Functional neuroimaging of self-ratings associated with cognitive effort

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Abstract. It is widely accepted that higher order thinking, such as working memory and mathematical problem solving are associated with activation in the pre-frontal cortex. Thinking about thinking, however, often referred to as meta-cognition is less well understood. Converging evidence suggests that the function of the prefrontal cortex is also key for meta-cognitive judgments, particularly the most anterior part of the prefrontal cortex, Brodmann Area (BA) 10. The current research examined functional magnetic resonance imaging (fMRI) signal associated with BA 10 during metacognition related to self-ratings of mental effort exerted during mathematical operations. We analyzed data from young adult participants who solved addition problems with three levels of difficulty. Our results showed fMRI signal in BA 10 is modulated during the metacognition task, with the left BA 10 showing decreasing fMRI signal with difficulty, whereas the right BA 10 is more stable. These preliminary findings point to further directions for research that should consider rostrolateral and medial aspects of BA 10, and individual differences in performance.

Keywords: prefrontal cortex, metacognition, mathematical cognition, self-reflection, cognitive effort

1 Introduction

1.1 Functional Neuroimaging and Mathematical Cognition

Functional magnetic resonance imaging (fMRI) is a technique used to visualize brain activity. When neural activity is initiated in an area of the brain due to certain tasks or stimuli then instantly oxygenated blood is transferred to that area, to replace deoxygenated blood [1]. Oxygen rich hemoglobin is less magnetic than oxygen depleted hemoglobin. This results in an intensified magnetic resonance signal, which in turn allows us to map the locations which are at the time in need of resources, thus considered active.

fMRI studies of mathematical cognition examine brain responses to processing numbers in a range of tasks starting from simple numerical judgments, to complex math problem solving, as well as metaphorical processes that underlie our understanding of concepts such as infinity. Studies show that language and calculation processes belong to the same network but are regionally differentiated [2]. Arabic digit processing seems to rely on the left angular gyrus and no digit specific visual number form area exists in the ventral visual cortex [3]. The left angular gyrus seems to be responsible not only for Arabic digit processing but also for simple and complex mathematical calculations [4]. Numbers in digit format and dot format are deciphered in occipital, frontal, temporal and parietal areas [5].

Prefrontal cortices also play a key role in mathematical processes. The inferior frontal gyri are involved in calculating simple numerical tasks and if the cognitive load is increased the middle frontal gyri are also involved [6]. Consistent with this interpretation, research shows that working memory load of math problems is reduced with training and in turn reduces the implication of the prefrontal lobes [7]. Indeed, individual difference in math performance is related to prior training in mathematics as the latter occurs simultaneously with development of the prefrontal cortex [8]. Critically, neuroimaging studies of mathematical cognition rarely evaluate retrospective self-ratings associated with performance [9]. Self-ratings related to thinking of one's own thinking is referred to as metacognition.

1.2 Metacognition of Effort

Metacognition is our ability to be self-reflective regarding our own thinking and knowing [10]. The prefix meta leads us to assume that reflecting upon our own cognition comes, in time, after cognition itself [11]. Metacognition is related to learning and degree of success in math problem solving [11]. Neuroimaging studies suggest that metacognition is important for learning and this is indicated by activations in the rostrolateral prefrontal cortex and angular gyrus [12]. Activation of the bilateral hippocampus shows that judgments of learning are related to associative memory representations [13]. Metacognitive functions have been correlated with medial frontal brain areas, such as the anterior cingulate cortex, which are active during conflict resolution, error correction, and emotional regulation [14]. However, it is not clear whether the anterior cingulate serves all types of task setting, selective attention or for creating a link between emotional and cognitive control [15]. The anterior cingulate cortex monitors conflict, which in turn signals a need for greater cognitive control [16]. Cognitive control is then implemented by the left dorsolateral prefrontal cortex [17]. There is a link between metacognition and consciousness, however conscious-ness has the potential to dissociate from second order behavior and meta-level depiction [18].

Measuring metacognition has limitations. One of them is due to metacognitive bias; the fact that we can observe differences in subjective confidence when task performance does not change [19]. Different people have different ability in distinguishing between their own judgments (metacognitive sensitivity) and metacognitive sensitivity in the same individual may vary according to the level of difficulty of the task (metacognitive efficiency) [19]. Age also seems to affect metacognitive ability. Younger adults show fewer high confidence errors than older adults [20]. One type of metacognition relies on our procedural knowledge, which is the way we perceive the difficulty of a task.

Converging evidence of brain imaging findings suggest the prefrontal cortex, Brodmann Area (BA) 10 plays a major role in retrospective metacognitive judgments [9]. Critically, this hypothesis has not been directly investigated in mathematical tasks. Mathematical tasks can be complex and more demanding in terms of cognitive load than simple math tasks [21][22]. For example, for most adults addition with single digits is easier that three-digit problems. This will be the first study to examine the role of BA 10 on mathematical operations of different difficulty in young adults. Specifically, participant's self-ratings on mental effort associated with addition problems of different difficulty were compared with fMRI signal elicited during the metacognitive task. We hypothesized that metacognitive self-rating of effort related to the arithmetic operation of addition will be associated with BA 10.

2 Methods

2.1 Participants

We report data on twelve healthy right-handed adults (6 females, 20 to 30 years old, 23.85 ± 3.27), without any MRI contraindications (i.e., metal in their body) and without formal expertise in mathematics (i.e., not math majors) participated in the fMRI study. All participants provided a signed consent form and the ethics committee at National Research University Higher School of Economics approved all procedures (approval dated on 15th January, 2018). For taking part in the study, participants received 1000 rubles and an anatomical picture of their brain.

2.2 Materials

Parametric Math Task: In this task, mathematical operations are presented on the top of the screen together with four possible answer options at the bottom of the screen. Participants were asked to solve the problem and choose the correct option. The experiment consistent of four math operations (addition, subtraction, multiplication, division) and three levels of complexity, indexed by the number of digits for each math operation (1-, 2-, and 3- digits), which were presented in blocks. Task blocks also included control tasks for each difficulty level during which participants viewed numbers at the top of the screen and four possible answers at the bottom of the screen and were asked to identify which font the numbers on the top of the screen was printed in. Each condition appeared in a block and was randomly presented three times. The timing for each block was thirty-two seconds. During this time participants were asked to give as many correct answers as they could. As soon as their time run out, they were asked to indicate cognitive effort exerted on the task on a scale from one to four. Participants had up to five seconds to respond and were encouraged to answer honestly, as their answer would help us know their opinion on the task. After their evaluation, a fixation cross appeared on the screen, which indicated that they had ten seconds a break before the next task block.

Behavioral scores included accuracy and reaction time during task conditions and self-rating during the metacognition task.

2.3 Procedures

Participants received training in a behavioral session before completing the task in the MRI on separate days.

MRI data acquisition

Data were acquired with a Siemens Magnetom Verio (Syngo MR B17), 32-channel head coiled, 3 Tesla scanner. Anatomy was collected with a 3D magnetization rapid gradient echo sequence (TR = 1470ms; TE = 1.76ms; 9° Flip angle; voxel size: 1mm ×1 mm ×1 mm). Functional scans were acquired using TR = 500ms; 300 measurements per run; voxel size = 3 mm × 3 mm × 3 mm. During the runs behavioral responses were acquired with a key pair of MRI button box for left and right hands.

MRI data processing and analyses

Data were pre-processed and analyzed using AFNI (Analysis of Functional Neuroimages, Medical College of Wisconsin; Cox, 1996). During pre-processing stage images were slice-time corrected, registered, normalized, motion corrected, masked and smoothed. Slice-time correction was performed using AFNI's "3dTshift", registration was done using the "align_epi_anat.py" command and normalization, motion correction smoothing and masking by using the commands "@auto_tlrc", "3dvolreg", "3dmerge", and "3dAutomask", respectively. In order to fit a model to the data a first level analysis was performed by using the timings for all mathematical operational conditions and the timings for the metacognition task for the mathematical operation of addition. This paper focuses on fMRI signal changes of metacognition tasks associated with addition problems. A region of interest analysis was conducted by creating separate anatomical masks for the left and right BA 10 of each participant (Fig. 1). Region of interest data associated with self-ratings of three levels of addition problems were extracted using AFNI's "3dmaskave" command.

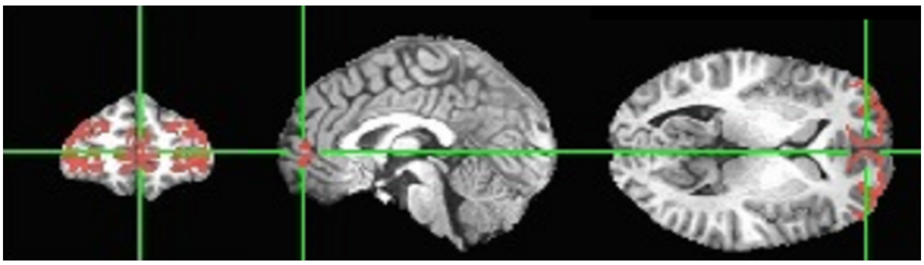

Fig 1. Anatomical location of the region of interest BA10.

3 Results

3.1 Functional Neuroimaging and Mathematical Cognition

Average accuracy percentage for difficulty levels with 1-, 2-, and 3-digit addition problems were 97.48%. 89.76%, 78.85%. Self-ratings for difficulty levels with 1-, 2-, and 3-digit are illustrated on Figure 2. Data of the region of interest analysis based on the Bold Oxygen Level Dependent (BOLD) signal change during the metacognition task of the mathematical operation of addition, for both left and right BA 10 for each level off difficulty are illustrated on Figure 3.

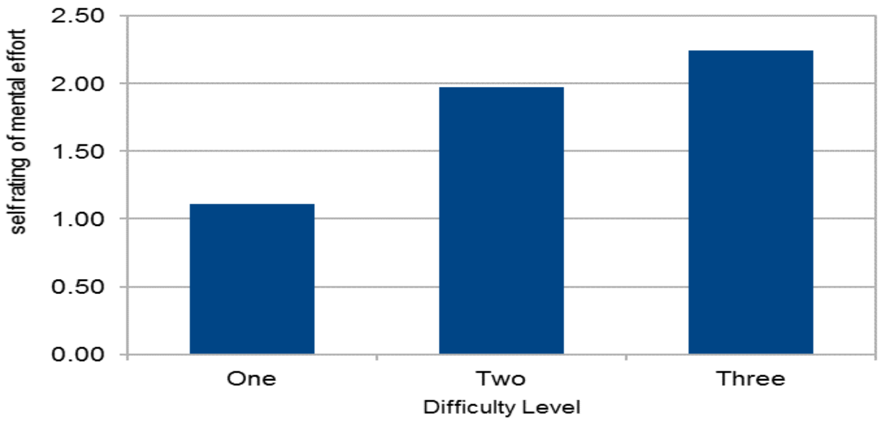

Fig 2. Average self-rating of mental effort for each level of difficulty

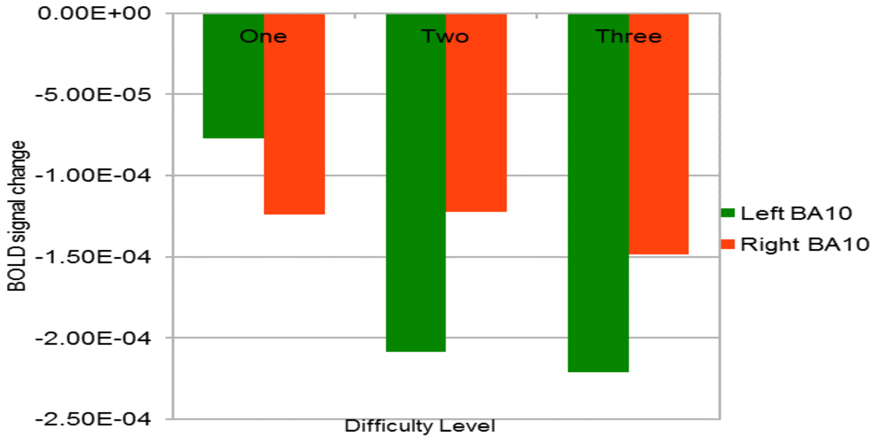

Fig. 3. BOLD signal change in BA 10 as a function of difficulty

4 Discussion

We examine brain signal in the most anterior regions of prefrontal cortex, BA 10, during a metacognition task that assessed cognitive effort exerted during addition problems with three levels of difficulty. Behavioral results show that self-ratings increase as a function of difficulty, as it was expected. Neuroimaging results show that brain signal in BA 10 is modulated by self-rating to different difficulty levels, albeit this relation differs by hemisphere. Negative BOLD signal change was observed for all three levels of difficulty. This preliminary finding was unexpected and potential explanation are discussed in terms of brain location and individual differences.

Our examination suggests that metacognition to increasing levels of difficulty is differs by hemisphere of BA 10 and it is expressed as a deactivation. Specifically, metacognition to difficulty level one shows the least deactivation, whereas level three shows the most deactivation. Interestingly, the second level of difficulty shows approximately the same but not equal deactivation to level three in the left hemisphere. For difficulty levels two and three, the right hemisphere becomes less deactivated than the left, whereas for level one the left hemisphere is less deactivated than the right hemisphere. The prefrontal cortex occupies a substantial proportion of the cortex and BA 10 constitutes about 1.2% of the total brain volume [23]. BA 10 covers parts of the middle and superior frontal gyri. Its medial parts are adjacent to the anterior cingulate. It has complex functional correlates that are usually associated with higher complexity, abstract cognitive thoughts, as well as mind wondering [24][25]. The proposal that BA 10 is involved in metacognition, thinking about thinking [9], appears to be consistent with this interpretation. Our data showed that BA 10 is modulated by ratings of mental effort and the relation varies by hemisphere. A potential explanation is that BA 10 is a large region of cortex and retrospective decisions may elicit activation in rostrolateral or ventromedial aspects of BA 10. Our anatomical mask did not distinguish between these regions and future analyses examining these regions separately may shed light into this explanation.

Variability in signal change may also relate to individual differences in performance. For example, it may be useful to match consistency in self-ratings and accuracy for each difficulty level. Specifically, a participant may have high accuracy on difficulty level three and rate the difficulty higher than another participant who has low accuracy on difficulty level three and rate this level with a low difficulty rating because the participant gave up trying. Further analyses are needed that consider signal change during task condition and individual differences in task performance.

5 Conclusion

Concluding, self-ratings to a metacognition task related to mental arithmetic modulate signal change in BA 10, however our findings suggest that this relation differs by hemisphere. Further research should consider more specific locations and examine relations in other regions that are highly interconnected with the most anterior parts of the frontal cortex. Understanding the brain correlates of metacognition would inform cognitive theories and practically benefit studies with samples with cognitive impairments.

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