Numerical Induction beyond Calculation: An fMRI Study in Combination with a Cognitive Model

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Introduction

The ability to detect environmental regularities is a cognitive skill essential for survival. Human beings have a capacity, called numerical reasoning, to identify and extrapolate number serial patterns in such diverse areas as scientific discovery, economics, and the weather. Numerical reasoning and calculation have long been intimately associated, leading to the suggestion that they share a common system of the manipulation of numbers. The question of interest is whether numerical inductive reasoning is fully embedded in number calculation, or operates beyond calculation? To directly address these issues, we run an fMRI experiment to compare the number series completion task with the addition calculation task, and to understand the results in a cognitive architecture.

On the basis of previous researches, we hypothesized that the numerical reasoning compared to calculation was more activation in parietal areas for visual representation of relationship between numbers and prefrontal areas for relational integration.

In addition, computational cognitive modeling was employed to make specific predictions about the different processes of numerical reasoning and calculation. We will test our understanding of these processes by modeling the data within an information-processing theory called the adaptive control of thought-rational (ACT-R) (Anderson J, 2004; 2007).

Material and Method

Subjects and Stimuli

Fifteen paid healthy graduate students (8 females) with the mean age of 22.1 ± 2.3 years participated in the experiment. Three types of problems were organized into a block design, the numerical reasoning task (Rea), calculation (Cal), and judgment baseline (Jud) (see Fig. 1).

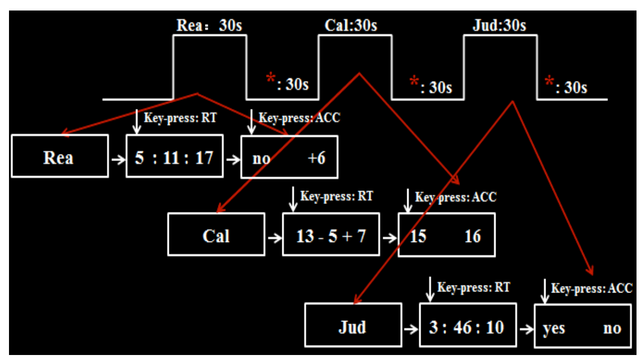

Fig. 1 Presentation paradigm of the stimuli.

FMRI Analysis

Data were analyzed using SPM5 software (http://www.fil.ion.ucl.ac.uk). Condition effects at each voxel were estimated according to the general linear model. The contrast of Rea vs. Jud would reveal regions for reasoning, the contrast of Rea vs. Cal would reveal regions specific to reasoning, and the contrast of Cal vs. Rea would reveal regions more involved in calculation. An uncorrected voxel-level intensity threshold of $p < 0.01$ with a minimum cluster size of 27 contiguous voxels was used to correct for multiple comparisons using the AlphaSim method (http://afni.nimh.nih.gov/pub/dist/doc/manual/AlphaSim.pdf). This procedure yielded a corrected threshold of $p < 0.01$.

The Modeling

To understand the results in the frame work of the ACT-R theory, the model we constructed primarily depends on the visual module to perceive the stimuli, the manual module to respond, the retrieval module to retrieve a fact from memory, and the imaginal module to encode and update its stored representation.

Results and the Model

Behavioral Performance

We carried out analyses of variance for Rea, Cal and Jud on both RT and accuracy (Fig. 2, solid lines). Response to Rea task was significantly longer [$F(1,14) = 115.20$, $p < 0.001$; $F(1,14) = 12.37$, $p = 0.003$] and less accurate [$F(1,14) = 12.50$, $p = 0.003$; and $F(1,14) = 35.72$, $p < 0.001$] than that of Jud and Cal respectively. As shown in Fig. 2 (dotted lines), the model predictions of the behavioral results fit the data reasonably well.

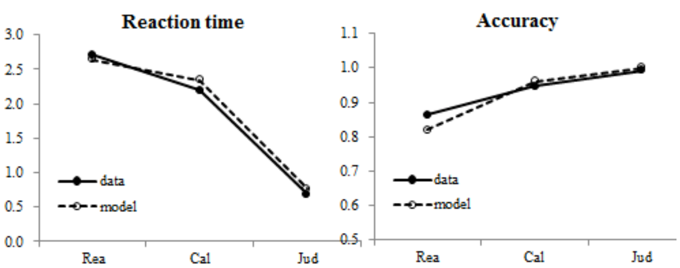

Fig. 2. Behavioral performance. Data (solid lines) and model fits (dotted lines) for Rea, Cal, and Jud problems.

FMRI Results

The Rea > Jud contrast revealed activation in the left dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC), bilateral intraparietal sulcus (IPS), and left occipital area (Fig. 3A). The Rea > Cal contrast revealed activation in the left DLPFC, precentral Gyrus, right superior parietal lobule (SPL), and left occipital Gyrus (Fig.3B), while the Cal > Rea contrast revealed activation in the bilateral thalamus, caudate, and posterior cingulate cortex (PCC) extending into cuneus (Fig.3C).

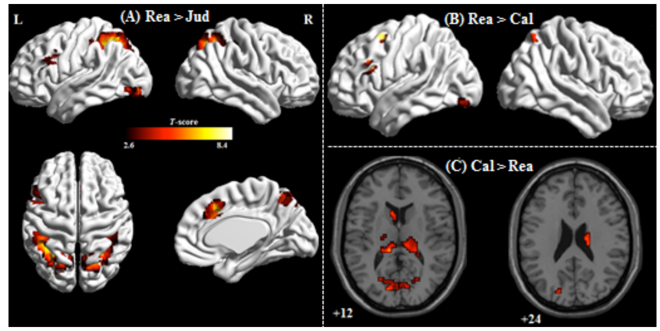

Fig. 3 Activation for the three contrasts

BOLD Responses

As shown in Fig. 4, four regions were of particular interest in this study: two regions of DLPFC and SPL specific to (Rea > Cal) (Fig. 4A); two regions of thalamus and caudate specific to (Cal >Rea) (Fig.4B).

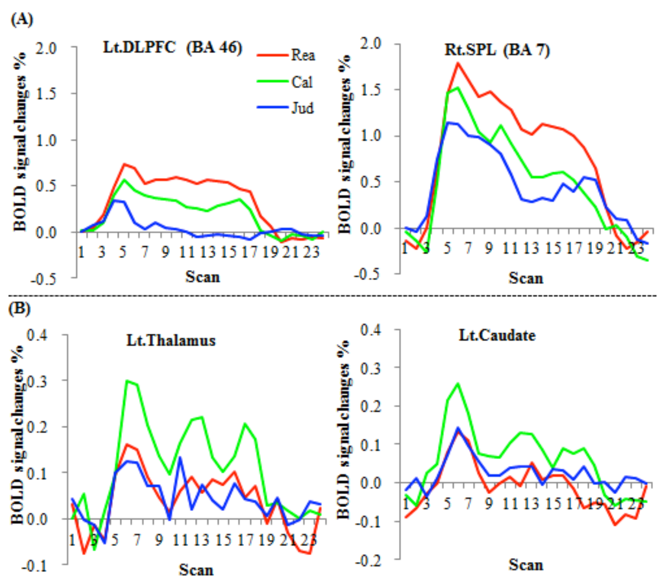

Fig. 4 BOLD responses for the ROIs.

Acknowledgments

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