Combining EEG and eye movement recording in free viewing: Pitfalls and possibilities

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ABSTRACT

Co-registration of EEG and eye movement has promise for investigating perceptual processes in free viewing conditions, provided certain methodological challenges can be addressed. Most of these arise from the self-paced character of eye movements in free viewing conditions. Successive eye movements occur within short time intervals. Their evoked activity is likely to distort the EEG signal during fixation. Due to the non-uniform distribution of fixation durations, these distortions are systematic, survive across-trials averaging, and can become a source of confounding. We illustrate this problem with effects of sequential eye movements on the evoked potentials and time-frequency components of EEG and propose a solution based on matching of eye movement characteristics between experimental conditions. The proposal leads to a discussion of which eye movement characteristics are to be matched, depending on the EEG activity of interest. We also compare segmentation of EEG into saccade-related epochs relative to saccade and fixation onsets and discuss the problem of baseline selection and its solution. Further recommendations are given for implementing EEG-eye movement co-registration in free viewing conditions. By resolving some of the methodological problems involved, we aim to facilitate the transition from the traditional stimulus-response paradigm to the study of visual perception in more naturalistic conditions.

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1. Introduction

For studying the visual system, two measures that offer excellent temporal resolution are eye tracking and electroencephalography (EEG). The information they provide is complementary: eye tracking can tell us where observers fixate their gaze, and thus where they get their information from; EEG registers how the brain responds to this information. Eye tracking and EEG together, therefore, offer a comprehensive record of the visual system.

The first attempts to study eye movement in combination with EEG were made in the early 1950ies (Evans, 1953; Gastaut, 1951). Research since then has mainly been focused on the immediate consequences of eye movement on the EEG signal (Becker, Hoehne, Iwase, & Kornhuber, 1973; Billings, 1989a; Boylan & Doig, 1989; Csibra, Johnson, & Tucker, 1997; Kazai & Yagi, 1999; Kurtzberg & Vaughan, 1982; Moster & Goldberg, 1990; Riemslag, Van der Heijde, Van Dongen, & Ottenhoff, 1988; Thickbroom, Knezevic, Carroll, & Mastaglia, 1991; Yagi, 1979). Correspondingly, measurement was restricted to activity evoked by single eye movements, within the framework of the traditional stimulus-response paradigm.

More recently, a new generation of video-based eye trackers has widened the use of co-registration of eye movements and EEG (Nikolaev, Pannasch, Ito, & Belopolsky, 2014). In particular, co-registration is increasingly becoming popular in conditions involving continued exploration, i.e., *free viewing*.[1] Because it can be used in naturalistic conditions, co-registration provides an exciting new paradigm for studying attention (Fischer, Graupner, Velichkovsky, & Pannasch, 2013), memory encoding (Nikolaev, Jurica, Nakatani, Plomp, & van Leeuwen, 2013; Nikolaev, Nakatani, Plomp, Jurica, & van Leeuwen, 2011), visual search (Dias, Sajda, Dmochowski, & Parra, 2013; Kamienkowski, Ison, Quiroga, & Sigman, 2012; Kaunitz et al., 2014; Körner et al., 2014), reading (Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011; Hutzler et al., 2007), and responses to emotionally charged visual information (Simola, Le Fevre, Torniainen, & Baccino, 2015; Simola, Torniainen, Moisala, Kivikangas, & Krause, 2013), just to mention some domains

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[1] Note, that in this paper we use "free viewing" as a shortening for any unconstrained eye movement behavior, regardless of whether this behavior serves any perceptual task or goal. This is different from the narrow usage of "free viewing" to describe visual exploration only, without specific task, as can sometimes be found in the literature.

of basic research in which this technique is successfully being used. In applied research, for instance on brain-computer interfaces, eye movements are used for navigation to a virtual target object, while real-time analysis of the co-registered EEG is used to confirm object selection (Lee, Woo, Kim, Whang, & Park, 2010; Zander, Gaertner, Kothe, & Vilimek, 2011). This paper is intended for researchers who are aiming to contribute to any of these fields, as well as those who want to explore new fields of research with co-registration techniques. Assuming some initial familiarity with either eye tracking or EEG measurement within a stimulus-response paradigm, we will introduce co-registration under free viewing conditions, with particular emphasis on what its pitfalls are and how they could be avoided.

In making the step from the stimulus-response paradigm to free viewing, we need to consider a crucial discrepancy. Traditionally, the EEG signal is segmented according to an external event, usually the onset of the stimulus or the response. Such markers are not available in free viewing. Instead, the eye movements themselves, in particular the saccades, serve as natural markers for EEG segmentation. To enable their use, some issues have to be addressed regarding analysis and interpretation of data. Most of these derive from the fact that eye movements, unlike experimenter-controlled signals in the stimulus-response paradigm, are self-paced and occur in quick succession. As a result, EEG responses evoked by sequential saccades overlap (Dandekar, Privitera, Carney, & Klein, 2012; Dias et al., 2013; Dimigen et al., 2011). This could distort or mask the effects of experimental conditions. Such distortions, moreover, can easily be mistaken for effects of experimental manipulation. To give a somewhat simplistic example, suppose we are interested in the effect of stimulus size on visual information processing. Inspecting the larger stimulus, however, will require larger saccades. The EEG may differ solely because of larger saccades rather than because of any differences in information processing.

Confounding effects are not always that obvious. For this reason, co-registration should start from an assessment of the liability to confounding of the design chosen. Ideally, eye movements should in all possible respects be equivalent between relevant conditions. In practice, more often the question arises: can we identify a limited set of eye movement characteristics that carries a risk of confounding, and what is the best strategy for controlling it? Which eye movement characteristics are to be controlled will depend on the particular task and experimental goal. For choosing the appropriate strategy, it is important to know which effects eye movements typically have on EEG and in which intervals these effects are typically encountered. Here we will describe the variety of forms these effects can take. This will motivate a solution based on matching eye movement characteristics between conditions. We believe that, in offering solutions to the problems of co-registration in free-viewing conditions, our paper will contribute to making it feasible for a wide scientific community.

1.1. The main peri-saccadic EEG activity

In simultaneous EEG-eye movement analysis, segmentation of EEG into epochs can either be done relative to saccade or to fixation onset, each of which may allow us to capture different aspects of visual processing. Intuitively, activity time-locked to fixation onset may reflect those processes better, which affect perception at the current fixation; whereas, activity time-locked to saccade onset may be better suited for revealing processes related to eye movement planning and execution. Since either way the epochs comprise the eye fixation interval, their averages are indistinctly called eye-fixation related potentials (EFRP).[2] Thus, EFRP is a hybrid

construct, combining an exploration-driven, eye movement induced signal with a stimulus-driven one, the potential evoked by the visual features at fixation. EFRPs during both controlled and free eye movement behavior have been studied for several decades (Billings, 1989b; Devillez, Guyader, & Guerin-Dugue, 2015; Dimigen et al., 2011; Fudali-Czyz, Francuz, & Augustynowicz, 2014; Kazai & Yagi, 1999; Körner et al., 2014; Nikolaev et al., 2011; Rama & Baccino, 2010; Thickbroom et al., 1991; Yagi, 1979).

Since EFRPs have such a venerable history, we will adopt its terminology for describing the time-frequency EEG activity around a saccade. Accordingly, we will distinguish: the *saccadic spike activity*, named after what is known as the saccadic spike potential and the *lambda activity*, named after the lambda wave/potential. Another important focus will be on the activity that precedes saccade initiation, i.e. *presaccadic activity*.

The *saccadic spike* potential (SP) is a sharp wave at the saccade onset. The SP is elicited even in darkness (Riggs, Merton, & Morton, 1974) as it originates from contraction of extra-ocular muscles during the execution of a saccade (reviewed in Keren, Yuval-Greenberg, & Deouell, 2010). In the frequency domain, the SP is manifested in a range between 20 and 90 Hz (Keren et al., 2010). Consistent with its myogenic nature, the main factors affecting SP amplitude are size (Boylan & Doig, 1989; Keren et al., 2010; Riemslag et al., 1988) and direction of the saccade (Keren et al., 2010; Moster & Goldberg, 1990; Thickbroom & Mastaglia, 1986). Its muscular origin makes the SP an unlikely focus of studies addressing the information processing aspects of visual perception. Yet, the SP plays an important role in co-registration research. Its dependence on saccade size is instrumental in assessing the reliability of various analytical steps, such as the correctness of EEG segmentation and the quality of oculomotor artifact correction, as well as for detecting mismatches between experimental conditions. Thus, the spike potential could be a valuable marker to ensure the adequacy of combined processing of eye movement and EEG.

The *lambda* potential is a positive wave about 100 ms after fixation onset (Evans, 1953).[3] There is common agreement that the lambda potential is a response of the visual cortex to changes in the retinal image due to the saccade (Dimigen, Valsecchi, Sommer, & Kliegl, 2009; Gaarder, Krauskopf, Graf, Kropfl, & Armington, 1964; Kazai & Yagi, 1999, 2003; Riemslag et al., 1988; Thickbroom et al., 1991). In point of fact, the lambda potential is not evoked when saccades are made in darkness or on a homogenous display (Evans, 1953; Fourment, Calvet, & Bancaud, 1976); moreover, the lambda amplitude depends on the difference in luminance between starting and ending locations of the saccade (Ossandón, Helo, Montefusco-Siegmund, & Maldonado, 2010). The association of the lambda potential with early visual processing is confirmed by the similarity in cortical sources of the lambda potential to those of the component P1 in event-related potentials (Kazai & Yagi, 2003). In the frequency domain, the lambda activity is manifested in the upper-theta and alpha bands (6–14 Hz) (Dimigen et al., 2009; Ossandón et al., 2010).

Presaccadic activity is described in EFRP research as a slow positive wave over parieto-occipital brain areas, which starts around 300 ms before saccade onset. This wave has sometimes been called the antecedent potential (Becker et al., 1973; Csibra et al., 1997; Kurtzberg & Vaughan, 1982; Moster & Goldberg, 1990; Parks & Corballis, 2008; Richards, 2003). It may co-occur with a positive wave over the frontal areas (Gutteling, van Ettinger-Veenstra,

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[2] It would be more exact to distinguish the potentials time-locked to the fixation and saccade onsets by calling them "fixation-related potentials" (FRPs) and "saccade-related potentials" (SRPs), respectively (e.g., Dimigen et al., 2011).

[3] In the 1970-80ies there has been a long discussion on whether the lambda potential is evoked by saccade or by fixation onset. On the one hand, latency of the lambda potential is time-locked to fixation rather than saccade onsets. This suggests that the lambda potential reflects processes initiated by fixation onset (Billings, 1989a; Yagi, 1979). On the other hand, averaging relative to the saccade and fixation onsets revealed different lambda subcomponents (Thickbroom et al., 1991), suggesting that the lambda potential may be a compound of activity evoked by both saccade and fixation onsets (Kazai & Yagi, 1999; Thickbroom et al., 1991).