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Research Report

Effects of learning on feedback-related brain potentials in a decision-making task

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ABSTRACT

This study investigated the neural mechanisms of feedback processing during learning. While their event-related potentials were recorded, subjects learned to make a sequence of correct choices in a decision-making task. Each choice was followed by gain or loss feedback. In subjects who learned the task, both the feedback-related negativity (FRN), the P3 and the late positivity decreased in the course of the experiment. In subjects who did not learn the task, only the FRN decreased. Moreover, from all ERPs investigated, only changes in P3 amplitude were able to predict performance. These results suggest that the motivational significance of the feedback decreased in all the subjects, but attentive processing of the feedback only decreased in subjects who learned the task. These findings support the view that learning leads to economy of effort and more efficient processing. Moreover, they show that the P3 with its close relationship to learning should be included in future studies investigating the effects of learning on ERPs.

1. Introduction

Performance monitoring is a crucial prerequisite for adjusting and improving behaviour. One useful indicator of monitoring processes such as detecting response conflicts, errors and unexpected outcomes is the so-called feedback-related negativity (FRN, also: feedback error-related negativity). The FRN is a frontocentral negative-going deflection in the event-related potential that occurs following negative feedback. It peaks 200–300 ms after the onset of a negative feedback stimulus (Miltner et al., 1997; Gehring and Willoughby, 2002; Yeung et al., 2005). The FRN is the feedback-locked variant of the response-locked error-related negativity (ERN) which peaks around 50–60 ms after an erroneous response (Falkenstein et al., 1991; Gehring et al., 1993).

Both components have been shown to be sensitive to response or decision conflict (Yeung and Sanfey, 2004), as well as to the emotional evaluation of an outcome (Gehring et al., 1993; Hajcak et al., 2005a). As a unified account of both the ERN and FRN, the reinforcement learning theory proposed that these components occur when perceived outcomes turn out to be worse than expected (Holroyd and Coles, 2002; Nieuwenhuis et al., 2004). The negative prediction error thus generated allegedly leads to decreased activity in the mesencephalic dopamine system. This reduced dopaminergic input is believed to disinhibit the ACC which then generates the ERN/FRN. Extending this theory, recent findings suggest that positive prediction errors also elicit an ERN/FRN. Thus, these components are not only produced when outcomes are worse than expected, but whenever they are different than expected (Oliveira et al., 2007).

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Since learning changes outcome expectations, performance increases should also change the FRN. Indeed, previous studies on learning effects have found decreases in the FRN after learning compared to before having learned (Nieuwenhuis et al., 2002; Pietschmann et al., 2008; Krigolson et al., 2009; Bellebaum and Daum, 2008). Decreases in the FRN have also been observed between subjects who learned compared to those who did not learn a probabilistic reward task (Santesso et al., 2008; Krigolson et al., 2009). However, the results are not always unequivocal, since some studies either did not find any FRN at all (Groen et al., 2007), or found learning-related changes only for positive feedback, not for negative feedback (Eppinger et al., 2008, 2009).

One factor that may contribute to the inconsistencies is that the FRN is embedded into the P3, a positive-going component with a maximum at parietal sites. Importantly, the P3 is affected by factors that also influence the FRN, in particular target expectancy. The P3's most prominent feature is that it gets smaller when target probability increases (Duncan-Johnson and Donchin, 1977; Donchin and Coles, 1988), possibly due to an increased conformity to expectations (Yeung and Sanfey, 2004; Hajcak et al., 2005b). Similar to the FRN, the P3 has been reported to decrease with learning both within (e.g., Groen et al., 2007; Jongsma et al., 2006; Lindin, 2004) and between subjects (Radlo et al., 2001) across various tasks.

Despite the fact that expectancy affects both the FRN and the P3 and that therefore, learning can be assumed to affect both components, only very few studies have investigated learning-related changes in both the FRN and the P3. One exception is the study of Bellebaum and Daum (2008) in which a reduction of both the FRN and the P3 was related to having learned. Similarly, Groen et al. (2007) reported a decrease in the P3 from the first to the second section of a probabilistic learning task in children. However, changes in the FRN with learning could not be investigated in this task, since the abstract feedback stimuli failed to elicit an FRN in the first place.

A further component that can be expected to be sensitive to learning is the late positivity. The late positivity has been suggested to indicate the strength of a memory trace (formed during encoding) (Azizian and Polich, 2007). The authors of this study also tentatively suggest that the late positivity is related to cognitive shifts which are essential for set shifting, as required, for example, in the Wisconsin Card Sorting Test. It has been suggested that the late positivity and the P3 reflect similar processes (Kok, 1997). Along these lines, the late positivity evoked by emotional pictures (e.g. Diedrich et al., 1997; Amrhein et al., 2004; Cuthbert et al., 2000) may indicate "a greater allocation of perceptual processing resources to motivationally relevant input" (Cuthbert et al, 2000, p.97).

Since all these three components have been reported to change with performance improvement, it is well possible that they interact during learning. However, to our knowledge, there are no studies that systematically investigate the changes in all these three components at the same time. Therefore, the aim of the present study was to further analyse changes in feedback processing with learning by examining learning-related effects on the FRN, the P3 and the late positivity. ERPs were compared for the first half, termed "early phase," and the second half, termed "late phase," of the experiment. We expected (1) a smaller FRN in the late phase of the experiment, when learning should have occurred, compared to the early phase of the experiment. This effect should be particularly pronounced for losses. We also expected (2) a smaller P3 and late positivity in the late than in the early phase of the experiment. Since not all of the subjects learned the given task, we also expected (3) a smaller FRN for subjects who learned the task (high learners) than for those who did not learn the task (low learners), particularly for losses, as well as (4) a smaller P3 and late positivity for high learners than for low learners.

2. Results

2.1. Behaviour

The fitted learning curves for each of the subjects are displayed in Fig. 1. Thirty-nine subjects were classified as high learners, and 23 as low learners (see Methods). High learners achieved a larger percentage of correct responses than low learners both in the early ($N=62$, $Z=-5.02$, $p<0.0001$) and the late phase ($N=62$, $Z=-6.55$, $p<0.0001$) of the experiment. Moreover, compared to low learners, high learners showed a larger increase in the mean percentage of correct responses across the two phases of the experiment, namely from 72% to 96% ($N=39$, $Z=-5.44$, $p<0.001$). The performance of low learners only increased from 55% to 59% ($N=23$, $Z=-2.37$, $p<0.05$).

For both high and low learners, response latency (see Table 1) was higher in the first than in the second phase of the experiment ($F(1,48)=18.79$, $p<0.001$). Latency was also higher for wrong than correct responses ($F(1,48)=11.49$, $p<0.01$). Moreover, an interaction between *learngroup* and *accuracy* ($F(1,48)=8.97$, $p<0.01$) showed that this effect was only due to the behaviour of high learners ($p<0.05$). Low learners had similar latencies when giving correct and wrong answers.

2.2. FRN

Grand-average ERP waveforms for the different groups are shown in Fig. 2. An ANOVA of the FRN amplitudes revealed main effects of *outcome* ($F(1,60)=28.54$, $p<0.0001$), *phase* ($F(1,60)=4.81$, $p<0.05$), and *learngroup* ($F(1,60)=6.32$, $p<0.05$), showing that the FRN was larger for losses than for gains, larger in the early than in the late phase, and larger for low learners than high learners. No further effects or interactions were observed.

2.3. P3

Similar to the FRN effects, there was a main effect of *phase* ($F(1,60)=97.63$, $p<0.0001$) and *learngroup* ($F(1,60)=31.96$, $p<0.0001$) on P3 amplitude. The P3 was both larger in the early than in the late phase and for low learners than for high learners (see Fig. 2). These main effects were further qualified by interactions of *phase* and *outcome* ($F(1,60)=6.63$; $p<0.05$) and of *phase* and *learngroup* ($F(1,60)=40.76$, $p<0.0001$). Post-hoc tests revealed that the P3 was only larger in low than high learners during the late phase, but not during the early phase ($p<0.01$).