Learning by doing: an fMRI study of feedback-related brain activations

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Extending meaningful information from the positive and negative outcomes of actions is a key requirement for learning. To define the neural correlates of feedback processing, rapid event-related functional magnetic resonance imaging was used in an associative learning paradigm in normal human volunteers. Positive (compared with negative) feedback was associated with activations in the ventral striatum, midbrain and anterior and posterior cingulate cortex. No activations were seen for the comparison negative feedback. Blood oxygenation level-dependent responses from the midbrain and the anterior cingulate cortex showed a phasic increase in response to positive feedback, whereas a decrease in response was seen for negative feedback. These results underscore the role of the reward system in feedback learning. NeuroReport 18:1423–1426 © 2007 Lippincott Williams & Wilkins.

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Introduction
The adaptation of behaviour based on the results of actions is a prerequisite for the refinement of actions and plans, and for avoiding errors. To determine whether actions have been performed correctly, external information about their results can be used to assess the appropriateness of behaviour. Applying such external information in the form of positive and negative feedback in a systematic fashion, as in conditioning experiments, will lead to the changes in behaviour that is learning. This learning process has been studied in animals, leading to the observation of phasic bursts of dopaminergic activity originating in the midbrain during positive reinforcement [1]. These bursts lead to the learning of rewarding behaviours and thus act as a teaching signal [1,2]. Conversely, negative feedback is associated with dopamine dips that drop below the baseline [1,3]. These neurophysiological findings have been incorporated into computational models of the basal ganglia–dopamine system in reinforcement learning [4].

How feedback is processed in the brain is, hence, a key point in understanding learning processes. A number of studies have addressed this issue using event-related brain potentials (ERPs) and functional magnetic resonance imaging (fMRI) in humans. In ERP studies, typically a frontocentral negativity associated with negative feedback has been observed to appear 250–400 ms after the presentation of the feedback signal, which probably has generators in the anterior and posterior cingulate cortex [5,6]. No specific ERP response has, however, been described for positive feedback. In contrast, most of the fMRI studies on feedback processing have found activations in anterior and posterior cingulate cortex, orbitofrontal cortex and striatum [6–10] in response to positive feedback, but fewer studies have found activations in response to negative feedback [11]. The aim of this study is therefore to reassess the neural correlates of positive and negative feedback during associative learning. Specifically, we were interested in the question of whether or not we could detect an fMRI correlate of the dopaminergic bursts and dips seen in animal experiments following positive and negative feedback, respectively. To reach this goal we performed rapid event-related fMRI during a learning paradigm, in which participants had to learn stimulus–response associations that were based on the information provided by external feedback.

Materials and methods
Participants
Twelve right-handed healthy volunteers (eight women, age range 19–31 years, mean age 23.5 years) participated in the study after giving their written consent. None of them had a history of neurological or psychiatric disorders. The experiment followed the Helsinki protocol and was approved by the ethical committee of the University of Magdeburg.

Experimental procedure
For each experimental run, eight different black-and-white images of animals or objects were presented 12 times each in a random order for a duration of 500 ms. Of these, four pictures were associated with a left-hand response, whereas the remaining four required a right-hand response. The participant was required to make a speeded button press and to determine the correct response for each picture from the response feedback. Following an interval of 1100 ms after the onset of the picture, feedback was given by presenting either a
and the associated prediction error were represented in the amygdala in the Yacubian et al. [16] study. This study used a fast event-related design; therefore, we are unable to resolve activations related to the anticipation of feedback vs. activation as a response to the feedback. Moreover, a purely cognitive feedback was used.

As a novel finding, however, we found two areas (midbrain and ACC) that presented a bidirectional response, that is an increase in activation for positive feedback and a decrease in activation for negative feedback trials. Moreover, the activity difference between negative and positive feedback trials in the midbrain was related to learning efficacy (Fig. 3). Recent studies have shown that some frontal [21] and subcortical areas [16,22,23] increase their activity after reward, whereas they show a decrease with punishment. The current results echo the above findings and extend them to the midbrain. It is intriguing to speculate that this bidirectional response is a correlate of the phasic increase/decrease in dopaminergic activity in the midbrain after positive/negative feedback, respectively; thus it is the brain-imaging manifestation of the teaching signal during the learning process.

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References