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Event-related brain potentials and the study of reward processing: Methodological considerations☆

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ABSTRACT

There is growing interest in using electroencephalography and specifically the event-related brain potential (ERP) methodology to study human reward processing. Since the discovery of the feedback related negativity (Miltner et al., 1997) and the development of theories associating the feedback related negativity and more recently the reward positivity with reinforcement learning, midbrain dopamine function, and the anterior cingulate cortex (i.e., Holroyd and Coles, 2002) researchers have used the ERP methodology to probe the neural basis of reward learning in humans. However, examination of the feedback related negativity and the reward positivity cannot be done without an understanding of some key methodological issues that must be taken into account when using ERPs and examining these ERP components. For example, even the component name – the feedback related negativity – is a source of debate within the research community as some now strongly feel that the component should be named the reward positivity (Proudfit, 2015). Here, ten key methodological issues are discussed – confusion in component naming, the reward positivity, component identification, peak quantification and the use of difference waveforms, frequency (the N200) and component contamination (the P300), the impact of feedback timing, action, and task learnability, and how learning results in changes in the amplitude of the feedback-related negativity/reward positivity. The hope here is to not provide a definitive approach for examining the feedback related negativity/reward positivity, but instead to outline the key issues that must be taken into account when examining this component to assist researchers in their study of human reward processing with the ERP methodology.

1. Introduction

The purpose of this review paper is to address several methodological issues that must be taken into consideration when using electroencephalography to study human reward processing – and more specifically the feedback related negativity (FRN: Miltner et al., 1997) and the reward positivity (Holroyd et al., 2008; Proudfit, 2015). It is important to emphasize that the point of this review is to address methodological concerns related to examination of the FRN and the reward positivity and not to summarize or argue for and against the theoretical and neural underpinnings of these components. Indeed, in recent years there have been multiple excellent reviews focused on the FRN and reward positivity and the factors that underlie its generation and modulation (e.g., Holroyd and Umemoto, 2016; Sambrook and Goslin, 2015; Walsh and Anderson, 2012). As such, a theoretical review is not the focus of this work. While this review will begin with a brief history of the electroencephalographic components associated with error and feedback processing the primary focus of this paper will be on ten key methodological concerns that must be taken into account when examining the FRN/reward positivity.

1.1. A brief history of the ERN and FRN

As we learn the mistakes that we make can be evaluated in two principle ways. First, early in learning we use and are reliant upon feedback – sensory information that is processed by us and indicates whether or not we have performed a given action correctly (Adams, 1971). Second, as we gain skill and learn to execute actions correctly we lose our reliance upon external feedback and gain an internal capability to evaluate the consequences of our actions via an efference copy of the motor command (Angel, 1976). Studies using electroencephalography have reported neural responses that appear to reflect both internal error evaluation (the error-related negativity) and external feedback evaluation (the feedback related negativity).

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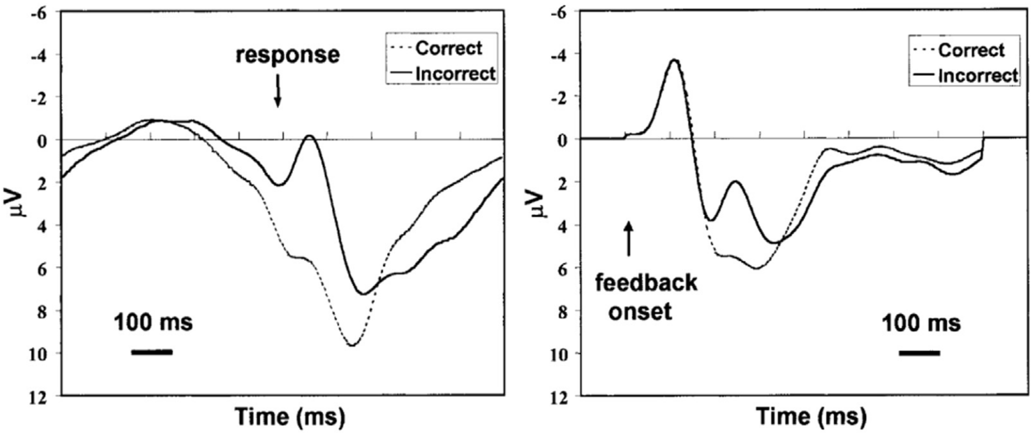

Fig. 1. Left Panel: The error related negativity shown at channel FCz where it is maximal. Right Panel: The feedback related negativity shown at channel FCz where it is maximal.
Reproduced with permission from Holroyd and Coles, 2002.

1.2. Internal error evaluation: the error related negativity (ERN)

The electroencephalographic study of error evaluation started with an examination of the event-related brain potentials (ERP) evoked by response errors – incidents during speeded response tasks when participants make an incorrect response. For example, if one contrasts the ERP response to correct and incorrect responses during performance of the Eriksen Flanker Task an error-related negativity (ERN) is observed as the difference between the average correct and incorrect waveforms time locked to the response (see Fig. 1, left panel). Within the literature, there is debate about the first reporting of the ERN but most authors now give joint credit to both Falkenstein et al. (1991) and Coles et al. (1991) for the initial observation of the ERN with a full report being made by Gehring, Goss, Coles, Meyer, and Donchin in 1993. As noted above, the ERN is typically evoked by erroneous responses in speeded response tasks. The ERN typically begins 30 ms post response and peaks at 100 ms but this latency is subject to how response onset is quantified (Burle et al., 2008). Specifically, the onset and peak of the ERN occurs at these times when the waveform is time locked to a button press or similar response. However, when response onset is defined as the onset of muscle activity using electromyography (EMG)[1] - the electrical burst of activity recorded from above the muscle belly that reflects the beginning of the contraction of the muscle – then the onset of the ERN is coincident with the onset of muscle activity and peaks around 50 ms post response (Gehring et al., 1993). The scalp topography of the ERN is typically front-central, with a maximum negativity typically occurring at electrode FCz (Burle et al., 2008; Gehring et al., 1993; Holroyd and Coles, 2002).

Perhaps the easiest way to describe the process that underlies the ERN would be to state that the ERN is the subconscious portion of the so called “oh fudge” response. However, a more precise description of the process that underlies ERN generation would be to say that the ERN reflects the evaluation of an efference copy of a motor command (Holroyd and Coles, 2002). More precisely, given that ERN onset is coincident with the onset of EMG activity it stands to reason that the evaluation process that generates the ERN is complete prior to the initiation of the physical response. As such, it has been hypothesized that when a motor command is issued a copy of the motor command – the efference copy – is sent to be evaluated almost instantaneously by a neural error detection system (see Holroyd and Coles, 2002). The ERN therefore in this framework reflects a surface-viewable signature of the detection of a response error by this underlying system. Although the ERN is an interesting and important ERP component as evidenced by the numerous studies examining it, given the scope of this review further discussion of the ERN is not warranted other than to point out to readers that it is a different ERP component from a later component associated with feedback evaluation – the feedback related negativity.

1.3. Evaluation of performance feedback: the feedback related negativity (FRN)

In 1997 Miltner and colleagues reported an ERP component evoked by performance feedback provided to participants during performance of a time estimation task. In their paradigm, participants were asked to guess the duration of 1 s. The task had a structure such that at the beginning of the task, participants had to be within ± 100 ms of 1000 ms with their guess. However, each time a participant was correct the tolerance window of ± 100 ms decreased by 10 ms (i.e., the window became ± 90 ms) and each time a participant was incorrect the tolerance window increased by 10 ms (i.e., the window became ± 110 ms). In this manner, participant performance hovered around 50% after an initial learning phase.[2] In an additional manipulation, Miltner and colleagues also manipulated how feedback was provided – in one condition it was visual, in another auditory, and in a third tactile. In all instances, a comparison of the average correct and incorrect waveforms revealed a difference at about 250 ms post stimulus onset which Miltner and colleagues referred to as the feedback-related negativity (FRN: see Fig. 1, right panel). As with the ERN, the FRN has a front-central scalp topography that is typically maximal at electrode FCz although as noted it occurs much later. Source localization of the FRN suggests a source within the human anterior-cingulate cortex (Bellebaum and Daum, 2008; Gehring and Willoughby, 2002; Gruendler, et al., 2011; Hewig et al., 2007; Mathewson et al., 2008; Miltner et al., 1997; Potts et al., 2006b; Ruchsow, et al., 2002; Tucker, et al., 2003; Walsh and Anderson, 2012; Zhou et al., 2010). The FRN is thought to reflect evaluation of performance feedback, however, there is a fair amount of debate as to the exact computations driving the difference between correct and incorrect average feedback waveforms. An abundance of recent studies have examined whether or not the FRN is sensitive outcome expectancy, outcome magnitude, and other external factors (see Holroyd & Umemoto, 2016; Sambrook and Goslin, 2015; Walsh and Anderson, 2012 for review).

As noted at the outset, a full review of the theoretical accounts that attempt to explain the FRN is beyond the scope of this review. However, briefly, perhaps the most cited account of the FRN posits that the component reflects a reinforcement learning prediction error (Holroyd and Coles, 2002). More specifically, the RL-ERN theory proposes that the anterior cingulate cortex, midbrain dopamine system, and basal ganglia compose a reinforcement learning system within the human

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[1] It is worth noting from a methodological perspective that defining response onset as EMG onset is more accurate as it comes after pre-motor time and before motor time.

[2] As it turns out, this is a very important manipulation. The FRN occurs coincident with the N200 which of course is extremely sensitive to stimulus frequency (see below and see Holroyd et al., 2008).