

Object-processing neural efficiency differentiates object from spatial visualizers

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Received 20 August 2008; accepted 1 September 2008

DOI: 10.1097/WNR.0b013e328317f3e2

The visual system processes object properties and spatial properties in distinct subsystems, and we hypothesized that this distinction might extend to individual differences in visual processing. We conducted a functional MRI study investigating the neural underpinnings of individual differences in object versus spatial visual processing. Nine participants of high object-processing ability ('object' visualizers) and eight participants of high spatial-processing ability ('spatial' visualizers) were scanned, while they

performed an object-processing task. Object visualizers showed lower bilateral neural activity in lateral occipital complex and lower right-lateralized neural activity in dorsolateral prefrontal cortex. The data indicate that high object-processing ability is associated with more efficient use of visual-object resources, resulting in less neural activity in the object-processing pathway. *NeuroReport* 19:1727–1731 © 2008 Wolters Kluwer Health | Lippincott Williams & Wilkins.

Keywords: individual differences, neural efficiency, object-processing ability, spatial-processing ability

Introduction

Research has provided evidence that higher-level visual areas of the brain are divided into two distinct visual pathways, that is, the object properties (ventral) and spatial relations (dorsal) pathways [1–3]. For example, neuroimaging studies have consistently revealed mediation of object processing by the lateral occipital complex (LOC), Brodmann's areas 19, 37, 20, and 21 [4,5], and mediation of spatial processing by parietal cortex [6], particularly intraparietal sulcus in Brodmann's areas 7. Although the object-spatial functional distinction has been shown for perception, working memory, and imagery tasks [1–3], it has received little to no attention in individual differences research, and this study is the first to explore the neural underpinnings of individual differences in object versus spatial visual processing.

Most earlier studies on individual differences in visual processing have focused primarily on understanding individual differences in spatial abilities. They have emphasized characterizing processing differences between participants having high versus low spatial ability for solving, for example, mental rotation [7], spatial working memory [8], and mechanical, physics, or engineering problems [9]. These studies have suggested that the ability to generate, maintain, and transform spatial images is related to capacity limitations of spatial working memory as well as available central executive resources (e.g. attention allocation) [8,9]. Furthermore, research on the neural underpinnings of spatial ability has revealed an inverse relationship between spatial task performance and

associated neural activity [10–12], suggesting that better performance is associated with less neural activity in hypothesized task-relevant regions (i.e. neural efficiency). Vitouch *et al.* [10], for example, found that low spatial ability participants showed greater activation in right parietal cortex, while performing a spatial comparison task, than high spatial ability participants. Lamm *et al.* [11] showed that low-spatial participants showed greater activation in parietal cortex when solving spatial rotation problems, and that this activation was more extended into frontocentral regions than that of high spatial ability participants. Reiche *et al.* [12] showed an inverse relationship between functional MRI (fMRI) blood-oxygenation-level-dependent (BOLD) signal change in parietal cortex and spatial ability (measured independently from performance on the fMRI task) when participants used a spatial strategy to encode and remember text descriptions of objects. Thus, together these studies show that high spatial ability is associated with less activation, and thus more efficient neural resource use, in regions identified as mediating spatial processes.

In contrast to individual differences in spatial processing, individual differences in object processing have received little attention. In fact, object-imagery abilities, like the ability to generate high-resolution images of objects [as often measured by the self-report Vividness of Visual Imagery Questionnaire (VVIQ) [13]] or apprehend and identify visual patterns in the presence of distracting stimuli (i.e. the closure flexibility and closure speed factors, [14]), have been considered separate 'visual factors' having little to do with performance on spatial ability measures [14–16].

Furthermore, in the field of education, research has associated the use of pictorial, object-like images with low spatial intelligence and the inability to form abstract spatial representations [17].

Recently, however, research has provided support for distinctions between individual differences in the use of object versus spatial-processing resources [18,19]. Kozhevnikov *et al.* [19] identified two types of individuals based on their imagery abilities: individuals with high object-imagery ability, called 'object visualizers', and individuals with high spatial-imagery ability, called 'spatial visualizers'. Although object visualizers used imagery to construct high-resolution images of the visual properties (e.g. shape and color) of individual objects and scenes, spatial visualizers used imagery to represent and transform spatial relations. In addition, object visualizers were found to perform above average on object-imagery tasks (e.g. generation of high-resolution objects, recognizing degraded shapes) but perform below average on spatial-imagery tasks (e.g. mental rotation, imagined paper folding). Spatial visualizers, in contrast, were found to perform above average on spatial-imagery tasks but perform below average on object-imagery tasks. These data suggested a mutual exclusivity of object versus spatial-processing abilities at the more extreme ends of the object and spatial abilities continua [19]. In addition, research has shown object and spatial abilities to be differentially distributed among particular professions, with visual artists having above average object-imagery skills and scientists (e.g. physicists and engineers) having above average spatial-imagery skills [18,19], thus providing ecological relevance to the object-spatial distinction in individual differences in imagery.

The neural underpinnings of the individual differences in object visual processing, however, have not been examined. This study was the first attempt to investigate differences in neural activity between object and spatial visualizers. If object-processing ability is in fact an identifiable individual difference that is functionally independent and distinct from spatial-processing ability, then object and spatial visualizers should show distinct patterns of neural activity, particularly in the ventral visual pathway, when working on the same object-imagery task. On the basis of earlier research showing that higher ability is associated with more efficient neural processing, we were interested in examining whether high object-processing ability would be associated with more efficient use of visual-object resources and result in less neural activity in the object-processing pathway.

Methods

Participant selection

As a part of a general prescreening, undergraduate psychology students were administered the following paper-and-pencil measures, which have been used to identify object and spatial visualizers in earlier research [18,19]:

Object-Spatial Imagery Questionnaire (OSIQ): The OSIQ is a self-report questionnaire designed to assess individual differences in object versus spatial-imagery preferences and abilities [18].

Vividness of Visual Imagery Questionnaire: The VVIQ is a self-report instrument designed to assess skills in generating vivid images of objects and scenes [13].

Paper Folding Test (PFT): The PFT is designed to measure spatial visualization ability [19]. Each item on the test shows

successive drawings of two or three folds to a sheet of paper and a final drawing showing the folded paper with a hole punched through it. Participants are to select from among five drawings the one correctly depicting how the punched paper would look when unfolded [20].

On the basis of classification criteria used in earlier studies for identifying object and spatial visualizers [18,19], all the participants who scored above 4.10 on the OSIQ Object scale, 69 or above on the VVIQ, below 2.87 on the OSIQ Spatial scale, and below 3.00 on the PFT were classified as object visualizers. Participants who scored above 3.30 on the OSIQ Spatial scale, above 8 on the PFT, below 2.93 on the OSIQ Object scale, and 60 or below on the VVIQ were classified as spatial visualizers. On the basis of above criteria, nine object visualizers (four males) and nine spatial visualizers (five males) from the pool of prescreened participants were contacted and agreed to participate in the fMRI study.

Materials and apparatus

Structural (T1-weighted magnetization-prepared rapid gradient-echo) and functional (echo planar imaging; TR=2000 ms; TE=30 ms; FOV=220 mm; flip angle=80°; matrix=64 × 64; and slice thickness=4 mm) MRI data were collected through a 3-Tesla Siemens Allegra head-only scanner (Allegra, Siemens Medical System, Malvern, Pennsylvania, USA) with a standard radio frequency head coil. During the fMRI session, all stimuli were back-projected on a screen through a projector connected to a PC. Participants viewed the projected stimuli through a mirror mounted to the head coil and heard the auditory stimuli through an MRI compatible headset.

Object-processing task: participants completed an object-processing task during the functional scan. Sixteen black line drawings of common objects on white backgrounds served as stimuli. Participants were to encode the stimuli, and when prompted by an auditory probe, indicate whether a particular property (i.e. horizontal symmetry, vertical symmetry, horizontal parallelism, vertical parallelism, x-junction, y-junction, t-junction, or arrow-junction) was present. Each drawing was presented twice during the experiment, paired once with a probe that was present and once with a probe that was not.

Procedure

The experiment was approved by the Institutional Review Boards at Rutgers University and the University of Medicine and Dentistry of New Jersey, USA and the experiment was conducted according to the principles expressed in the Declaration of Helsinki. Written informed consent was obtained from each participant before testing. After the participant read through and signed the consent and MRI contra-indicator forms, the experimenter reviewed the task with the participant using printouts of stimulus examples consisting of line drawings of common objects with the relevant properties highlighted. The participant also reviewed slides illustrating the properties, while in the bore of the scanner before the functional scan.

On each trial, a line drawing of an object was shown for 4 s and then disappeared. During the next 4 s, participants were explicitly asked to imagine the object on the blank screen. Then, one of the properties was heard through the headset, and participants had 8 s to indicate whether the

property was present or not. The participant indicated the presence of the property by pressing a designated key on a response box. Finally, a 10-s rest period followed the response period. The screen remained white during the imagery and rest periods.

Imaging analysis

Analyses of the functional data were performed using Brain Voyager QX software (version 1.7, Brain Innovation, Maastricht, The Netherlands). The data were preprocessed using interscan slice time correction, three-dimensional motion correction, voxel-wise linear detrending, high-pass frequency filtering (3 cycles/time course), and Gaussian spatial filtering (full-width-at-half-maximum=6 mm) algorithms. Anatomical volumes were transformed into a common stereotaxic space, and the functional data were coregistered to these anatomical volumes.

A covariate covering the entire image-processing period (i.e. covering the first 8 s of each trial and the first 2 s of the response period, when the auditory prompt played; a total of 10 s) was used to identify active regions. Separate covariates for each period also were examined in a subsequent analysis, and this additional analysis yielded similar results to those reported below. On account of concerns about sequential overlapping BOLD responses not being able to be uniquely identified given the design [21], the analysis using the 10-s image-processing covariate are reported.

The response period was included in the task to assess task performance while in the scanner (i.e. whether the participants were indeed attending to the stimuli). An additional covariate for the response period (i.e. the first 4 s from the onset of the auditory probe, given that participants on average took less than 4 s to respond) was included in the analysis. This covariate was included in the analysis to account for any residual BOLD signal-change variability because of the response requirement (e.g. motor activity) and not image processing, *per se*.

A two-stage analysis of the functional data was carried out: first at the participant level and then at the group level. For the above described covariates, a boxcar reference function was convolved with a hemodynamic response function (HRF); with two- γ HRF settings of onset=0, response undershoot ratio=6, time to response peak=5 s, time to undershoot peak=15 s; response dispersion=1, and undershoot dispersion=1. The remaining 14-s trial periods served as rest periods. Whole-brain, voxel-wise regression was then performed on the individual participants' data with the BOLD signal data (normalized time courses) regressed on the HRF-convolved task-reference function. Random-effects analyses were then performed on the obtained parameter estimates (β) to examine the differences between the groups. For the group analysis, a false-discovery rate =0.05 and a 50-voxel cluster threshold was applied.

Results

The data for one spatial visualizer were excluded from the final analysis because of her performance on the object-processing task being low relative to her respective group's performance. The remaining groups of nine object visualizers (four males) and eight spatial visualizers (four males) performed equivalently on the object-processing task at the

behavioral level: $t(15)$ less than 1 for reaction time (3122 vs. 3041 ms for spatial vs. object visualizers) and $t(15) = 1.91$, $P=0.07$ for accuracy (75 vs. 68% for spatial vs. object visualizers). Given overall better behavioral performance of object visualizers on object tasks than that of spatial visualizers [18,19], associated differences in neural activity on such tasks might merely reflect differences in neural activity between low and high-performing participants in general, rather than their differential use of object imagery-related cognitive resources. A difficult object-processing task might exceed the available object resources of spatial visualizers, and as a result, they either might lose motivation to complete the task or attempt to use compensatory nonvisual object (e.g. verbal) strategies. Thus, to avoid this confound, we removed the low-performing spatial visualizer mentioned above, leaving the groups with relatively equivalent behavioral performance.

For the remaining 17 participants, significant bilateral cortical activations were found in LOC, superior parietal, and prefrontal regions. Bilateral deactivations also were found in posterior cingulate/medial parietal and ventral anterior cingulate/medial prefrontal regions [22], the intrinsic/default network.

To investigate group differences, functional regions of interests (ROIs) were drawn for brain regions that showed significant activity during the image-processing period and that earlier research had shown to mediate visual-object, visual-spatial, and working memory processes [1]. Specifically, ROIs were drawn around LOC, superior parietal, dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), and occipital-parietal junction brain regions (the anatomical location of these regions was based on the Talairach coordinates, and the centroid of the Talairach coordinates and voxel counts for the ROIs are given in Table 1; the ROIs and mean β s for each group are shown in Fig. 1). The ROIs were drawn manually to around the contours of the statistically significant voxel-clusters confined within DLPFC, VLPFC, parietal cortex, and LOC. For each ROI, random effects contrasts between the groups' β s were computed to test whether the neural activity in these regions significantly differed between the groups.

Significant differences between the groups were found bilaterally in LOC. Spatial visualizers showed greater activity than object visualizers [left LOC $t(15)=2.21$, $P=0.04$; right LOC $t(15)=2.21$, $P=0.04$]. These data are consistent with the neural efficiency hypothesis in that object visualizers showed lower activity in these object-processing areas than spatial visualizers.

Significant differences between the groups were also found in right DLPFC and VLPFC. Spatial visualizers showed significantly greater right DLPFC activity than object visualizers, $t(15)=3.57$; $P=0.003$. For right VLPFC, spatial visualizers spatial also showed greater activity than object visualizers, $t(15)=2.36$; $P=0.03$. The groups, however, did not significantly differ in left DLPFC activity [$t(15) < 1$] or left VLPFC activity [$t(15)=1.55$, $P=0.14$]. In addition, the groups did not significantly differ in parietal activity [left $t(15)=1.21$, $P=0.24$; right $t(15) < 1$] or left occipito-parietal junction activity [$t(15)=1.06$, $P=0.31$].

Discussion

The key finding in this study was that object processing was associated with differences in neural activity patterns

Table 1 Regions of interests: descriptive statistics

Region	Brodmann's areas	Hemisphere	Number of voxels	Talairach coordinates		
				x	y	z
DLPFC	9/10/46	Right	1956/1042/367	43/26/37	20/51/44	36/3/24
DLPFC	9/46	Left	3525	-39	30	30
VLPFC	44/47/45	Right	12 325	40	17	17
VLPFC	44/47/45	Left	14 283	-39	18	14
Parietal cortex	7	Right	6176	37	-49	40
Parietal cortex	7	Left	10754	-40	-41	40
Occipito-parietal junction		Left	1249	-27	-61	34
LOC	20/21/37	Right	3034	57	-38	1
LOC	21/37	Left	6909	-51	-41	-4

DLPFC, dorsolateral prefrontal cortex; LOC, lateral occipital complex; VLPFC, ventrolateral prefrontal cortex.

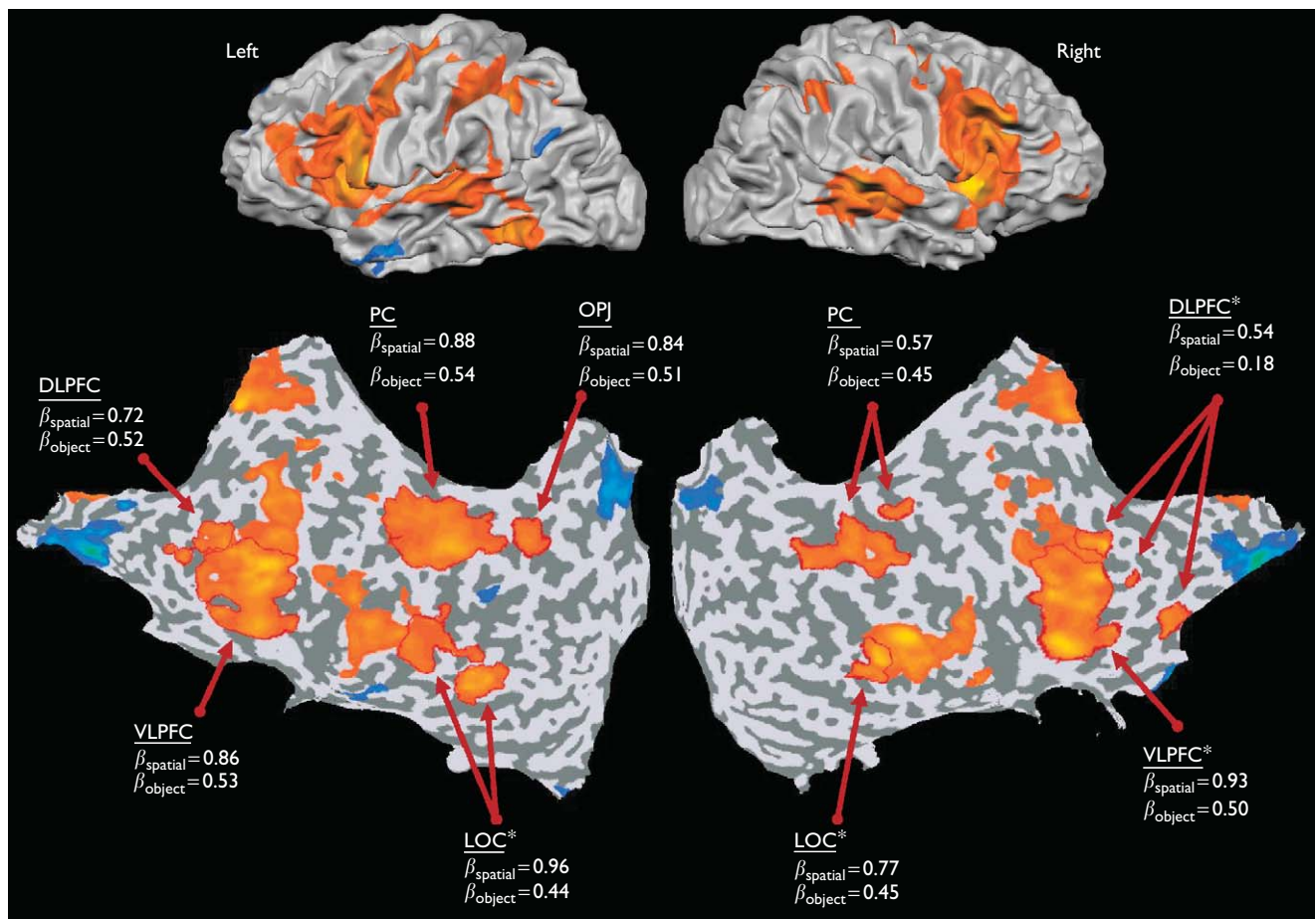


Fig. 1 Statistical parametric map overlaid on flattened cortical mesh showing significant activation (red to yellow scale) and significant deactivation (blue). For spatial reference, the data also are shown on a mesh of the gray-white boundary (above). Functional regions of interest are outlined in red. Asterisks (*) indicate regions where the β s significantly differed between groups ($P < 0.05$). DLPFC, dorsolateral prefrontal cortex; LOC, lateral occipital complex; OPJ, occipital-parietal junction; PC, parietal cortex; VLPFC, ventrolateral prefrontal cortex. As indicated, data are shown in the neurological convention (right=right).

between the two types of visualizers. When instructed to study and visualize line drawings of objects to later identify whether different properties of the drawings were present or not, both spatial and object visualizers showed bilateral task-related activity in LOC, but object visualizers showed lower LOC activation than spatial visualizers. Given that LOC mediates object processing [23], the data suggest that the object visualizers recruited fewer object processing-related neural resources yet still performed as well as the

spatial visualizers. This neural efficiency difference is the first to be reported for the object imagery dimension.

In addition, although both object and spatial visualizers showed bilateral task-related activity in parts of DLPFC, object visualizers showed less neural activity in right DLPFC than did the spatial visualizers. DLPFC has been hypothesized to mediate executive attentional processes brought online when task demands exceed basic processing capacity [24]. Thus, the greater DLPFC activation for the

spatial visualizers might reflect compensatory activity for lower object-processing capacity and the use of attention to modulate LOC-mediated object processes.

Differences in VLPFC activity also were found. VLPFC has been hypothesized to mediate verbal working memory storage, and bilateral activity has been associated with supracapacity storage requirements [24]. Thus, the greater right VLPFC activity found for the spatial visualizers might reflect the use of verbal coding and storage strategies to mediate the retention of the object properties to compensate for less efficient object-related image-processing systems.

Finally, both groups of visualizers showed task-related parietal activation, but the two groups did not significantly differ in the degree of activation. Although equivalent parietal activation between the groups does show that the differential LOC and PFC activation was not merely because of the object visualizers having lower task-related neural activity in general, one might have expected the spatial visualizers to have shown lower parietal activation than the object visualizers based on hypotheses that parietal cortex mediates visual-spatial processes [1–3] and neural efficiency mediating spatial ability. The spatial processing requirements of the object-processing task used, however, were not high and, particularly, did not require complex spatial transformation processes (e.g. mental rotation) that have been shown to mediate parietal activation [6]. Spatial task demand might mediate the detection of efficiency profiles, as shown previously with verbal working memory tasks [24]. Thus, on more demanding spatial visualization tasks, spatial visualizers should show more efficient use of parietal cortex than object visualizers.

Overall, the results indicate that object-processing draws from a relatively independent pool of object-processing resources that spatial visualizers do not seem to possess to the same degree as object visualizers. Furthermore, high object-processing ability is associated with more efficient use of visual-object resources resulting in less neural activity in the object-processing pathway. High object or high spatial individuals might rely on their processing strengths and fail to engage task-relevant cortical resources if the imagery task does not suit their strengths.

Conclusion

Given earlier evidence [10–12] that higher spatial ability is associated with less neural activity in spatial areas and our findings that higher object ability is associated with less neural activity in object-processing areas, this study provides evidence that the object-spatial distinction extends to individual differences in visual processing. Thus, important considerations for future neuroimaging studies of 'imagery' are that imagery is not a unified construct and that the degree and localization of brain activity will vary considerably depending on participants' imagery abilities and the type of imagery required for the task.

Acknowledgements

This research was conducted at Rutgers University (Newark) and the University of Medicine and Dentistry of New Jersey, and it was supported by the Office of Naval Research under

grants ONR_N00012040515 and ONR_N000140611072 to Maria Kozhevnikov.

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