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Research Report

The P300 and reward valence, magnitude, and expectancy in outcome evaluation

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ABSTRACT

The P300 in event-related potentials (ERPs) has been implicated in outcome evaluation and reward processing, but it is controversial as to what aspects of reward processing it is sensitive. This study manipulated orthogonally reward valence, reward magnitude, and expectancy towards reward magnitude in a monetary gambling task and observed both the valence and the magnitude effects on the P300, but only when the amount of reward was expected on the basis of a previous cue. The FRN (feedback-related negativity), defined as the mean amplitudes of ERP responses to the loss or the gain outcome in the 250–350 ms time window post-onset of feedback, was found to be sensitive not only to reward valence, but also to expectancy towards reward magnitude and reward magnitude, with the violation of expectancy and the small magnitude eliciting more negative-going FRN. These findings demonstrate that while the FRN may function as a general mechanism that evaluates whether the outcome is consistent or inconsistent with expectation, the P300 is sensitive to a later, top-down controlled process of outcome evaluation, into which factors related to the allocation of attentional resources, including reward valence, reward magnitude, and magnitude expectancy, come to play.

1. Introduction

The P300 has been one of the most studied components of the event-related potentials (ERPs) since it was first reported in 1965 (Desmedt et al., 1965; Sutton et al., 1965). It is implicated in a large number of cognitive and affective processes and is traditionally associated with allocation of mental resources (Duncan-Johnson and Donchin, 1977; Polich, 2007; Polich and Kok, 1995; Squires et al., 1975). In recent years, differential effects on the P300 has also been observed in tasks involving decision making or outcome evaluation (Hajcak et al., 2005, 2007; Luu et al., 2009; Sato et al., 2005; Toyomaki and Murohashi, 2005; Yeung and Sanfey, 2004; Yeung et al., 2005; Yu et al., 2007), and these effects are thought to reflect the evaluation of the functional significance of feedback stimuli. However, it is controversial as to what aspects of the significance the P300 is sensitive.

In ERP studies on outcome evaluation or feedback processing, it has been found that two ERP components are particularly sensitive to the valence of reward or performance outcome. The first component is called FRN (i.e., feedback-related negativity)

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or MFN (i.e., medial-frontal negativity), which is a negative deflection at frontocentral recording sites that reaches maximum between 250 and 300 ms post-onset of feedback stimulus (Gehring and Willoughby, 2002; Heldmann et al., 2008; Holroyd and Coles, 2002; Holroyd, 2004; Nieuwenhuis et al., 2004; Miltner et al., 1997; Yu and Zhou, 2006a, 2006b). The FRN is more pronounced for negative feedback associated with unfavorable outcomes, such as incorrect responses or monetary losses, than for positive feedback. Another component is the P300, which is the most positive peak in the 200–600 ms period post-onset of feedback and which typically increases in magnitude from frontal to parietal sites.

It has been claimed that the FRN and the P300 encode different aspects of outcome evaluation (Yeung and Sanfey, 2004). While the FRN is sensitive to feedback valence, the P300 is sensitive to the magnitude of reward, with a more positive response to a larger (whether positive or negative) than to a smaller reward (Sato et al., 2005; Yeung and Sanfey, 2004). In contrast, feedback valence has no impact upon the P300 (Sato et al., 2005; Yeung and Sanfey, 2004). Yeung and Sanfey (2004), for example, asked the participant to choose between cards that were unpredictably associated with monetary gains or losses of various magnitudes. After selection, a positive or a negative number appeared on the chosen card to indicate how much money the participant won or lost on that trial. After an additional interval, the participant was shown what he would have won or lost had he selected the alternative card. It was found that the P300 was insensitive to the valence of the actual outcome but was sensitive to the valence of the alternative outcome, with a larger P300 associated with a positive outcome. The authors concluded that the valence effect on the P300 is observed when valence is defined in terms of high-level motivational/affective evaluations, such as regret or disappointment, but not when valence is defined in terms of the straightforward reward value. However, other studies found that the P300 is sensitive to reward valence as well as to reward magnitude in monetary gambling tasks, with more positive amplitudes for positive feedback than for negative outcomes (e.g., Hajcak et al., 2005, 2007; Holroyd et al., 2006; Yeung et al., 2005).

Another aspect of the significance of feedback is the probability of the positive or negative outcome experienced by the participant. This probability, manipulated either on a trial-by-trial basis (Hajcak et al., 2005, 2007) or in a blocked manner (Cohen et al., 2007; Hajcak et al., 2005; Holroyd et al., 2003; Holroyd and Krigolson, 2007), would allow the participant to form expectancy towards a particular outcome and hence could affect brain responses to the upcoming feedback. Although these studies reported inconsistent results regarding whether the FRN effect is affected by this probability manipulation, they provided evidence that the P300 is modulated by the probability, with more positive amplitudes to unexpected feedback than to expected feedback (Hajcak et al., 2005, 2007). This pattern of the P300 effect is consistent with earlier studies employing the classic oddball paradigm and manipulating the probability of the appearance of a particular stimulus (Courchesne et al., 1977; Duncan-Johnson and Donchin, 1977; Johnson and Donchin, 1980).

The main purpose of this study is to provide further evidence for the impacts of reward valence, reward magnitude, and a previously unexamined form of expectancy, magnitude expectancy, upon the P300 in outcome evaluation. Importantly, we investigate to what extent these aspects of feedback would interact to determine the pattern of the P300 effect (and also the pattern of the FRN effect). To achieve this aim, we used a cued gambling task in which a cue about the amount of monetary reward in the current trial (e.g., the number “25”, standing for 2.5 Chinese yuan) was first presented, followed by the participant's selection of a choice card. Finally, a feedback stimulus (e.g., “+25” or “+5”) was presented, which encoded information concerning the valence of reward (gain or loss), the magnitude of reward (a small or a larger amount of money), and magnitude expectancy (whether the amount of reward was consistent or inconsistent with expectation built upon the magnitude of the cue number). Note that, most previous studies manipulated reward expectancy by presenting a particular, valenced outcome with a specific probability in a testing block or in the whole experiment. Here the magnitude expectancy was built upon whether the magnitude of reward (the gain or loss outcome) was consistent with the magnitude of the cue presented at the beginning of a trial. Although this cue was valid in 80% of the trials (i.e., the cue “25” was followed by the reward “25” or the cue “5” was followed by the reward “5”), the valence of feedback was still unpredictable (i.e., gain or loss in 50% of the trials). By measuring ERP responses to the feedback stimuli, we would be able to examine the main effects of reward valence, magnitude and expectancy, as well as interactions between them on the P300.

We hypothesized that outcome evaluation can be roughly divided into two related processes: an early evaluation of the cognitive or motivational significance of the feedback stimuli, followed by more elaborative evaluation, in which factors that affect the allocation of attentional resources, such as intentionality or expectancy, come into play in a top-down controlled manner (Goyer et al., 2008; Leng and Zhou, in revision). On this view, reward valence, reward magnitude, and magnitude expectancy may modulate the amplitude of the P300, which represents the controlled process in outcome evaluation. It is not clear, however, whether these factors would interact in modulating the amplitude of the P300. Previous studies found that the impacts of reward valence and reward expectancy on the P300 are generally non-interactive (e.g., Hajcak et al., 2005, 2007). On the other hand, it is not clear either whether reward magnitude or magnitude expectancy would affect the early process represented by the FRN given that evidence concerning this issue is either contradictory or lacking. While some studies found that the FRN is insensitive to the reward magnitude (Hajcak et al., 2006; Holroyd et al., 2006; Sato et al., 2005; Polezzi et al., 2008; Toyomaki and Murohashi, 2005; Yeung and Sanfey, 2004), other studies obtained a magnitude effect on the FRN (Goyer et al., 2008; Marco-Pallares et al., 2008). The inconsistency may partly be caused by different parameterization of the FRN in those studies.

There are essentially three ways to measure the FRN or the FRN effect. The first way is to measure the base-to-peak or peak-to-peak difference, defining the FRN as the difference between the most positive point (P2) and the most negative point (N2) in the 150–350 ms time window post-onset of