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# Modulation of ventral striatal activity by cognitive effort

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ABSTRACT

Effort discounting theory suggests that the value of a reward should be lower if it was effortful to obtain, whereas contrast theory suggests that the contrast between the costly effort and the reward makes the reward seem more valuable. To test these alternative hypotheses, we used functional magnetic resonance imaging (fMRI) as participants engaged in feedback-based learning that required low or high cognitive effort to obtain positive feedback, while the objective amount of information provided by feedback remained constant. In the low effort condition, a single image was presented with four response options. In the high effort condition, two images were presented, each with two response options, and correct feedback was presented only when participants responded correctly to both of the images. Accuracy was significantly lower for the high effort condition, and all participants reported that the high effort condition was more difficult. A region of the ventral striatum selected for sensitivity to feedback value also showed increased activation to feedback presentation associated with the high effort condition relative to the low effort condition, when controlling for activation from corresponding control conditions where feedback was random. These results suggest that increased cognitive effort produces corresponding increases in positive feedback-related ventral striatum activity, in line with the predictions made by contrast theory. The accomplishment of obtaining a hard-earned intrinsic reward, such as positive feedback, may be particularly likely to promote reward-related brain activity.

## 1. Introduction

Human behavior is motivated by a wide variety of goals, from simple goals, such as getting to work on time, to more complex goals, such as finishing a major project. The reward experienced when a goal is achieved depends on the value one places on the goal. The ventral striatum (VS) has been shown to play an important role in processing goal values, both for extrinsic, or tangible, outcomes (such as food rewards and monetary gain or loss) (Knutson et al., 2001; Kurniawan et al., 2013; Tricomi and Lempert, 2015) and for intrinsic, or nontangible, outcomes (such as positive and negative feedback during learning) (Ullsperger and von Cramon, 2003; Lutz et al., 2012; Dobryakova and Tricomi, 2013; DePasque Swanson and Tricomi, 2014).

However, goal value is influenced not only by expected outcomes, but also by the effort required to achieve those outcomes (Braver et al., 2014; Westbrook and Braver, 2015; Kurniawan et al., 2013). Depending on the context in which the goal has to be attained, more or less effort might be expended to achieve a goal. For example, acquiring a good grade for a class that required 20 h of work per week might be more rewarding than getting the same grade for a class that required only 5 h of work per week. In this example, the same outcome is preceded by different amounts of effort. Thus, the experienced reward value of an outcome is context-dependent and related to the amount of effort expended to achieve a reward.

There are two theories that make opposite predictions about how effort exerted during goal-directed actions impacts outcome valuation. According to effort discounting theory, effort decreases outcome value, such that rewards from effortful actions are devalued due to the greater amount of effort required to perform them (Botvinick et al., 2009). Thus, in the above example, a good grade for a class that required only 5 h of work per week would be more rewarding than a good grade that required 20 h of work per week. This principle has been shown to hold in the context of both physical (Kurniawan et al., 2010, 2013; Skvortsova et al., 2014) and cognitive effort requirements (e.g. Kool et al., 2010). In accordance with effort discounting theory, human neuroimaging studies show that outcomes associated with greater effort lead to decreased activity of the VS (Botvinick and Rosen, 2009, Kool et al., 2010, McGuire and Botvinick, 2010).

On the other hand, according to contrast theory, outcomes resulting from increased effort would be valued more due to a greater contrast

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between the aversive action and the rewarding nature of the outcome (Singer et al., 2007; Zentall and Singer, 2007). Thus, in the above example, a good grade for a class that required 20 h of work per week would be more rewarding than a good grade that required only 5 h of work per week. While neuroimaging evidence is lacking, contrast theory would predict increased activation of the VS in association with outcomes that follow effortful actions.

The focus of previous effort-based decision-making studies has primarily been on how extrinsic (e.g., monetary) outcomes are anticipated and valued after different degrees of effort (e.g. Botvinick and Rosen, 2009; Croxson et al., 2009; Schmidt et al., 2012), and whether individuals prefer, or are more likely to choose, high vs. low effort actions (e.g. McGuire and Botvinick, 2010; Kool and Botvinick, 2013). Less is known about the processing of less tangible outcomes, such as the knowledge that one has answered correctly. Unlike money, this sort of performance feedback has no value outside of the task, and therefore, its value is quite subjective (Labroo and Kim, 2009; Braver et al., 2014). Thus, in the current study, we examined the effect of varying cognitive effort demand on VS activity and outcome valuation during learning with performance-related feedback.

Participants were presented with a trial-and-error learning task, in which they had to learn to associate abstract images with specific responses based on the feedback presented after each trial. Cognitive effort was manipulated to be greater in one condition than the other through increased difficulty. As both the affective and informative aspects of feedback activate the striatum (Tricomi and Fiez, 2012; Smith et al., 2016), we kept the initial amount of information provided by feedback the same across conditions. Further, two additional conditions were presented that did not require cognitive effort. For these two conditions, participants had to respond with either one or two button presses, without feedback reflecting their performance accuracy. This design allowed us to compare 1) neural activation associated with outcomes after high and low cognitive effort, as well as 2) neural activation associated with outcomes obtained without any cognitive effort. On the basis of the competing theories, we had two alternative hypotheses: the effort discounting hypothesis predicts that rewards earned after high cognitive effort would produce *less* VS activation than rewards earned after low cognitive effort, whereas the contrast theory hypothesis predicts that rewards earned after high cognitive effort would produce *more* VS activation than rewards earned after low cognitive effort.

## 2. Methods

### 2.1. Participants

Twenty-four individuals participated in the experiment for $50 each in monetary compensation. All participants provided written informed consent. Data from one participant were not included in the main analysis due to a diagnosed brain abnormality. Data from one other participant were not included due to the participant not being able to finish the experiment. Therefore, data from 22 participants were analyzed (9 females; age $M$=23.3 years, $SD$=5.4). The research was approved by the Institutional Review Board of Rutgers University.

### 2.2. Materials

A 3-Tesla Siemens (Erlangen, Germany) Trio scanner was used to acquire all MRI data. Behavioral data acquisition and stimulus presentation was administered using the "E-Prime" software (Schneider et al., 2002).

### 2.3. Procedure

#### 2.3.1. Scan session

A T1-weighted pulse sequence was used to collect structural images in 41 contiguous slices (3x3×3 mm voxels). Similarly, 41 functional images were collected using a single-shot echo EPI sequence amounting to 142 acquisitions (TR=2500 ms, TE=25 ms, FOV=192 mm, flip angle=80°) tilted 30° from the AC-PC line (Deichmann et al., 2003).

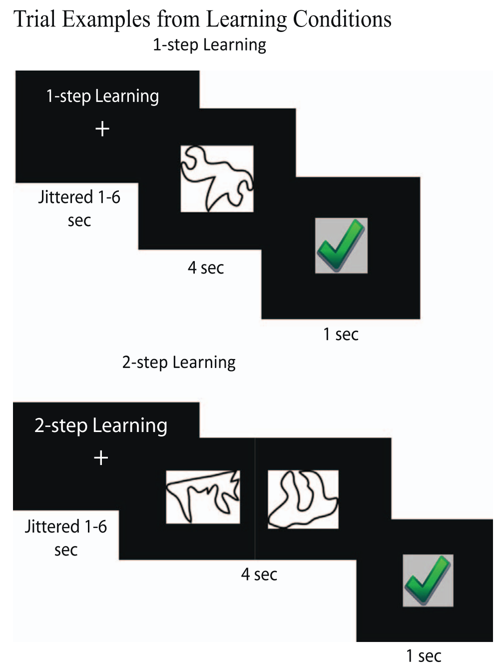


**Fig. 1.** Depiction of trials for 1-step (low effort) and 2-step (high effort) conditions. 1-step random and 2-step random conditions resembled the above set-up; however, random feedback did not reflect performance accuracy.

#### 2.3.2. Behavioral paradigm

Participants had to learn through trial-and-error to associate abstract images with one of the four specific buttons. Specifically, participants were presented with two learning conditions that represented high and low cognitive effort conditions, and two random feedback conditions that required no cognitive effort but only a motor response. In the 1-step learning condition (low cognitive effort), participants were presented with one abstract image and had to respond with one of the four buttons, only one of which led to the presentation of the correct feedback (green √). The other three buttons led to the presentation of the incorrect feedback (red X) (Fig. 1).

During the 2-step learning condition (high cognitive effort), participants were presented with two abstract images, side by side (Fig. 1). Participants had to respond to both images. First, participants had to respond to the image on the left side of the screen with buttons 1 or 2. Then, participants had to respond to the second image on the right side of the screen with buttons 3 or 4. Participants were presented with cumulative feedback after they responded to both images. Correct feedback was presented only when participants responded correctly to both images. At all other times, incorrect feedback was presented. The side each of the images was presented on remained consistent throughout the experiment. Importantly, feedback provided the same amount of information in both the 1-step and 2-step learning conditions. That is, since there are four possible responses per trial in both learning conditions, there is an initial 25% chance of being correct in each trial (as learning progresses, the observed probability of making a correct response differs based on accuracy). The 2-step condition required more effort than the 1-step condition, however, because it places more demands on working memory, as it requires two images and two responses to be held and updated in working memory.

The 1-step and 2-step random conditions resembled the learning conditions described above in all respects, except that feedback did not reflect participants' accuracy (i.e. correct and incorrect feedback