Errors of mathematical processing: The time course of dorsolateral prefrontal and anterior cingulate cortex activity when solving algebra equations

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INTRODUCTION

❖ Our goal was to assess regions important for successful mathematical problem-solving

❖ Prefrontal regions are more engaged when recognizing incorrect equations (e.g., 2 + 2=5)(Menon, et al., 2002)

❖ However, no study has examined whether prefrontal activity is related to the production of correct solutions

Question 1: Will activity in prefrontal regions differ between correct and error trials?

❖Regions of the anterior cingulate cortex (ACC) have been dissociated based on whether conceptual or response conflict is present (VanVeen & Carter, 2005)

❖In this design, we assume that the problem solving phase should include both types of conflict whereas only response conflict should be present in the response stage

Question 2: Will dissociable regions of the ACC be active in the problem-solving and response phases?

❖This is the first event-related study that examines number size effects

❖ We predict that regions associated with successful calculation regardless of number size are important for general problem-solving.

❖ Regions that are crucial for solving equations with large but not small numbers may be important for numerical manipulation and/or working memory.

Question 3: What regions are important for general problem-solving vs. regions that are engaged by greater numerical processing or working memory demands?

METHODS

Subjects: n=9, average age = 23.8

Only subjects who achieved between 25% - 75% correct in pre-testing were included

Stimuli:

Small **(x - 6)/3 = 7**

Large **5 * (x - 7) = 65**

METHODS

Procedure:

Participants had 40 s to solve the equation. When they had an answer, they pressed a key and then used their index and middle fingers to key in an answer.

Analyses:

❖ 7 – 9 runs of 12 trials each were acquired for each participant

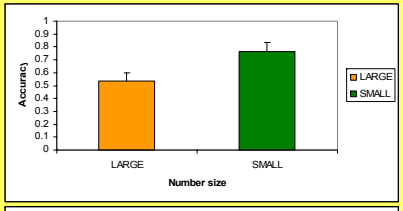
❖ROIs were obtained using a number size (2) x time (21) ANOVA or an accuracy x time (21) ANOVA. We were unable to include both accuracy and number size in an omnibus ANOVA because participants made too few errors in the small number condition.

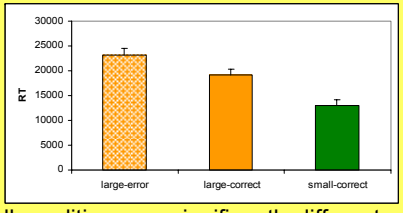
❖ Voxel-wise tests used a threshold of p < .001 and a cluster size of 8 voxels

Type	EPI	Slices	36
Scanner	3T Siemens Trio	TR	2000 ms
Voxel size	3.438 x 3.438 x 3.4mm	TE	25 ms
Flip angle	90	FOV	220 mm

RESULTS

Behavioral Results



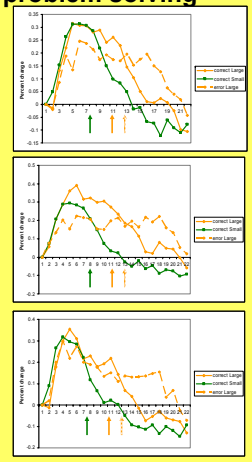


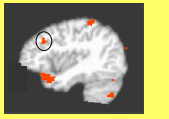
All conditions are significantly different from each other (p < .005)

RESULTS

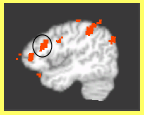
Accuracy x time

Errors are associated with reduced activity in the DLPFC & ACC during problem solving

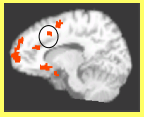




BA 9 (38,26,33)



BA 9 (-45,23,29)



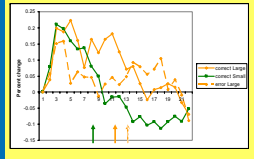
BA 32 (-11,17,44)

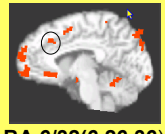
= time of response in each condition

Other regions showing this pattern are the SMA, left BA 19, left thalamus, & right cerebellum

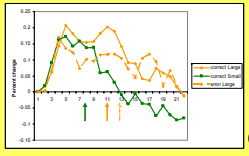
RESULTS

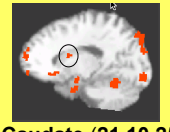
ACC & caudate are active during problem-solving and at response





BA 6/32(6,26,36)



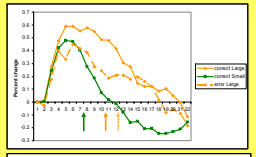


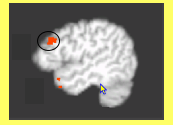
Caudate (21,10,25)

RESULTS

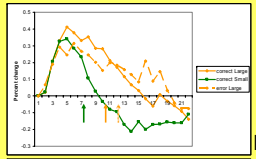
Number size x time

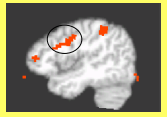
DLPFC, VLPFC, & parietal cortex are more active when correctly solving equations with large numbers



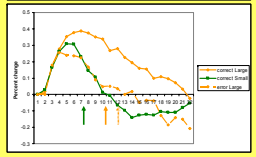


BA 9 (50,-23,29)





BA 6/44/45 (-53,-3,36)



BA 39 (31,-63,32)

DISCUSSION

❖ **Question 1: DLPFC was more active when participants solved the equation correctly regardless of number size.**

❖ **Question 2: The region of the ACC previously associated with conceptual conflict was primarily active in the problem-solving phase whereas a more ventral region was active in both phases.**

❖ **Question 3: DLPFC and cingulate (and other regions) were important for general problem-solving whereas parietal, DLPFC, and VLPFC were specifically involved for correctly solving equations where numerical processing and working memory demands were high.**

❖**These results constitute the first step in being able to relate errors in mathematical problem-solving with reduced neural function.**