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Short Communication

Mathematically gifted male adolescents activate a unique brain network during mental rotation

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Abstract

Mental rotation involves the creation and manipulation of internal images, with the later being particularly useful cognitive capacities when applied to high-level mathematical thinking and reasoning. Many neuroimaging studies have demonstrated mental rotation to be mediated primarily by the parietal lobes, particularly on the right side. Here, we use fMRI to show for the first time that when performing 3-dimensional mental rotations, mathematically gifted male adolescents engage a qualitatively different brain network than those of average math ability, one that involves bilateral activation of the parietal lobes and frontal cortex, along with heightened activation of the anterior cingulate. Reliance on the processing characteristics of this uniquely bilateral system and the interplay of these anterior/posterior regions may be contributors to their mathematical precocity.

Theme: Neural basis of behavior
Topic: Cognition

Keywords: Mathematical giftedness; fMRI; Visuospatial processing; Mental rotation

There is intrinsic interest in how the brain of a budding Einstein may work and the scientific importance in understanding the nature of the neural system that mediates precocious mathematical ability. To investigate these issues, we used fMRI to measure blood oxygen-level-dependent (BOLD) brain activation of math-gifted and average ability adolescents doing 3-dimensional mental rotation. The later is a complex visuospatial task that highlights the engagement of at least two fundamental cognitive processes: the creation and manipulation of mental images [10]. These later capacities are thought to be particularly useful when applied to the mastery of high-level mathematical thinking and reasoning [16]. By having math-gifted and average ability participants perform this task in conjunction with state-of-the-art neuroimaging techniques, we were able to isolate a pattern of brain activation that was unique to the math-gifted brain, one that is both quantitatively and qualitatively different from those of average math ability, and whose processing characteristics may be significant contributors to their precocious mathematical ability.

Six math-gifted males (3 left-handed, 3 right-handed [modified Edinburgh Handedness Inventory], age 14.3 years) and 6 matching average ability control adolescents were psychometrically identified using the Australian version of the SAT-Math and SAT-Verbal tests (School and College Abilities Test (SCAT) III, Form Y, CareerWise Pty. Ltd., Melbourne, Australia). Math-gifted participants performed at the 99th percentile on the SCAT-Math, while controls performed at the 50th percentile. SCAT-Verbal scores for the two groups were equivalent and somewhat above average (85th percentile). Ravens Progressive Matri-

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ces (nonverbal IQ) scores for the gifted were also at the 99th percentile, while scores for the controls were slightly above average (70th percentile). Written consent was obtained from the parents of each participant and the study was approved by the University of Melbourne Human Subjects Review Committee.

Eighteen mental rotation (Fig. 1a) and 18 baseline trials (Fig. 1b) were presented in 6 alternating blocks of 6 trials each for a total of 36 stimulus presentations. In the rotation condition, a target and four test stimuli were presented one above the other for 10 s (with a 1 s inter-stimulus interval). Angles of disparity between target and test stimuli ranged from approximately 80° to 180° (see Fig. 1 for further details of stimulus construction).

A simple matching task was also conducted as part of the study to provide an additional interpretive backdrop for the patterns of activation obtained. In this simple matching task, all four of the block stimuli except for one were identical to each other, and the single differing test stimulus was the sole match to the target. Thus, stimulus encoding, decision processes, and response execution were all involved in the matching task, but no mental rotation was required. Parallel to the design used to investigate mental rotation, 18 match and 18 baseline trials were presented in 6 alternating blocks of 6 trials each for a total of 36 stimulus presentations.

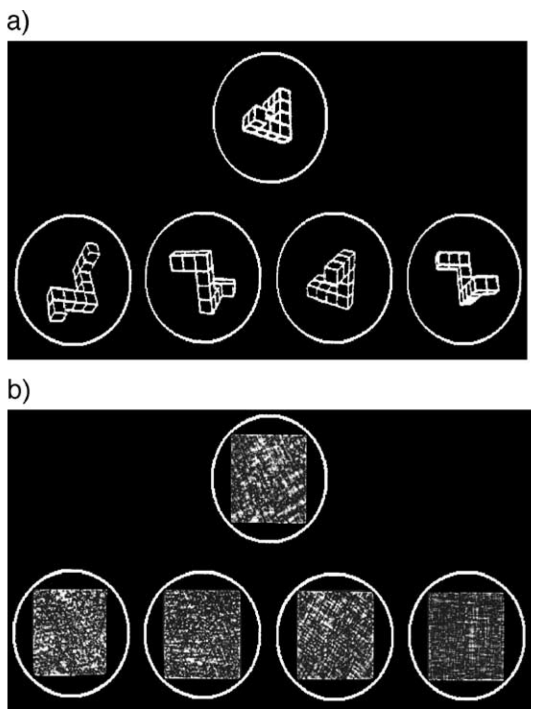

Fig. 1. Examples of (a) mental rotation and (b) baseline trials. Stimuli were rear-projected on to a 1.6 (wide) × 1.2 (high) m^2 screen at a distance of 3.5 m, and viewed by the participant via a reflector mirror located inside the scanner. Participants pressed one of four fiber-optic buttons (corresponding to the index and middle fingers of each hand, and spatially compatible with the position of the test stimuli) to indicate which of four options matched the target when mentally rotated. Baseline trials had the same presentation parameters as the rotation trials but were Fourier scrambles of the original stimuli (i.e., identical in visual frequency, luminance and contrast, but had no identifiable shape per se). In this condition, participants simply judged which of the four test stimuli they believed to be the "best" visual match to the target stimulus, and to indicate their choice by pressing one of the four buttons; there were no correct or incorrect answers.

Math-gifted and control participants did not differ in mental rotation accuracy (Gifted = 42%; Controls = 44%, $t(214) = -0.410$, $P < 0.68$), and both groups were significantly better than chance (i.e., Gifted: $t(107) = 3.49$, $P < 0.0001$; Controls: $t(107) = 4.05$, $P < 0.0001$). These accuracy levels were lower than anticipated, and the fact that the math-gifted did not outperform controls was not expected given that mental rotation ability is sometimes, though not uniformly, reported to correlate with high mathematical ability [16]. In this particular case, however, having adolescents perform such a complex task in the context of a novel and somewhat intimidating brain scanning environment may have artificially brought the performance levels of the two groups closer together. The later is actually a fortuitous outcome as subsequent differences in activation profiles between the groups cannot therefore be attributed to differences in task difficulty or ability level confounds.

Mean processing times (correct trials) for the math-gifted and controls did not differ (Gifted = 6.3 s, Controls = 6.1 s, $t(91) = 0.391$, $P < 0.69$). And for all participants, latency to make the correct response generally took longer as the estimated angular disparity between target and test stimuli got larger. Although not conclusive given the number of dimensions and multiple directions in which these 3-dimensional stimuli might be rotated into congruence, the pattern is at least compatible with the idea that participants were actually engaged in image generation and mental rotation [18].

When mentally rotating 3-dimensional stimuli, average math ability adolescents activate a neural substrate that is much the same as that reported for other young adults [1,2,10]. In this network (see the top portion of Table 1; Fig. 2a), there is significant (relative to baseline) activation of the right superior parietal lobule (BA 7), as well as the left inferior parietal lobule (BA 40). This is consistent with other neuroimaging studies reporting that the creation and manipulation of mental images are mediated primarily by the parietal lobes [5,12,13]. Significant activation of premotor cortex bilaterally (BA 6) but particularly on the right, along with the right inferior frontal gyrus (BA 9), the right precuneus (BA 7), and the right cerebellar declive were also found, and are in keeping with previous research implicating a more dominant contribution from the right (as compared to the left) hemisphere when performing 3-dimensional mental rotations [6]. Note that all of the aforementioned areas (Brodmann) were also found to be active in math-gifted participants, but their level of engagement appears to be much larger, hinting at greater availability of cortical resources and potentially enhanced information processing capacities (Fig. 2b).

Mathematically gifted adolescents had a larger number of brain regions significantly engaged when performing the

Table 1
Significant activations during mental rotation (compared to baseline) for control and math-gifted participants (fixed-effects, within-group analyses), and significant differences in regions of activation between the two groups (random-effects, between-groups analyses)

Region of significant activation	Brodmann area	Talairach coordinates (mm)	Z score
Control (fixed-effects)[a]			
R superior parietal lobule	BA 7	36 −57 51	3.71
L inferior parietal lobule	BA 40	−42 −48 42	4.49
R premotor cortex	BA 6	21 −9 45	4.29
L premotor cortex	BA 6	−21 3 45	3.88
R inferior frontal gyrus	BA 9	54 9 30	4.36
R precuneus	BA 7	18 −72 51	3.50
R cerebellar declive		42 −60 −21	3.93
Gifted (fixed-effects)[b]			
R inferior parietal lobule	BA 40	33 −60 42	>7.52
L superior parietal lobule	BA 7	−36 −63 54	>7.52
R premotor cortex	BA 6	27 −12 54	>7.52
L premotor cortex	BA 6	−27 −12 51	>7.52
R precuneus	BA 7	18 −75 45	>7.52
L precuneus	BA 7	−18 −81 36	>7.52
R medial frontal gyrus	BA 32	9 21 36	5.49
L medial frontal gyrus	BA 6/32	−12 15 48	7.24
L middle occipital gyrus	BA 19	−42 − 63 −3	6.10
L cingulate gyrus	BA 32	−12 21 −9	5.94
R middle frontal gyrus	BA 9	45 9 33	>7.52
R middle frontal gyrus	BA 46	45 39 21	4.90
R cerebellar declive		42 −60 −21	7.39
Gifted > Control (random-effects)[a]			
R anterior cingulate	BA 32	21 27 15	4.21
L superior temporal gyrus	BA 39	−33 −54 27	4.01
L premotor cortex	BA 6	−36 −12 39	3.61

[a] Cluster-level significance $P_{corrected} < 0.05$ (cluster size > 10 at $t > 2.76$).
[b] Cluster-level (as above) and voxel-level significance $P_{corrected} < 0.05$ ($t > 4.29$).

very same mental rotation task (see the middle portion of Table 1; Fig. 2b). And while there is some overlap with the areas that were active in the average ability group, for the mathematically gifted, these regions have a distinctly bilateral characteristic to them. They include activation of the right inferior parietal lobule (BA 40), the left superior parietal lobule (BA 7), bilateral activation of premotor cortex (BA 6), bilateral activation of the precuneus (BA 7), bilateral activation of the medial frontal gyri (BA 6/32), activation of the left middle occipital gyrus (BA 19), the left cingulate gyrus (BA 32), the right middle frontal gyri (BA 9/46), and right cerebellar declive.

Additionally, between-group random-effects analyses confirmed significantly greater activation for the math-gifted compared to controls in three specific brain areas, namely the right anterior cingulate (BA 32), the left superior temporal gyrus (BA 39), and the left premotor cortex (see Fig. 2c). These regions represent components of a larger anterior neural system thought to mediate a variety of cognitive control processes relating to general intelligence including spatial attention [15], working memory [14], the parsing of executive processes into strategic and evaluative functions, error detection, conflict resolution, and the on-line monitoring of performance [3,4].

Notably, when comparing activation patterns between the groups for the simple matching task relative to baseline, we found no significant differences between the math-gifted and average ability participants. And even when using a more lenient voxel threshold [$t(10) > 2.76$, $P_{uncorrected} < 0.01$], the brain areas found to be differentially active for each group during mental rotation showed no significant

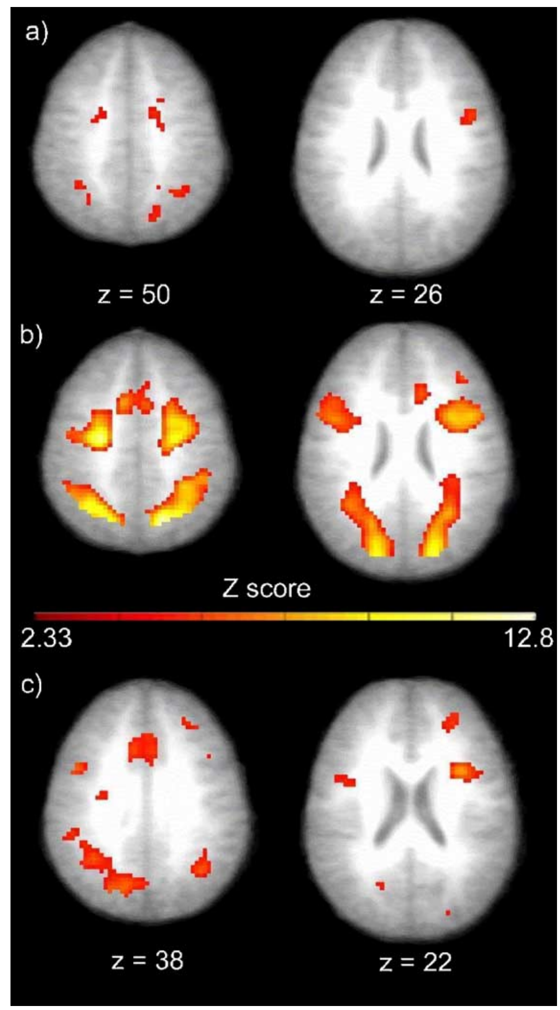

Fig. 2. Activation (significant) maps during mental rotation for (a) average ability and (b) math-gifted participants. Panel (c) illustrates the regions having significantly greater activation in the math-gifted as compared to controls. fMRI data were collected using a 3.0 T GE Signa MRI scanner. High-resolution T1 images were acquired (TR = 120 ms, 256 × 256 × 128 matrix, voxel = 0.9 × 0.9 mm^2, slice thickness = 1.4 mm), and echoplanar images [EPI] (TR = 3000 ms, TE = 40 ms, 128 × 128 matrix, voxel size = 1.875 × 1.875 mm^2, slice thickness = 4.5 mm + 0.5 mm gap, slices = 22) were taken with 132 volumes per scanning session. Images were motion corrected, spatially normalized (using the SPM99 EPI template) into Talairach coordinates, and spatially smoothed with an 8 mm full-width, half-maximum Gaussian function. Statistical analysis was performed in SPM99, modeling each stimulus as a single event with both temporal and dispersion derivatives included. Group analysis used independent t tests (second-level random-effects fMRI analysis) to examine the difference in activation patterns between gifted and control participants.

differences in the match versus baseline comparison. This strongly suggests that the differences found in the activational profile of math-gifted as compared to control participants are due to processes associated with mental rotation rather than differences in any baseline activity level between the two groups.

Thus, when engaged in higher-order visuospatial thinking like the mental rotation of 3-dimensional block stimuli, mathematically gifted male adolescents recruit a quantitatively and qualitatively different brain network than those of average math ability. They exhibit greater overall cortical activation, which is suggestive of heightened processing power, as well potentially enhanced imagery capability, the later being reflected in their extensive engagement of the parietal lobes. And while other research has occasionally reported significantly *lower* (rather than higher) activation levels for those brains more efficiently performing a given task (i.e., lower activation reflecting better or more successful processing), we did not. And in fact, we have yet to find evidence of lower activational levels in math-gifted adolescents compared to controls in any of our previous studies employing a variety of stimulus types (e.g., Raven's Progressive Matrices, calculation and mathematical reasoning problems) and differing processing demands.

As can be seen in Fig. 2b, the math-gifted are extensively bilateral in their activation during mental rotation, while those of average math ability are more unilaterally and predominantly right hemisphere engaged. Interestingly, in the mathematically gifted, their bilateral engagement of the parietal lobes is complemented by selective activation of the anterior cingulate and frontal cortex on both sides of the brain. The enhanced involvement of these regions, taken in conjunction with extensive engagement of the parietal lobes, may be related to the emergence of their mathematical giftedness as recent studies have shown that activation levels of the frontal lobes and the anterior cingulate correlate with fluid intelligence levels [9,11], and that numerical intuition and mathematical reasoning (via mental imagery formation and manipulation) may emerge from the interplay of these two anterior/posterior regions [7]. Of particular note is the fact that activation of these anterior areas, particularly the cingulate, is virtually absent in those of average math ability. This may be interpreted as reflecting a relatively more immature state of brain specialization, one that is potentially less developed in terms of executive processing capabilities, e.g., the ability to maintain access to stimulus related working memory representations and/or the implementation and maintenance of processing goals and strategies within interference rich contexts [8,14].

The extent to which this neural system is specific to giftedness in mathematics or common to individuals who are precocious in other domains (e.g., verbally, artistically, or musically gifted) is not yet known. By way of speculation, it may be that enhanced (and bilateral) activation of the parietal lobes, frontal cortex, and the anterior cingulate are critical parts of a an all-purpose information processing network, one that is relied upon by individuals who are intellectually gifted, irrespective of the nature of their exceptional abilities. The later network may provide finely-tuned general information processing capacities for handling and integrating various types of stimuli and task demands across a variety of domains. In keeping with such theorizing, it might be mentioned that many individuals who are mathematically precocious are also gifted verbally [16]. This type of "balanced" gifted ability profile could be supported by extended working memory capacity and/or enhanced executive attentional resources [14]. Congruent with this possibility are results from a recent fMRI investigation finding general fluid intelligence to be positively correlated with activation levels of prefrontal cortex [11].

Alternatively, several components of the neural system found in the math-gifted adolescent (e.g., selective engagement of right frontal cortex) have also been reported to be uniquely active in the brain of an adult calculation prodigy [17]. And although not directly comparable, these findings dove-tail nicely with the idea of a processing system that may in-part be math (or at least visuospatially) specific, one that highlights the use of imagery based memory representations, which are particularly useful for encoding mathematical concepts and applying them to high-level mathematical reasoning and thinking. In either case, one further intriguing speculation is that the unique pattern of brain activation manifested in the math-gifted adolescent is not only a matter of biology, but may also be shaped by exposure to enhanced learning environments. Should the later prove so, it would have important implications for the nature and timing of mathematics instruction.

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