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The better, the bigger: The effect of graded positive performance feedback on the reward positivity

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ABSTRACT

In this study on skill acquisition in a computerized throwing task, we examined the effect of graded correct-related performance feedback on the reward positivity of the event-related brain potential (ERP). Theories of reinforcement learning predict effects of reward magnitude and expectancy on the reward prediction error. The later is supposed to be reflected in reward positivity, a fronto-central ERP component. A sample of 68 participants learned to throw at a beamer-projected target disk while performance accuracy, displayed as the place of impact of the projectile on the target, served as graded feedback. Effects of performance accuracy in successful trials, hit frequency, and preceding trial performance on reward positivity were analyzed simultaneously on a trial-by-trial basis by means of linear mixed models. In accord with previous findings, reward positivity increased with feedback about more accurate performance. This relationship was not linear, but cubic, with larger impact of feedback towards the end of the accuracy distribution. In line with being a measure of expectancy, the reward positivity decreased with increasing hit frequency and was larger after unsuccessful trials. The effect of hit frequency was more pronounced following successful trials. These results indicate a fast trial-by-trial adaptation of expectation. The results confirm predictions of reinforcement learning theory and extend previous findings on reward magnitude to the area of complex, goal directed skill acquisition.

1. Introduction

In order to reach our goals, actions need to be evaluated regarding their conduciveness for goal achievement. To this end effective motor programs need to be learned, refined, and selected. Simple actions, like pressing the correct button in a two-choice task can be evaluated based on proximal afferent motor feedback. In contrast, when it comes to complex goal directed actions, feedback on the distal effects of actions is required (Henderson, 1977). Consistent with this notion, simple and complex tasks often show very different effects of variables, such as the feedback about performance (Wulf & Shea, 2002).

In motor learning, external feedback on performance in relation to the goal, termed Knowledge of Results (KR) is a key variable and has been shown to improve performance (for a review see Salmoni, Schmidt, & Walter, 1984). Processing of both, positive and negative feedback predicts behavioral adaptation and learning (Cavanagh, Frank, Klein, & Allen, 2010; Van Der Helden & Boksem, 2012). Moreover, in some settings, positive feedback fosters learning to a larger extent than negative feedback (Arbel, Goforth, & Donchin, 2013; Arbel, Murphy, & Donchin, 2014; Chiviacowsky & Wulf, 2007; Eppinger, Kray, Mock, & Mecklinger, 2008; Wulf, Shea, & Lewthwaite, 2010).

1.1. Feedback in the reinforcement learning framework

Reinforcement learning theory provides a framework of how feedback is utilized in behavioral adaptation and learning (Sutton & Barto, 1998). Here, the actual outcome (feedback) is compared to the predicted outcome to trigger adaptation. Previous outcomes are the basis for prediction/expectations and the difference between actual outcome and the expectation is termed prediction error. In turn, the prediction error in a given trial is used to adjust the prediction of the outcome in subsequent trials and select responses in order to optimize performance. The size of the difference determines the magnitude of the prediction error. Take, as an example, someone who wants to learn basketball free throws. Learners will estimate the likelihood of scoring a goal based on their previous

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performance and generate a corresponding expectation. As long as their relative number of baskets is low, they will not expect to score a goal. Doing so would be a better-than-expected outcome (positive prediction error). Based on this new experience, learners will adapt their expectation for the next trial, as scoring a goal is now more likely. They will moreover adapt their movements based on the visual information obtained during the previous throws. This adaptation process is termed temporal difference learning. The reinforcement learning framework comprises two components: the critic that computes the prediction error, and the actor that selects actions that maximize the outcome by repeating successful behavior (Walsh & Anderson, 2012).

1.2. Reinforcement learning in the human brain

An implementation of reinforcement learning theory at the neural level has been suggested as "reinforcement learning theory of the error-related negativity" (RL-ERN) by Holroyd and Coles (2002). According to RL-ERN, the reward prediction error is reflected by phasic changes of activity in anterior cingulate cortex (ACC). Depending on the learning situation and stage, performance-monitoring activity in the ACC is computed either on the basis of external feedback or internal information obtained by the response itself (Bellebaum & Colosio, 2014; Holroyd & Coles, 2002; Holroyd, Nieuwenhuis et al., 2004). Internal feedback is generated from response monitoring and even stimulus evaluation (Eppinger et al., 2008; Holroyd & Coles, 2002; Luque, Moris, Rushby, & Le Pelley, 2015; Schacht, Adler, Chen, Guo, & Sommer, 2012). At the beginning of motor learning and skill acquisition, individuals rely mostly on external feedback, whereas during later stages of learning internally generated feedback signals acquire more importance. If based on internal processes, ACC activity seems to be reflected in the ERN; if based on external feedback, error detection is reflected in the feedback-related negativity (FRN).

The FRN is a fronto-central negative deflection in the scalp recorded event-related potential (ERP) with a maximum around 200–400 ms after feedback onset (Holroyd, Pakzad-Vaezi, & Krigolson, 2008). Typically, the FRN is determined as the difference wave between ERPs to feedback signals about incorrect and correct responses or between non-reward and reward signals. The FRN is larger for negative as compared to positive outcomes (Miltner, Braun, & Coles, 1997) and it is sensitive to both, utilitarian (reward/punishment) and performance feedback (Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen, 2004).

The FRN is interpreted as reflecting the reward prediction error (Holroyd, Nieuwenhuis, Yeung, & Cohen, 2003). Consistent with this interpretation, the FRN is context dependent, with amplitude to a specific outcome depending on alternative outcomes (Holroyd, Larsen, & Cohen, 2004; see Kujawa, Smith, Luhmann, & Hajcak, 2013 for divergent findings; Nieuwenhuis et al., 2005). Moreover, reward probability or reward magnitude modulations of the FRN were observed to error- and correct-related feedback ERPs, but more consistently for the later (Cohen, Elger, & Ranganath, 2007; Hajcak, Holroyd, Moser, & Simons, 2005; Hajcak, Moser, Holroyd, & Simons, 2006; Kreussel et al., 2012; Potts, Martin, Burton, & Montague, 2006; Potts, Martin, Kamp, & Donchin, 2011; San Martin, Manes, Hurtado, Isla, & Ibanez, 2010). Compared to negative feedback, positive feedback elicits ERPs that are larger in amplitude and of different polarity (Walsh & Anderson, 2012). The interpretation of the FRN reflecting the signed prediction error is supported by a recent meta-analysis (Sambrook & Goslin, 2015).

1.3. Reward positivity and goal orientation

Not all sources of errors are processed by the medial frontal monitoring system, but error processing is hierarchical with this system being specialized for high-level error processing. Instead, low-level motor errors, such as target perturbations are processed in posterior parietal cortex (Krigolson & Holroyd, 2007). High-level outcome errors, that is measures of goal attainment, processed in medial frontal cortex, possibly subserve future motor adaptation (Krigolson & Holroyd, 2006; Krigolson, Holroyd, Van Gyn, & Heath, 2008). The hypothesis that error monitoring in medial frontal cortex supports goal-oriented motor adaptation is supported by studies on agency. The FRN is increased when participants feel responsible for the outcome of their actions (Bednark & Franz, 2014; Li, Han, Lei, Holroyd, & Li, 2011; Peterson, Lotz, Halgren, Sejnowski, & Poizner, 2011). Moreover, enhanced FRN amplitudes to paid-out money as compared to fictive rewards support the relevance of usefulness (Weinberg, Riesel, & Proudfit, 2014).

Variations of feedback values indicated that the FRN is related to goal achievement, as neutral and irrelevant feedback elicited similar FRNs as negative feedback (Band, van Steenbergen, Ridderinkhof, Falkenstein, & Hommel, 2009; Holroyd, Hajcak, & Larsen, 2006). Holroyd, Pakzad-Vaezi and Krigolson (2008) introduced the feedback correct related positivity. They argued that the lack of a typical N2 to correct feedback was due to cancellation with an overlapping positivity, other than the P3 and related to performance monitoring. Recent fMRI findings also support the assumption of a reward positivity. An increase in BOLD response in areas related to reinforcement learning was observed following positive but not negative feedback. This increase of activity was related to more positive ERP amplitudes (Becker, Nitsch, Miltner, & Straube, 2014). Because these and other recent findings suggest a different interpretation of the FRN difference wave, we will henceforth refer to feedback related ERPs as reward positivity (Baker & Holroyd, 2011; Holroyd, Krigolson, & Lee, 2011; Kujawa et al., 2013; Lukie, Montazer-Hojat, & Holroyd, 2014).

1.4. Graded feedback, graded processing?

The above-mentioned studies mostly rely on dichotomous feedback or reward delivery vs. omission. Still, evidence on reward magnitude effects suggests, that errors and rewards are not processed in a dichotomous way. Thus, in a gambling experiment with a fortune wheel, the reward positivity amplitude was larger for full (win/miss), as compared to near (narrow win/near miss) outcomes, indicating that the visual feedback was processed in a graded, not in dichotomous fashion (Ulrich & Hewig, 2014). In motor learning, graded feedback, such as the reaction time just produced is related to better performance than dichotomous feedback relative to a standard, as this kind of feedback allows for more flexible goal-setting and hence improvements (Locke, 1968). Evidence on graded error monitoring in the response-locked ERN has been provided with larger amplitudes for larger errors (Anguera, Seidler, & Gehring, 2009). Similar effects have been reported for feedback-related potentials. In a time estimation task, the exact timing was returned as feedback information with larger errors resulting in more negative reward positivity amplitudes (Luft, Takase, & Bhattacharya, 2014).

1.5. The present study

The studies above did not address grading within successful trials. When playing a ball game, you can hit your team member's location more or less precisely. Moreover, your team member might be able to catch the ball or not. In the first case, your action would attain the goal – pass the ball successfully to your team member – in the later case not. If the outcome is evaluated only based on goal attainment, no further improvement is possible. Still, people do refine their skills, hence even successful actions should be processed in a graded fashion.