NeuroReport 7, 773–776 (1996)

Quantitative relations between parietal activation and performance in mental rotation

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THE quantitative relationships between functional activation of the superior parietal lobule (SPL) and performance in the Shepard–Metzler mental rotation task were investigated in 16 human subjects using magnetic resonance (MR) imaging at high field (4 Tesla). Subjects were shown pairs of perspective drawings of three-dimensional objects and asked to judge whether they were the same or mirror images. Increased SPL activation was associated with a higher proportion of errors in performance. The increase in errors, and the concomitant increase in SPL activation, could be due to an increased difficulty in, and therefore increased demands for, information processing at several stages involved in making a decision, including encoding of the visual images shown, mentally rotating them, and judging whether they are the same or mirror images.

Key Words: Mental rotation; Functional MRI; Superior parietal lobule

Introduction

The neural mechanisms underlying mental rotation of visual objects[1,2] are largely unknown. In general, the objective has been to identify the brain areas involved in the task. For that purpose, electrophysiological methods[3–7] and techniques measuring changes in regional blood flow[8–11] have been employed. A consistent finding of these studies has been that parietal areas are involved in mental rotation of visual images. However, crucial morphological and functional aspects remain to be elucidated, including the anatomical localization of changes and the quantitative relationships between brain activity and task performance. We have used functional MR imaging to identify the brain areas involved during performance of mental rotation.[12] In the present study we sought to determine the quantitative relationships between performance in mental rotation and the intensity of the functional activation in SPL, a parietal area consistently activated in this task.[12]

Subjects and Methods

Sixteen right-handed volunteers (eight women and eight men, age (mean ± s.d) 31.9 ± 9.7 and 30.5 ± 5.0 years, respectively) performed a mental rotation task as follows. During the task period, they looked at pairs of perspective drawings of three-dimensional objects in various orientations. The objects shown were similar to those used previously by Shepard and Metzler[1] and were generated on a computer screen (Fig. 1A,B). Five different objects and five isomeric (mirror) forms of them were used. For each object seven perspective views were generated by a rotation in depth, around the vertical axis; the rotation angles used were 0, 20, 100, 180, 200, 240, and 320°. From these 70 object views (5 objects × 7 views × 2 isomeric forms = 70), 300 pairs were formed. One half of these pairs consisted of the same object (in different orientations; referred to as 'same pairs'), whereas the other half consisted of mirror forms ('mirror pairs'). The pairs of the same objects were formed in such a way that a clockwise rotation of the right object, as seen from the top of the vertical axis, would bring it into congruence with the left object through the smallest angle. Pairs of all possible angular departures from 20 to 180°, in steps of 20°, were included. During the experiment, the objects were projected on a screen in a randomized sequence and were viewed by the subject with the help of a small mirror, fixed in the interior of the magnet. Subjects had to decide, by

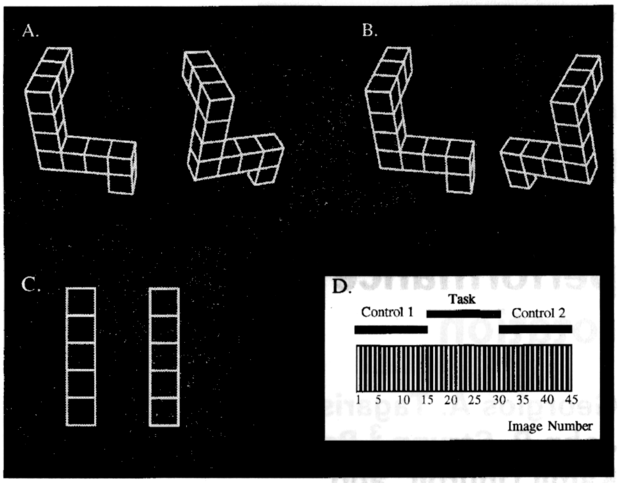

FIG. 1. Examples of pairs of perspective drawings of objects used and experimental design. (**A**) 'same' 3D objects (angular departure = 20°); (**B**) 'mirror' 3D objects; (**C**) identical 2D objects (control); (**D**) temporal arrangement of the control and task periods, and of the MR image acquisition.

pushing one of two buttons on a specially designed keypad, whether the two objects of the pair projected were the same or mirror images. The subjects used the index and third finger for same and mirror, respectively, and were randomized with respect to the hand used for the response. Each response by the subject was followed by the immediate presentation of the next pair of objects. The maximum time allowed for each pair was 8 s. In two control periods, preceding and following the task period, subjects looked at pairs of identical two-dimensional longitudinal rectangles (Fig. 1C) and pushed one of the two buttons, as they wished. We measured the response time and identified whether the response was correct or not. Before the experiment, subjects performed the task 2–4 times outside the magnet (total duration 6–12 min) and 1 or 2 times inside the magnet (total duration 3–6 min) before the scanning session.

Performance: The proportion of errors (E) made in identifying the paired objects as same or mirror was calculated as

$$E = (b + c) / (a + b + c + d) \qquad (1)$$

where a is the number of correct same judgements, b is the number of same stimuli judged as mirror, c is the number of mirror stimuli judged as same, and d is the number of correct mirror judgements.

Functional MR imaging: During the control and task periods successive multislice functional MR images were acquired using a 4 Tesla whole body system with actively shielded head gradients and a homogeneous RF coil (SIS Co., Sunnyvale, CA/Siemens, Erlangen, Germany). A head support system with a deflatable vacuum pillow was used to minimize head movements during the experiment. First, sagittal anatomic images were acquired to define the location of the anterior and posterior commissures and to determine the position of slices for functional imaging. Multislice T_1-weighted anatomical images were obtained using a turbo-FLASH sequence with 5 mm slice thickness and in-plane spatial resolution of $1.6 \times 1.6\ \text{mm}^2$. For functional imaging, a T_2*-weighted turbo-FLASH sequence was employed (TE = 28 ms, TR = 6 ms, flip angle = 11°). Interleaved multislice images were collected covering an 8 cm span (slice thickness = 10 mm, center-to-center interslice distance = 5 mm, 15 slices). The in-plane resolution was $3.1 \times 3.1\ \text{mm}^2$. Imaging planes were parallel to the line defined by the anterior and posterior commissures in a midline sagittal view. The acquisition time for a single slice was 400 ms. However, because of a delay period of 400 ms between slices, the time that was necessary for the collection of all 15 slices was 12 s. This time interval was the effective temporal resolution in this study. Images were collected continuously during the experiment (Fig. 1D). The duration of the experiment was 9 min (3 min for each of the first control, the task, and the second control periods). Fifteen images were collected during the first control, the task, and the second control periods. Possible artifacts due to movement of the head induce spatially interleaved positive and negative alterations in image intensity and are usually generalized and over large areas, including the borders of the brain image. All of our images were screened for such artifacts and rejected if artifacts were present.

Normalized functional activation: For the quantification of functional activation, a normalized activation was calculated as follows. The SPL in each hemisphere was defined from the anatomical MR images as the area posterior to postcentral sulcus, superior to intraparietal sulcus and lateral to the midline. In general, it covered three consecutive non-overlapping slices, and ranged in volume from 49.9 to $65.2\ \text{cm}^3$ (average $54.9\ \text{cm}^3$). It corresponded to coordinates (2–4, F–H, a–c) of the Talairach coordinate system[13]. For each SPL, a normalized proportional activation, ω, was calculated as

$$\omega = t - c$$

where

$$c = \frac{1}{M} \sum_{i=1}^{M} \ln\left(\frac{C_i}{W_i}\right)$$

$$t = \frac{1}{M} \sum_{j=1}^{M} \ln\left(\frac{T_j}{W_j}\right)$$

where C_i is the SPL signal intensity for the *i*th image during the control period preceding the task period, W_i is the signal intensity of the corresponding whole *i*th image, T_j is the SPL signal intensity for the *j*th image during the task period, W_j is the signal intensity of the corresponding whole *j*th image, and $M = 15$ images. Logarithmic transformation was applied to normalize the distribution of the ratios.

Data analysis: Standard statistical methods, including linear regression analysis, were used to determine the relations between functional MRI activation and performance.

Results

The SPL was consistently activated during task performance.[12] The mean ($\pm$s.e.m.) proportion of errors in performance, E, was 0.126 ± 0.021 ($n = 16$ subjects). SPL activation, ω, in both the left and the right hemispheres was correlated with E (Fig. 2; correlation coefficient 0.535 ($p = 0.03$) and 0.546 ($p = 0.03$) for the left and right SPL, respectively; $n = 16$). In general, these relationships were qualitatively similar in men and women.

Discussion

For the quantitative analyses of the data obtained in the present study, we used a measure of MR functional activation based on a normalized change in the intensity of the signal rather than on the area being activated. The latter measure involves the choice of a threshold based on some statistical test of significance (e.g. *t*-test) and its application to all the voxels in an area; however, this threshold may differ from subject to subject. The present approach avoids problems related to the choice of a thresholdas well as its variation among subjects, since the normalized activation employed is a quantitative measure that is not based on any test of significance but instead simply reflects the change in the normalized signal intensity during the task period from that observed in the control period, and is derived in the same way for all subjects. Nevertheless, a similar analysis of our data using a threshold based on a *t*-test and the resulting area of significant activation gave qualitatively similar results.

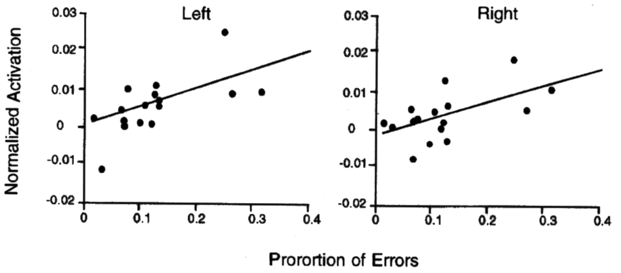

FIG. 2. Normalized proportional activation ω for the left and the right SPL plotted against proportion of errors E in task performance ($N = 16$ subjects). The regression equations were: Left SPL, $\omega = -0.00066 + 0.0475E$ ($p = 0.0329$, F-test); Right SPL: $\omega = -0.00134 + 0.0432E$ ($p = 0.03$, F-test).

Mental rotation is an attention-intensive task which presumably involves imagined motion of visual objects with the ultimate goal of identifying them as the same, or discriminating them as mirror images. It may not be surprising, therefore, that the SPL was activated in the present study, since this cortical area has been implicated in a range of tasks involving spatial attention,[14] spatial localization,[15] visual object motion processing,[16] visual perception of forward motion in depth[17] and visuomotor coordination.[18]

The results of this study document a statistically significant correlation between the intensity of SPL activation and performance. Specifically, SPL activation increased with the proportion of errors in identifying pairs of objects as the same or mirror images. Errors in this task could be due to several, not mutually exclusive, factors, including imprecise encoding of the stimulus images, unsuccessful transformation (i.e. mental rotation) of the images, wrong judgement of the (transformed) images as same or mirror, etc. These factors are probably interrelated. For example, imprecise encoding could lead to unsuccessful transformation, and a wrong judgement could be the result of imprecise encoding, distorted transformation or both. It is also reasonable to suppose that, for example, a degraded internal representation of the stimulus images will probably impose higher demands on the ensuing process of mentally rotating those images: this could involve increased demands on processing by the SPL, resulting in its increased activation, and, at the same time, would also increase the probability of error. The hypotheses that the SPL may be involved in encoding the images, rotating the encoded images, or judging the rotated images are not mutually exclusive and can be tested experimentally by appropriate manipulations of task variables.

Conclusion

These results document a statistically significant relationship between SPL functional MRI activation and errors in mental rotation. This finding indicates stronger involvement of the SPL in processing information under conditions of increased task demands, reflected in higher proportion of errors in performance.

**Received 11 October 1995;
resubmitted 4 January 1996;
accepted 8 January 1996**

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ACKNOWLEDGEMENTS: This study was supported by United States Public Health Service grants NS32919 and RR088079, the Unites States Department of Veterans Affairs and the American Legion Chair in Brain Sciences.