviews Neuroscience*, **5**(3), 229–240.

Marton, M. and Szirtes, J. (1988a). Context effects on saccade-related brain potentials to words during reading. *Neuropsychologia*, **26**(3), 453–463.

Marton, M. and Szirtes, J. (1988b). Saccade-related brain potentials during reading correct and incorrect versions of proverbs. *International Journal of Psychophysiology*, **6**(4), 273–280.

Miwakeichi, F., Martínez-Montes, E., Valdés-Sosa, P.A., Nishiyama, N., Mizuhara, H., and Yamaguchi, Y. (2004). Decomposing EEG data into space-time-frequency components using parallel factor analysis. *NeuroImage*, **22**(3), 1035–1045.

Mørup, M., Hansen, L.K., and Arnfred, S.M. (2007). ERPWAVELAB a toolbox for multi-channel analysis of time-frequency transformed event related potentials. *Journal of Neuroscience Methods* **161**(2), 361–368.

Mørup, M., Hansen, L.K., Herrmann, C.S., Parnas, J., and Arnfred, S.M. (2006). Parallel factor analysis as an exploratory tool for wavelet transformed event-related EEG. *NeuroImage*, **29**(3), 938–947.

Moster, M.L. and Goldberg, G. (1990). Topography of scalp potentials preceding self-initiated saccades. *Neurology*, **40**(4), 644–648.

Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function**.** *Behavioral and Brain Sciences*, **13**, 201–288**.**

Näätänen, R. Gaillard, A.W.K. and Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, **42**, 313–329.

Picton, T.W., Bentin, S., Berg, P., Donchin, E., Hillyard, S.A., Johnson, R., Jr, *et al.* (2000). Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology*, **37**(2), 127–152.

Rämä, P. & Baccino, T. (2010). Eye-fixation related potentials (EFRPs) during object identification. *Visual Neuroscience*, **27**, 187–192.

Raney, G.E. and Rayner, K. (1993). Event-related brain potentials, eye movements, and reading. *Psychological Science*, **4**(5), 283–286.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, **124**(3), 372–422.

Richards, J.E. (2004). Recovering dipole sources from scalp-recorded event-related-potentials using component analysis: principal component analysis and independent component analysis. *International Journal of Psychophysiology*, **54**(3), 201–220.

Roberts, S.J. (1998). Independent component analysis: source assessment and separation, a Bayesian approach. *Vision, Image and Signal Processing, IEE Proceedings*, **145**(3), 149–153.

Rossell, S.L., Price, C.J., and Nobre, A.C. (2003). The anatomy and time course of semantic priming investigated by fMRI and ERPs**.** *Neuropsychologia*, **41**(5), 550–564.

Rugg, M.D., and Coles, M.G.H. (1995). The ERP and cognitive psychology: Conceptual issues. In M.D. Rugg, and M.G.H. Coles (eds.) *Electrophysiology of Mind* (pp. 27–39). London: Oxford University Press.

Rugg, M.D., and Nagy, M.E. (1989). Event-related potentials and recognition memory for words. *Electroencephalography and Clinical Neurophysiology*, **72**(5), 395–406.

Sato, W., Kochiyama, T., Uono, S., and Yoshikawa, S. (2008). Time course of superior temporal sulcus activity in response to eye gaze: a combined fMRI and MEG study. *Social Cognitive and Affective Neuroscience*, **3**(3), 224–232.

Schwind, J., and Dormann, W.-U. (1986). Off-line removal of ocular artifacts from event-related potentials using a multiple linear regression model. *International Journal of Psychophysiology*, **4**(3), 203–208.

Sereno, S. and Rayner, K. (2003). Measuring word recognition in reading: eye movements and event-related potentials. *Trends in Cognitive Sciences*, **7**(11), 489–493.

Sereno, S., Rayner, K., and Posner, M.I. (1998). Establishing a time-line of word recognition: evidence from eye movements and event-related potentials. *Neuroreport*, **9**, 2195–2200.

Shaw, P.J. (2003). *Multivariate Statistics for the Environmental Sciences.* New York: Oxford University Press.

Simola, J., Holmqvist, K., and Lindgren, M. (2009). Right visual field advantage in parafoveal processing: Evidence from eye-fixation-related potentials. *Brain and Language*, **111**(2), 101–113.

Summerfield, C., Jack, A.I., and Burgess, A.P. (2002). Induced gamma activity is associated with conscious awareness of pattern masked nouns. *International journal of psychophysiology*, **44**(2), 93–100.

Tallon-Baudry, C., Bertrand, O., Delpuech, C., and Pernier, J. (1996). Stimulus specificity of phase locked and non-phase-locked 40 Hz visual responses in human. *Journal of Neuroscience Methods*, **16**, 4240–4249.

Tallon-Baudry, C., Bertrand, O., Delpuech, C., and Pernier, J. (1997). Oscillatory gamma-band (30–70 Hz) activity induced by a visual search task in humans. *Journal of Neuroscience Methods*, **17**, 722–734.

Talsma, D., and Woldorff, M.G. (2005). Methods for the Estimation and Removal of Artifacts and Overlap in ERP Waveforms. In T.C. Handy (ed.) *Event-Related Potentials: A Methods Handbook* (pp. 115–148). Cambridge, MA: The MIT Press.

Tanenhaus, M.K., Spivey-Knowlton, M.J., Eberhard, K.M., and Sedivy, J.C. (1995). Integration of visual and linguistic information in spoken language comprehension. *Science*, **268**(5217), 1632–1634.

Unema, P.J.A., Pannasch, S., Joos, M., and Velichkovsky, B.M. (2005). Time course of information processing during scene perception: The relationship between saccade amplitude and fixation duration. *Visual Cognition*, **12**(3), 473–494.

Velichkovsky, B.M. (2002). Heterarchy of cognition: The depths and the highs of a framework for memory research. *Memory*, **10**(5), 405–419.

Vigário, R.N. (1997). Extraction of ocular artefacts from EEG using independent component analysis. *Electroencephalography and clinical neurophysiology*, **103**(3), 395–404.

Wallstrom, G.L., Kass, R.E., Miller, A., Cohn, J.F., and Fox, N.A. (2004). Automatic correction of ocular artifacts in the EEG: a comparison of regression-based and component-based methods. *International Journal of Psychophysiology*, **53**(2), 105–119.

Whitham, E.M., Pope, K.J., Fitzgibbon, S.P., Lewis, T., Clark, C.R., Loveless, S., *et al.* (2007). Scalp electrical recording during paralysis: quantitative evidence that EEG frequencies above 20 Hz are contaminated by EMG. *Clinical Neurophysiology*, **118**(8), 1877–1888.

Woldorff, M.G. (1993). Distortion of ERP averages due to overlap from temporally adjacent ERPs: Analysis and correction. *Psychophysiology*, **30**(1), 98–119.

Yagi, A. (1981). Visual signal detection and lambda responses, *Electroencephalography and Clinical Neurophysiology*, **52**, 604–610.

Yagi, A., and Ogata, M. (1995). Measurement of work load using brain potentials during VDT tasks. In Y. Anzai, K. Ogawa, and H. Mori (eds.) *Symbiosis of Human and Artifact* (pp. 823–826). Hyogo: Elsevier.

Yagi, A., Imanishi, S., Konishi, H., Akashi, Y., and Kanaya, S. (1998). Brain potentials associated with eye fixations during visual tasks under different lighting systems. *Ergonomics*, **41**(5), 670–677.

Yuval-Greenberg, S., Tomer, O., Keren, A.S., Nelken, I., and Deouell, L.Y. (2008). Transient Induced Gamma-Band Response in EEG as a Manifestation of Miniature Saccades. *Neuron*, **58**(3), 429–441.