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When two become one: Electrocortical correlates of the integration of multiple action consequences

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ABSTRACT

In a recent study we have demonstrated that the feedback-related negativity (FRN) reflects the integrated value of instantaneous and delayed decision consequences (Osinsky et al. 2017). In the present work, we extend this research by using a novel choice task in which instant and delayed consequence values of a single decision outcome can be manipulated independently of each other in a trial-wise manner. Fifty-nine healthy participants completed this task while EEG was recorded. Twenty-two of them returned one week later for a retesting, allowing for investigating temporal stability of individual FRN indices. Our results show that the FRN mainly reflects the additively integrated value of instant and delayed outcome consequences. Individual differences in the FRN sensitivity to the two consequence dimensions were specifically predictive for consequence-driven adjustments in choice behavior and moderately stable over time. Altogether, our findings are inconsistent with the idea that the FRN reflects a simple binary distinction between favorable and unfavorable action outcomes. Rather, the FRN appears to mirror a fine-grained scaling of action outcomes, which results from stable personal reward preferences and which is used for adjusting choice behavior. Given that the FRN is generated in the anterior midcingulate cortex, our study adds to recent literature according to which this structure uses multiple information to learn complex action-outcome values.

1. Introduction

Cognitive neuroscience of action and decision evaluation is a vivid field in which the technique of electroencephalography (EEG) has repeatedly proven its immense utility. This especially holds when it comes to the chronometry of involved neurocognitive mechanisms in the working human brain. In this vein, hundreds of studies have mainly focused on a particular event-related potential (ERP), the so-called feedback-related negativity (FRN). The FRN was first described by Miltner et al. (1997) and emerges as a frontomedial negative-going deflection about 300 ms after the onset of a non-optimal compared to an optimal action outcome in a given task context. Its neural generator is probably located in the anterior midcingulate cortex (aMCC[1]; e.g., Emeric et al. 2008; Hauser et al. 2014; Luu et al. 2003; Warren et al. 2015; but also see Foti et al. 2011), which has been identified as a central part of the brain's action monitoring system (Ullsperger et al. 2014). Initial studies on the FRN therefore mainly dealt with its link to mechanisms of performance evaluation and behavioral adjustments (e.g., Luu et al. 2003; Miltner et al. 1997). Soon, however, it became apparent that the FRN effect might reflect more general mechanisms of reward processing (e.g. Gehring and Willoughby 2002; Holroyd and Coles 2002; Yeung and Sanfey 2004). Accordingly, the FRN was often used as an instrumental index of reward and punishment processing in more recent years, also for means of group comparisons and analyses of individual differences (e.g., Mussel et al. 2015; Riepl et al. 2016; Smillie et al. 2011; Wang et al. 2017; Weinberg et al. 2015; Zhu et al. 2017). Yet, the detailed meaning of the FRN is still a matter of debate.

To study the functional properties of the FRN, researchers have often used simple choice paradigms in which they systematically manipulated basic aspects of action outcomes such as valence (e.g., Holroyd et al. 2006), reward magnitude (Hajcak et al. 2006), reward probabilities (e.g., Cohen et al. 2007), cue induced expectancies (e.g., Osinsky et al. 2016), sequential outcome order (e.g., Osinsky et al. 2012), or the combination of several of such factors (e.g., Kreussel et al. 2012; Yeung and Sanfey 2004). In the used experimental tasks, the outcomes typically referred to a single consequence for the individual, such as winning or losing a small amount of money. However, real life actions and choices often lead to much more complex outcomes that are associated with multilayered consequences on various time scales. For example, the decision to buy a brand new luxury car instead of a

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[1] Please note that aMCC is frequently also referred to as dorsal anterior cingulate cortex (see Vogt 2016).

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second-hand compact van may entail both, positive (e.g., enjoying envious glances from other drivers) as well as negative consequences (e.g., an empty bank account). Of course, it is not possible yet to fully emulate such complex real life decisions and the outcomes thereof in an EEG recording environment. Nevertheless, we think that future research on the FRN and, more broadly, outcome processing should consider the fact that decision and action outcomes can entail more than just one single consequence. Thereby, we could not only further our understanding of the mechanisms and generators underlying the FRN, but generally delve deeper into the neuronal foundations of more complex and realistic decision making and outcome evaluation.

In a recent work, we have already shown that the FRN amplitude can reflect the integration of multiple outcome consequences (Osinsky et al. 2017). By the term *integration* we mean the combination of at least two different variables into an integral whole. Such integration can be, among others, interactive (e.g., $c = f(a \times b)$), additive (e.g., $c = f(a + b)$), or a combination of both (e.g., $c = f((a + b),(a \times b))$). Results of our first study on this topic indicated that the FRN reflects the interactive integration of delayed and instantaneous outcome consequences (Osinsky et al. 2017). In this previous study, we conducted two experiments in which participants completed simple guessing tasks very similar to those used in prior works on the FRN (e.g., Gehring and Willoughby 2002; Hajcak et al. 2006; Holroyd et al. 2003; Holroyd et al. 2006; Osinsky et al. 2012; Yeung and Sanfey 2004). However, in contrast to these previous reports, each outcome in our task was associated with an instantaneous monetary (experiment 1) or emotional value (experiment 2) AND with a task-related and therefore delayed value (i.e., completing the task as a whole). Importantly, the latter was manipulated block-wise and independent of the instantaneous value. Thus, instantaneous and delayed consequences of each outcome could either converge (e.g., both negative or both positive) or diverge (e.g., a positive instantaneous value but a negative task-related value). Our findings indicated that the FRN effect mainly arises from a reward positivity (RewP; cf. Holroyd et al. 2008) which is only present when both the instantaneous as well as the delayed task-related value are positive. More generally, our study therefore showed that the FRN is sensitive not only to a single consequence of a particular outcome but also to the (interactive) integration of multiple outcome consequences. This is also in line with a theoretical assumption according to which the aMCC, as the probable source of the FRN, acts as a hierarchical reinforcement learning system, integrating numerous information to learn the value of timely extended behavioral sequences (Holroyd and Yeung 2012). However, the task design in our mentioned prior study also had some weaknesses. First, the instantaneous and delayed consequences did not only differ on time-scale but also with regard to concreteness and maybe relevance for the participants. For instance, in experiment one the instantaneous consequences of losing or winning some money might have been of higher relevance than winning or losing the task, which had no monetary consequence at all. Moreover, we manipulated the delayed task-related value of the outcomes in a block-wise manner. This may have allowed participants to reformulate the outcome values at the beginning of each block. The observed effects do therefore not necessarily reflect a trial-wise online integration of instantaneous and delayed values. Finally, the outcomes were presented in a pseudorandom fashion so that no learning of optimal behavioral strategies was possible. If the system underlying the FRN is indeed involved in hierarchical reinforcement learning sensu Holroyd and Yeung (2012) it is probably more engaged when learning is generally possible.

In the present study, we aimed to further investigate the link between the FRN and the integration of multiple outcome consequences, thereby also overcoming the abovementioned limitations of our prior work (Osinsky et al. 2017). For this purpose, we designed a novel choice-learning task, in which each outcome was associated with an instantaneous monetary consequence and with a more delayed monetary consequence (see Fig. 1). Thus, the two consequences of each outcome referred to the same kind of reward (i.e., money) and were manipulated in a trial-wise manner. Moreover, outcomes were probabilistically linked to the choice alternatives, so that participants could identify the optimal option in a trial-and-error fashion. Across all participants, we expected the most positive FRN amplitudes (i.e., a RewP) for the best possible outcomes, having both a positive instantaneous value as well as a positive delayed value (cf. Osinsky et al. 2017). If the mechanism that underlies the FRN differentiates between action outcomes in a dichotomous fashion, all other possible outcomes should evoke very similar and more negative FRN amplitudes (cf., Hajcak et al. 2006; Osinsky et al. 2017; Yeung and Sanfey 2004). However, there is also evidence that the FRN can reflect a more fine-grained, continuous scaling of outcome values (e.g., Frömer et al. 2016; Sambrook and Goslin 2015). We analyzed our data with regard to these possible alternative patterns. Moreover, we were also interested in individual differences in the FRN sensitivity to the two consequence-dimensions. We therefore tested how these differences relate to outcome-based adjustments in behavior and whether they are stable over time. Finally, we also conducted exploratory analyses for the outcome-locked P300 component, which may generally reflect the motivational saliency of a particular event (Nieuwenhuis et al. 2005) and has been functionally dissociated from the FRN (e.g., Hajcak et al. 2005; Osinsky et al. 2014; Pfabigan et al. 2011; Yeung and Sanfey 2004).

2. Methods and materials

2.1. Participants and general procedure

In total, 60 individuals from the student population of the University of Osnabrück took part in this study. All had a normal or corrected-to-normal vision, reported to be free of any mental or neurological disorders and gave written informed consent. The study was in accordance with the declaration of Helsinki. We could not analyze data of one participant, since trigger signals were not sent properly during the respective recording session. Thus, the final sample comprised 59 individuals (47 women; mean age = 22.3 years, SD = 3.0, range 18–34). For their participation they received course-credit and the money they won during the experimental task (Mean = 7.70 Euro, SD = 0.70, range 5.82–9.84). A subsample of 22 individuals completed the task twice with a time interval of one week between the two sessions.

After arrival at the laboratory, participants received written information about the study content before completing a number of self-report measures,[2] data of which are not reported here. Afterwards, participants completed the behavioral task while EEG was recorded. Following the task, we asked participants to rate the valence of each of the nine outcomes on a five-point Likert scale, ranging from 1 (very negative) to 5 (very positive). Before leaving, participants received the sum of immediate monetary trial outcomes plus, if applicable, an extra amount of 3 Euro (see task description).

2.2. Choice task and behavioral data

Participants completed a computerized choice task, during each trial of which they pressed a corresponding button to choose one of nine virtual doors presented on a screen in front of them. They were told that after each choice they would see a single uppercase letter, which represents a mythical creature hidden behind the chosen door. Moreover, we informed them that each creature has a particular instantaneous consequence for their monetary account. A fairy (F for the German word Fee) would give 5 Euro Cent to them, an Orc (O for Ork) would steal 2 Cent from them, and a dwarf (Z for Zwerg) would neither give nor steal money.[3] Moreover, participants were informed that each

[2] Action Control Scale (Kuhl 1994), Delay Discounting Test (Kirby et al. 1999), State-Trait-Anxiety Inventory (Spielberger et al. 1983).