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Modulation of corticospinal excitability by reward depends on task framing

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ABSTRACT

Findings from previous transcranial magnetic stimulation (TMS) experiments suggest that the primary motor cortex (M1) is sensitive to reward conditions in the environment. However, the nature of this influence on M1 activity is poorly understood. The dopamine neuron response to conditioned stimuli encodes reward probability and outcome uncertainty, or the extent to which the outcome of a situation is known. Reward uncertainty and probability are related: uncertainty is maximal when probability is 0.5 and minimal when probability is 0 or 1 (i.e., certain outcome). Previous TMS-reward studies did not examine these factors independently. Here, we used single-pulse TMS to measure corticospinal excitability in 40 individuals while they performed a simple computer task, making guesses to find or avoid a hidden target. The task stimuli implied three levels of reward probability and two levels of uncertainty. We found that reward probability level interacted with the trial search condition. That is, motor evoked potential (MEP) amplitude, a measure of corticospinal neuron excitability, increased with increasing reward probability when participants were instructed to “find” a target, but not when they were instructed to “avoid” a target. There was no effect of uncertainty on MEPs. Response times varied with the number of choices. A subset of participants also received paired-pulse stimulation to evaluate changes in short-intracortical inhibition (SICI). No effects of SICI were observed. Taken together, the results suggest that the reward-contingent modulation of M1 activity reflects reward probability or a related aspect of utility, not outcome uncertainty, and that this effect is sensitive to the conceptual framing of the task.

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1. Introduction

Estimating the expected value and risk associated with potential action is essential for successful learning and decision-making. The expected value of an action's outcome is the product of the magnitude of the potential reward and the probability of achieving the outcome. When reward magnitude is constant, expected value increases linearly with reward probability. The risk of failure associated with a choice is described by the uncertainty of achieving a particular outcome. Uncertainty also varies with reward probability and is maximal when the probability of reward is 0.5. Single-cell recordings in monkeys show that midbrain dopamine (DA) neurons encode reward probability and uncertainty (Fiorillo et al., 2003). Phasic firing in these neurons increases with both reward probability and magnitude, but the firing rate does not distinguish between these two parameters when the expected reward value is constant. A tonic response, appearing to code uncertainty, peaks when the probability of reward is 0.5 (Fiorillo et al., 2003). In humans, functional magnetic resonance imaging (fMRI) reveals midbrain activations associated with these features (Aron et al., 2004; Dreher et al., 2006).

Transcranial magnetic stimulation (TMS) is a useful tool for noninvasive study of motor system physiology in humans. Motor evoked potential (MEP) amplitude reflects the aggregate excitability of primary motor cortex (M1) output cells (Wassermann and Zimmermann, 2012). In a few recent human studies, investigators applied TMS over M1 to measure changes in corticospinal output excitability in response to reward-related events. These studies found increased corticospinal excitability with the desirability of an outcome (Gupta and Aron, 2011) or a momentary reward (Thabit et al., 2011), and increased paired-pulse inhibition

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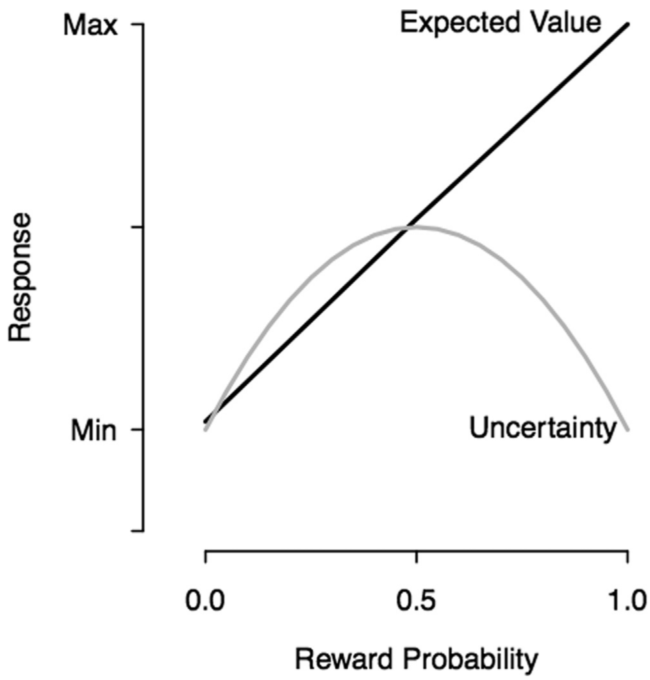

Fig. 1. Reward processing in M1 may reflect either outcome uncertainty or expected reward value. Outcome uncertainty is reflected by an inverted U-shaped function with maximal response under maximal outcome uncertainty (50/50). Expected reward value is the product of the reward probability and reward magnitude and is reflected by a linear increase in response to increased reward probability.

with increased expectation of receiving a reward while passively viewing a slot-machine simulation (Kapogiannis et al., 2008; Kapogiannis et al., 2011). The neural basis of these effects remains unknown, but they almost certainly reflect neural signaling about outcomes and values (Kapogiannis et al., 2011).

Missing from these studies, however, is information on whether reward effects in M1 reflect reward probability or uncertainty coding. This is an important omission, since such data could help identify the source of the signals driving the M1 excitability changes. We designed a paradigm, which delivered a fixed reward with varying probability, allowing us to distinguish between reward probability and uncertainty (Fig. 1). In a task where a fixed reward is either delivered or withheld, outcome uncertainty is a function of reward probability and maximal when reward probability is least certain ($p_{reward}=0.5$) and minimal when reward probability is most certain ($p_{reward}=1$ or 0). Our prediction was that if M1 excitability is affected by reward probability, then increasing reward probability should produce a change in MEP amplitude, whereas, if M1 excitability reflects primarily outcome uncertainty, then varying reward probability should produce an inverted U-shaped response, as probability varies from zero to unity with a maximum effect at 0.5.

2. Materials and methods

2.1. Participants

We studied 40 healthy, right-handed volunteers (21 women, 19 men) (aged 21–41), all of whom were screened and examined by a neurologist. Exclusion criteria were neuroactive medication use, history of central nervous system disorders, or neurological abnormalities. Participants gave written informed consent and the CNS Institutional Review Board of the National Institutes of Health approved the study.

2.2. Task and stimuli

Fig. 2 depicts the stimuli and experimental design. We devised a task where the combination of a trial instruction and a visual stimulus informed the participant about the outcome uncertainty and probability of reward for that trial. The objective of the task was to find or avoid a target stimulus. Successful responses resulted in a prize of 25 cents ($0.25 USD).

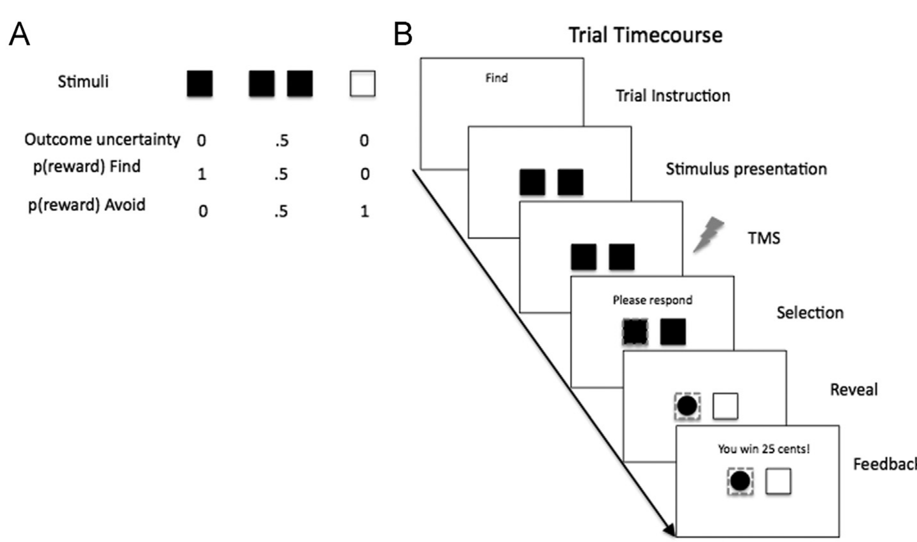

Fig. 2. (A) Reward probability and outcome uncertainty associated with each stimulus for the *Find* and *Avoid* search conditions for the *Circle* instruction group. Stimulus was a filled square (left), two filled squares (middle), or an empty square (right). Probability values below indicate the probabilities of choosing correctly in each condition. Separate groups participated in the *Circle* and *No Circle* instruction groups. For the *No Circle* instruction group, the same stimuli were presented, however the trial contingencies were reversed from what is shown here for the Avoid and Find search conditions. (B) Time course of a trial. For each trial, participants were instructed either to *Find* or *Avoid* the designated target stimulus for that experiment. After the trial instruction was given, the initial stimuli appeared on the screen; after 1 s, participants were prompted to indicate their selection on a button box; after a 500-ms delay, the selection was fed back to the participant by the appearance of a red outline around the selected square (dashed gray line in the figure). TMS was delivered to the left M1 250 ms after stimulus onset and 750 ms before the response prompt. Finally, the location of the circle, if present, was revealed, accompanied by a message indicating whether the response was correct and whether a prize was awarded.