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Visual–spatial ability and fMRI cortical activation in surgery residents

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Abstract

Background: We previously reported that a particular type of visual–spatial ability, mental rotation of visual forms, correlates with surgical performance in residents. In the current study, we used functional magnetic resonance imaging (fMRI) to identify patterns of cortical activation associated with mental rotation ability in those same residents.
Methods: Seventeen surgery residents underwent fMRI scan while performing a mental rotations test (MRT) and a perceptual matching task as a control (CON) for nonimagery components, such as visual attention. A contrast analysis (MRT greater than CON) revealed cortical regions engaged during mental rotation by all participants, and parametric statistical analysis identified regions having the strongest association with MRT performance.
Results: Significant bilateral (left greater than right) activation was seen in all participants for rotation-versus-perceptual CON contrast. Better MRT performance was associated with greater activation in several cortical regions related to visual imagery and motion processing.
Comments: Surgery residents represent a unique population in which to study individual differences in visual–spatial abilities and associated neural substrates because they may relate to technical skills. These findings suggest that variation in performance on spatially complex tasks involving imagery may reflect different spatial problem-solving strategies in surgery students.

Keywords: Brain imaging; fMRI; Mental imagery; Mental rotations test; Surgical education; Visual–spatial ability

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One important goal of surgical education research is to understand surgical performance by way of underlying cognitive abilities that may be influenced through directed training. For example, it has been shown that performance on spatially complex procedures–such as those involved in plastic and reconstructive surgery–is related to performance on visual–spatial tests [1,2] and that surgical performance can be successfully predicted if measures are chosen carefully (see references [3] and [4] for a review of the issues). Our approach is to use previously validated tests of surgical performance [5] and select standardized tests on the basis of relevant theoretical work, such as the mental rotations test (MRT) of visual–spatial ability [6].

In the current study, we examined patterns of cortical brain activity in a group of surgery residents while they performed the MRT. We previously reported [1] a correlation between MRT scores on a paper-and-pencil variant of the MRT and a measure of surgical performance (Z-plasty procedure). Of interest, this rotation ability was the only 1 of several visual–spatial ability measures to demonstrate such correlation, suggesting that using the “mind’s eye” to visualize spatial rotations is a significant determinant of surgical skill for spatially complex procedures. Other visual–spatial tests included form completion, shape memory, and

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picture recognition. As predicted by visual perception theory, none of these were found to correlate with performance on the Z-plasty procedure.

Several reasons exist for using functional MRI to expand our investigation of this relationship. First, the typical patterns of cortical activation during mental rotation have been fairly well characterized [7–9], and we wished to explore whether our surgical residents as a group differed in any important respects from the general population. Second, given our previous findings of variation within the resident group on MRT, we sought to identify cortical networks associated with the highest levels of performance on MRT, thereby establishing an indirect association with surgical performance. Finally, cognitive models suggest that various strategies can be employed in mental rotation (eg, piecemeal versus holistic), and there is an expectation that these will be reflected in recruitment of different brain regions. To the extent that we can characterize "optimal" patterns of cortical activation, we might then be better able to examine stability across time and training of this important cognitive ability. Our expectation is that an increased understanding of the mental processes related to good surgical performance might lead to new methods of assessment and/or teaching.

Methods

Study participants

Eighteen surgery residents voluntarily participated in the current study. These residents were invited to participate from the pool of 30 residents from the previous study of Wanzel et al [1]. Of note, it was approximately 12 months between their participation in the previous and current studies, and that interval had been filled with variable amounts of additional surgical training and experience across participants. Thus, we could not use their earlier MRT scores to correlate with brain activation but had to rely on MRT data collected at the time of scanning. Because of technical failure, behavioral data for 1 participant were not recorded and therefore not included in the statistical analyses. All participants provided informed consent for scanning and, ethics approval was obtained from the Institutional Review Board. The mean age of the group was 29.1 years, and 14 participants were men. All residents were in postgraduate year 2 year of training. Exclusion criteria included left handedness, neurologic condition, severe claustrophobia, and in vivo metal fragments.

Procedure

Once participants were securely and comfortably situated in the fMRI device, they were presented with either an MRT or a visual CON task. Ten alternating task sequences (CON or MRT) in 25-s blocks were run for a total of 8 min 20 s. A maximum of 7 s was allowed for each response, and there was a 500-ms interstimulus interval. During scanning, images were back projected onto a screen at the foot of the scanning table. Participants used a mouse to indicate response choice. Speed and accuracy were given equal weight in the instructions, and a brief practice run with similar stimuli was conducted to ensure understanding of the task.
MRT: Stimuli for the MRT consisted of cube figures derived from the original published study by Shepard and Metzler [10]. Similar stimuli have been used in previous fMRI experiments [7–9]. Two figures were presented, and participants decided whether they were (1) the same but rotated or (2) different (Fig 1a). The stimuli represented a range of degrees of through-plane rotation and were equally divided as to the correct response.
CON Task: As in all hierarchical (block) fMRI designs, a reference task was required to allow for the subtraction of brain activity not related to mental rotation, such as visual attention, scanning, perceptual feature analysis, and decision making. When contrasted with brain activity during the mental rotation task, any residual brain activity can then be attributed exclusively to the mental rotation process. Here, we designed a CON task using (nonrotated) pairs of cube figures filled with simple patterns requiring a same–different (physical match) decision (Fig 1b). Of note, such perceptual matching operations were not related to surgical performance in our previous study [1], providing further evidence that this represented a good CON.

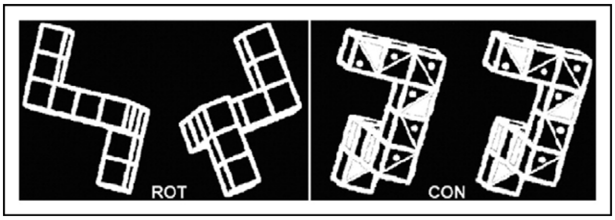

Fig. 1. Examples of visual stimuli for the 2 conditions: mental rotation (**ROT**) and perceptual control (**CON**). In each condition, the subject was asked to decide if the 2 stimuli were the same or different either by mental rotation or by comparing the surface patterns.

Image acquisition

Functional data were acquired on a 1.5-Tesla Signa MR System (GE Medical Systems, Milwaukee Wisconsin) using single-shot spiral acquisition (TE 40 ms; TR 2,000 ms; FOV 220 mm). Slices were 4.4 mm thick, with 25 axial slices covering the entire brain. The first 3 frames were subtracted to allow for signal equilibrium. To acquire anatomic images, a standard 3-dimensional T1-weighted sequence (FOV = 200) was used to generate 60 axial slices (2.2-mm thick).

Data processing and statistical analyses

All preprocessing and analyses of imaging data were performed using analysis of functional images software [11]. All functional images were coregistered to a structural image, realigned for motion correction, corrected for within-frame time of acquisition, spatially normalized, and smoothed using a Gaussian kernel of 7.6 mm full-width half maximum. A contrast between blood oxygen level–dependent (BOLD) signal during MRT versus perceptual CON was conducted to identify regions demonstrating greater engagement during mental rotation beyond those processes attributable to visual scanning and spatial attention. For the CON task contrast, Student *t* tests were performed on each cluster of 10 voxels (270 μL) to identify brain regions selectively involved in mental rotation (statistical threshold

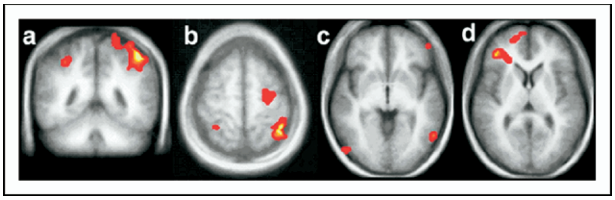

Fig. 2. Cortical regions showing increased activation for MRT versus CON include the bilateral parietal region (**a and b**), the left premotor region (**b**), the bilateral inferior and middle frontal gyri regions (**c and d**), and the left middle temporal gyrus region in approximate area MT+ (**c**). This figure shows the cortical activity that can be linked directly to the mental rotations task irrespective of performance on that task. The left side of the image represents the right hemisphere of the brain.

$P < .01$, uncorrected, 1-tailed). To identify brain regions with the strongest association to MRT performance, regression analysis was used on each cluster of 5 voxels (135 μL; statistical threshold $P < .005$, uncorrected).

Results

Behavioral data

The range of performance for the mental rotation task was 17 to 42 correct responses out of a possible 50 (average 33). The range of mean response times for correct items was 504 to 1170 ms (average 888 ms). Of interest, scores on this occasion did not correlate very highly with those from the original paper-and-pencil variant of the test, $r(16) = .14$ (not significant). Possible explanations for this poor correlation and implications of this finding are discussed later.

fMRI data

CON Task: Fig. 2 depicts areas that were selectively active during MRT compared with activity during the CON task for the whole group. This figure shows that the pattern of activity associated with mental rotations in our group of surgery residents was similar to that of the general population. As expected from previous research on mental rotation [7–9], there was robust activation in both the left and right inferior parietal regions (Figs. 2a and 2b), several prefrontal regions (Figs. 2c and 2d), right occipital region (Fig. 2c), and left motor region (Fig. 2b). Consistent with other findings in this domain, left inferior parietal activation was the strongest with respect to signal intensity and spatial extent. All results are based on statistically significant Student t test comparisons as described previously.

MRT: The relation between MRT performance and cortical activation for the MRT—CON contrast is shown in Fig. 3. Subjects with better performance on the MRT showed greater cortical activity in a number of areas.

Areas in color represent those with a statistically significant positive relationship at the level of $P < .005$, based on regression analysis (better MRT performance associated with stronger activity). Supratentorial (cerebral) regions showed greatest activity modulated with ability as did several clusters of significant activity in the cerebellum (both left and right). Of interest, the strongest modulatory effect was observed in left motor (2 separate areas in precentral gyrus, $F = 10.92$ and 7.80, respectively) and cingulate regions (2 separate areas in Brodmann Area 31, $F = 8.16$ and 7.41, respectively; see Figs. 3c, 3d, and 3e). There was also a small cluster within the left parietal lobe (Brodmann Area 39, $F = 6.64$; see Fig. 3b) and several other regions within the left lateral and medial temporal regions in which the rotation effect correlated with performance. Of particular interest was the left middle temporal gyrus (Brodmann Area 39, $F = 7.73$; see Fig. 3a), which is coextensive with area MT+, a region sensitive to motion detection and activated in illusory motion [12–13].

Comments

The goal of the current study was to better characterize visual–spatial abilities that might underlie surgical performance on spatially complex procedures, such as those involved in plastic and reconstructive surgery, by examining variations in cortical activation on relevant tasks. Consistent with previous studies in the general population, this group of surgery residents showed bilateral (left greater than right) parietal activation as well as lateral prefrontal and left middle temporal activation during the mental rotation task [7–9]. More importantly, we were able to identify increased activation in some of these cortical regions that correlated with MRT performance across participants. These regions appear to be specifically engaged in the complex visual–spatial skill that we previously found to be selectively correlated with surgical performance [1]. Specifically, these regions, such as the left inferior parietal, MT+, and precuneus regions [12–13], are known to be sensitive to perceiving or imagining motion. This finding is consistent with the contention that engagement of task-relevant brain regions is predictive of skill-relevant behavior.

Several other studies have examined individual differences in patterns of brain activation in mental rotation. In particular, studies of sex differences suggest that different patterns of activation may be associated with particular task strategies. Weiss et al [14] reported that men show stronger parietal activation, which they argue is consistent with a "Gestalt"-type strategy in solving rotation problems, whereas women show greater right frontal activation, a pattern they suggest is consistent with an analytic–serial task strategy. Because their study controlled for performance differences by selecting only high-performing subjects, it is not possible to draw direct comparisons with the activation patterns revealed in our parametric analysis. Nonetheless, it is interesting to speculate that the high performers here were also using a more "gestalt" strategy and were able to "see" patterns

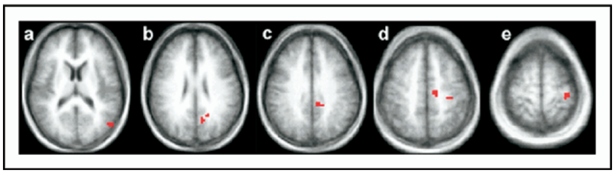

Fig. 3. Cortical regions in which activation associated with mental rotation increased as a function of MRT performance (number of correct responses). These predominantly left-hemisphere regions included the middle temporal region (**a**), the posterior cingulate–precuneus region (**b and c**), and the premotor region (**d and e**). This figure shows cortical regions in which the increased activity was related to performance on the MRT. The left side of the image represents the right hemisphere of the brain.

rotate in the "minds eye" given the specific parietal, middle temporal, and precuneus regions showing enhanced activity. Similar conclusions regarding activity–ability correlations were reached in a study demonstrating differences in activation patterns in parietal, frontal, and cingulate cortices in male adolescents who were mathematically gifted versus those having average math ability [15].

A limiting factor in drawing direct links between brain activation patterns in MRT and surgical performance is that within our own sample of residents, there was poor correlation between scores on the MRT test, which predicted surgical performance (time 1) and the MRT test used in the current fMRI study (time 2). Several possible explanations exist for this poor correlation, including variability in skill acquisition across the residents during the test–retest interval, changes in task strategy between the 2 occasions, and differences in motivational factors or speed–accuracy biases between test times. Irrespective of the exact basis for the changes in performance across time, it does suggest that mental rotation is not an invariant "trait" within this population and therefore underscores the potential for training to achieve "optimal" ability in relation to surgical performance. Although it would have been useful to have achieved a measure of surgical skill (such as Z-plasty performance) at time 2, we left this for a future study, and thus the link to the target ability of interest is only indirect at present.

Implications

To the extent that there is an "optimal" visual imagery strategy that relates to spatially complex surgical performance, such as that tapped by the MRT, it may be possible to devise training programs that specifically target its development and implementation. Indeed, mental visualization and rehearsal has proven highly effective in training athletes, with performance improvements going beyond what would be anticipated with nonspecific enhancements in arousal or self-efficacy [16–18]. In addition, the portions of the brain that were activated in the current study are known to be associated with highly learned processes [19–20]. Thus, mental rehearsal may strengthen neural connections in these brain areas and indirectly influence surgical performance for spatially complex tasks. However, our research on MRT presents only the beginning steps in identifying the particular embedded cognitive operations, a necessary condition before designing targeted training and instruction. The use of brain imaging techniques as an adjunct to behavioral studies affords us the ability to identify specific component processes and their neural bases so that there can be a stronger foundation for conclusions about *how* such processes vary across individuals and with experience rather than simply *that* they do.

Differences in cortical activation patterns associated with MRT, known to be related to surgical performance, may reflect application of different visual–spatial problem-solving strategies. Furthermore, there is growing evidence that brain networks change and adapt during practice of motor skills as one progresses from novice to expert. Therefore, fMRI may hold potential as a novel and objective method of monitoring motor learning in surgery and could provide a measure of the sustainability of these learned skills. Further investigation into this domain could broadly impact motor skills instruction, resident selection, remediation procedures, and continuing surgical education.

Acknowledgments

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