学 位 論 文 の 要 旨

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学　位　論　文　名	Neural Mechanisms for Adaptive Learned Avoidance of Mental Effort
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INTRODUCTION

Humans tend to avoid mental effort. Previous studies have demonstrated this tendency using various demand-selection tasks; participants generally avoid options associated with higher cognitive demand. However, it has yet to be experimentally demonstrated whether humans adaptively learn to avoid higher cognitive demand through experience in uncertain and non-stationary environments, i.e., when the association between cues and demand levels fluctuates and changes over time. If so, what neural mechanisms underlie this learned avoidance and whether they remain the same irrespective of cognitive-demand types.

To address these questions, we formed two hypotheses. First, we hypothesized that humans adaptively learn, through experience, to avoid an option that presently requires higher cognitive demand in the situation where the demand level of options changes over time. This learning process was assumed to be approximated by reinforcement-learning models in which the expected cost of mental effort is updated according to prediction error. Second, we hypothesized that the expected cost estimated from the model is represented in the same brain regions regardless of the types of cognitive demand, as well as the cost prediction error.

MATERIALS AND METHODS

There were 33 participants (4 females; mean age, 25.5 ± 5.4) in Experiment (Exp.) 1 and 20 participants (2 females; mean age, 24.7 ± 6.2) in Exp. 2. The present study was approved by the ethics committee of the Graduate School of Medicine, the University of Tokyo.

To test the above-mentioned hypotheses, we developed novel demand-selection tasks where associations between choice options and cognitive-demand levels change over time, with two variations. We conducted two experiments, which had the same task structure but used different types of problems that were considered to impose different kinds of cognitive demand. Specifically, we used mental arithmetic problems to divide a 5-digit number by 7 and report whether the remainder was small (<= 3) or large (>= 4) in Exp. 1, and spatial reasoning (mental cube-folding) problems to judge whether a 3D cube with three visible colored faces and a concurrently presented unfolded cube matched or not in Exp. 2. For both experiments, we prepared two sets of problems that required different levels of cognitive demand, i.e., low-demand problems and high-demand problems. In Exp. 1, the dividend in low-demand problems (e.g., 35426) consisted of "two consecutive two-digit numbers that were multiples of 7" followed by a single one-digit number from 1 to 6, whereas the dividend in high-demand problems (e.g., 48106) did not contain any numbers that were multiples of 7. In Exp. 2, the difference between low- and high-demand problems was whether the three faces shown on the 3D cube were neighboring on the unfolded cube or not. In both experiments, the probability that a high- or low-demand problem appeared at each trial depended on a cue that participants chose at the start of the trial: there were two cues, the left and right arrows, and the probabilistic associations between each of the cues and high- and low-demand problems changed across trials. After participants chose a cue, a problem, either high-demand or low-demand, was presented, and they were asked to answer it. There was no time limit for response.

We first tested whether each participant chose the opposite option after solving a high-demand problem more frequently than after solving a low-demand problem. Specifically, we conducted a Chi-square test on the contingency table consisting of the problem types of the previous trials and the choices of the current trials for each participant. We next analyzed the effect of the demand experienced two trials prior on the choice at the current trial for participants who showed avoidance.

We fitted participants' choices who showed avoidance using the prediction error-based models, updating based on (1) time spent solving the problem, (2) demand level of the problem, (3) incorrect solving, (4) sum of (1) and (3), with a weighting parameter, and (5) sum of (2) and (3), with a weighting parameter, as cost. In addition, we attempted the prediction error models, updating based on (6) rest time in the scanner as reward and sum of (6) and (2) as reward and cost, respectively, since the model of (2) was best fitted among the above-mentioned five prediction error models. In addition to the prediction error models, we also examined probabilistic Win-Stay-Lose-Shift models and full Probabilistic-Selection models. For either type of model, Win and Lose were defined in two ways: (1) experiences of low- and high-demand problems or (2) solving correctly and incorrectly. We conducted model comparisons and simulations.

Further, we explored brain regions representing the expected mental effort cost and cost prediction error through model-based functional magnetic resonance imaging (fMRI) analyses. At the individual level, we examined the following three general linear models designed to explore the correlates of the expected cost for the chosen option and the cost prediction error, adjusted for the response time for choosing an arrow, actual demand level of the problem, and solve-time. These general linear models almost differed in the regressors with parametric modulation by cost prediction error at the time of problem presentation, midpoint between problem presentation and answer, or time of answer. We also conducted conjunction analyses for detecting common regions in both Exp. 1 and 2.

RESULTS AND DISCUSSION

We found that most participants learned to avoid higher cognitive demand in the changing environments, and their choices depended on the demand experienced during the preceding two trials. We have then shown that their behavior could potentially be captured by the prediction-error-based model assuming that the experienced demand level constituted actual cost, comparing other models.

Model-based fMRI analyses revealed that activity in the dorsomedial and lateral frontal cortices was positively correlated with the trial-by-trial expected cost for the chosen option commonly across the different types of cognitive demand, and also revealed a trend of negative correlation in the ventromedial prefrontal cortex. We further identified correlates of cost prediction error at time of problem-presentation or answering the problem, the latter of which partially overlapped with or were proximal to the correlates of expected cost at time of choice-cue in the dorsomedial frontal cortex.

Comparing our results to previous studies on mental-effort avoidance, ventromedial prefrontal cortex might specifically serve for experience-based learned choices of values. On the other hand, the anterior middle frontal gyrus region might serve for mental effort avoidance when experience-based learning occurs and/or when reward effects are absent. As for the latter, existence of such a specialized system for no reward-effect conditions seems in line with the suggestion that systems for appetitive and aversive learning can be separated to some extent.

We hypothesized the existence of neural representations of the expected cost of chosen option, which are updated according to cost prediction error and used for decision making to avoid higher demand. Possible substrates of this could be captured in our finding that the cue-time activity of the frontoparietal-insular clusters and the answer-time activity of the clusters including fronto-insular regions were correlated with the expected cost of chosen option and cost prediction error, respectively, both commonly across tasks, and these two correlates partially overlapped or were adjacent in the right dorsomedial frontal cortex and possibly also anterior insula. In reference to reinforcement learning theory, this mechanism could be called model-free reinforcement learning based on the "cached cost" of options. Our current study presents, for the first time, an empirical indication that humans might also learn to avoid high cognitive demands, even without reward-learning, in a reinforcement-learning-like fashion although different decision strategy may also be used.

CONCLUSION

These results suggest that humans adaptively learn to avoid mental effort, having neural mechanisms to represent expected cost and cost prediction error, and the same mechanisms operate for various types of cognitive demand.