Parietal activation during visual search in the absence of multiple distractors

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Search for a target object embedded in a visual scene involves the posterior parietal cortex. This region is thought to play a role in visual attention by counteracting the effects of distractors on targets or by inhibiting distractors. Using fMRI, we investigated whether the parietal cortex is also engaged in visual search without distractors. Cortical activation was compared between two 'single object' search tasks differing only in difficulty. Activation differences between both tasks were found in the anterior and inferior part of the intraparietal sulcus, but in neither its posterior part nor the frontal eye fields. Thus a subset of parietal regions participates in the control of visual search even in the absence of distractors. *NeuroReport* 14:2257–2261 © 2003 Lippincott Williams & Wilkins.

Key words: fMRI; Frontal eye fields; Human; Parietal cortex; Visual attention

INTRODUCTION

Searching complex visual scenes for a specific object requires the deployment of selective visual attention. The increase of search time with the number of objects in the search array (i.e. the set size) is widely accepted as a behavioral measure of search difficulty, i.e. the attentional demands of a search task [1,2]. Finding a single conspicuous visual feature (such as color or contour orientation) is generally easier than finding a specific conjunction of two features [1–3]. A classic model postulates that focal attention is necessary for feature integration, but not for feature detection [3]. Accordingly, a target with a unique feature can be found without attention, while searching for a feature conjunction requires the serial sampling of the search array. By contrast, parallel models postulate a selection mechanism, which operates in parallel across the visual scene and which is driven by a memory representation of the target. In particular, the target representation is thought to bias competition between multiple object representations towards the target [4]. In parallel-serial hybrid models, the serial selection of locations is guided by parallel bottom-up and top-down selection processes: Bottom-up processes activate locations containing conspicuous features and top-down processes activate all locations containing features of the searched-for target [2,5]. Thus, top-down activation is a form of spatially global feature-based selection.

Evidence from single-unit recordings in monkeys [6], as well as functional imaging [7–12], transcranial magnetic stimulation [13], and lesion studies [14] in humans suggests that sub-regions of the posterior parietal cortex (PPC) are engaged in the visual selection mechanisms of search. Very similar sub-regions have been implicated in the control of spatial attention [15–18]. It has been suggested that this anatomical overlap supports spatially serial search models [7]. However, PPC engagement is a very general feature of difficult visual tasks [16,17], implying that parietal activity during search is not an unambiguous index of a spatially serial process [1]. For example, there is evidence for an engagement of several parietal sub-regions in simpler tasks than visual search requiring non-spatial, feature-based attention [16,19–21]. Therefore, it has even been suggested that the absence of activation in an attentionally demanding visual task is more informative about parietal function than its presence [17]. Two mechanisms have been proposed to account for this general role: (1) The PPC is a source of top-down signals counteracting suppressive effects of distractors on the target, thereby biasing object competition towards the target [22]. (2) The PPC actively inhibits distractors [16]. The common characteristic of both hypotheses is the critical significance of the presence of multiple distractors for a PPC involvement in visual tasks.

The aim of the present fMRI study was to test whether attentional control of conjunction search engages the PPC even in the absence of multiple distractors. In order to isolate attention-related parietal activation, the fMRI signal was compared between a difficult conjunction task and an easy feature task matched in sensory stimulation and in motor requirements. In both tasks subjects had to classify

single objects appearing at unpredictable peripheral locations as targets or non-targets. Tasks were presented in a blocked fashion and the analysis of the fMRI-signal was based on functionally defined regions of interest (ROIs) for maximizing the probability of detecting subtle attention-related fMRI responses. Those components of the frontoparietal attention network [15,18,22] which are most reliably activated during visual search for the same conjunctive target in multi-object arrays [9] and during spatial attention shifts [15–18] were selected as ROIs: the frontal eye field (FEF), as well as the anterior (AIPS), posterior (PIPS), and inferior (IPTO) part of the intraparietal sulcus.

MATERIALS AND METHODS

Subjects: Four male students (JS, SS, TD, TS) from the Humboldt-University of Berlin served as subjects in the study which was conducted in accordance with the Declaration of Helsinki. All subjects were without a history of neurological or psychiatric disorders and reported normal color vision as well as sufficient visual acuity. Their age ranged from 23 to 30 years. Subjects gave informed consent and were paid for their participation.

Stimuli and tasks: Visual search arrays were composed of a texture of black diagonal bars on a light gray background which contained square windows filled with colored bars (Fig. 1a). Each window subtended 7° of visual angle and was centered on a virtual circle 7° off the fixation point. The orientation of bars within a window was either vertical or horizontal. Bar color was either yellow or blue. We consider each cluster of bars in each peripheral window an object of visual search and neglect the presence of the background texture. This rationale can be justified by the fact that the visual system segments visual scenes according to similarity of local features [23] and presumably selects perceptual groups as a whole rather than single elements in visual search [2,4,5].

In the ROI-defining multi-object experiment subjects searched covertly (i.e. without moving their eyes) for a cluster of vertical and yellow bars in the experimental condition (conjunction) and for a cluster of yellow bars (regardless of their orientation) in the control condition (feature). All search arrays contained four objects. The comparison of both conditions eliminated effects of visual encoding and of motor response execution, yielding a relatively pure measure of attention-related fMRI responses. In the single object experiment, subjects searched for the same conjunction target in the experimental condition and for the same feature target in the control condition. Again, the comparison of both conditions yielded a measure of attention-related fMRI responses. Yet, the search arrays contained only one object appearing randomly at one of four possible locations.

Procedure and control experiments: Stimuli were controlled by a personal computer and projected onto a back-projection screen by means of an LCD projector (NEC 8000 G, Stuttgart, Germany). Lying in the magnet, subjects fixated the screen via a mirror. Subjects' heads were stabilized with a bite bar. Subjects used a fiber-optic two-button response-box for report. In all conditions, they were instructed to

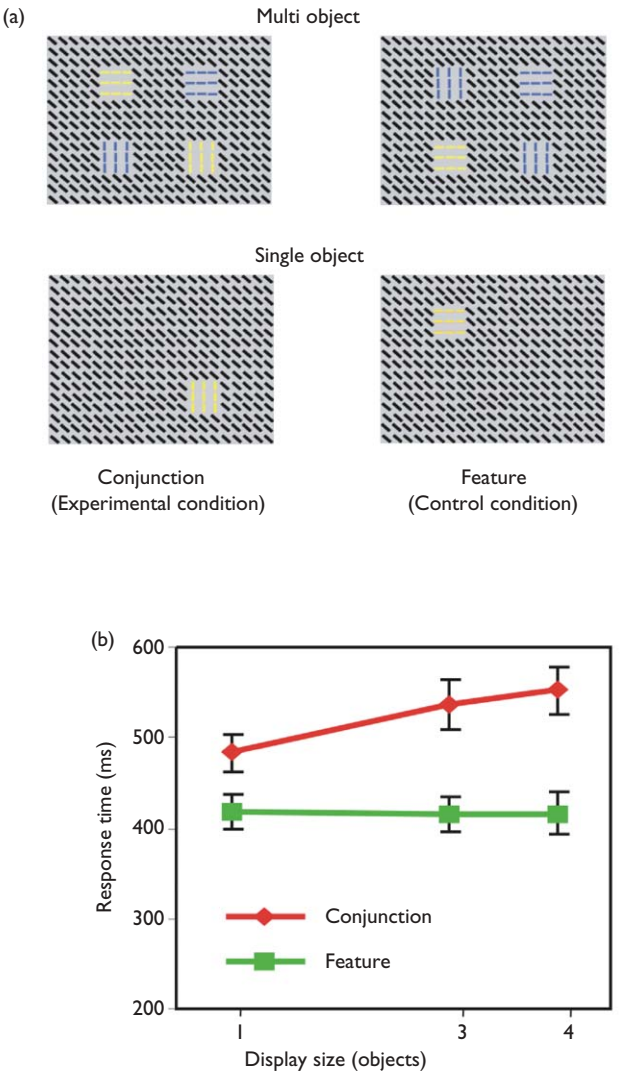

Fig. 1. (**a**) Search arrays from exemplary target-present trials during the conjunction and feature conditions in the multi-object and in the single object experiment. Subjects had to maintain central fixation and to indicate the absence or presence of the target. Search arrays were masked after 80 ms presentation time. (**b**) Response time × set size functions for conjunction and feature. Error bars represent s.d.

indicate the target's presence with the index finger and the target's absence with the middle finger of their dominant hand. Targets were presented randomly in 50% of the trials. Speed and accuracy of response were stressed. In addition, subjects were instructed to maintain stable fixation during the whole experiment. Response times and correctness of response were recorded. Conditions were performed in alternating blocks of 24 s duration consisting of eight contiguous trials. One run consisted of eight blocks of each condition. Each subject completed four runs. A visual cue instructed subjects at the beginning of each block to switch from one task to the other.

In order to minimize the occurrence of saccadic eye movements the search arrays were masked after a presentation time of 80 ms. In addition, subjects' eye movements

during conjunction and feature were recorded with an infrared oculography system (AMTech, Weinheim, Germany) prior to the fMRI experiments. The difficulty of conjunction and feature was determined in a psychophysical experiment of a previous study [11].

Data acquisition: MRI data were acquired using a 1.5 T MAGNETOM Vision magnetic resonance imaging system (Siemens Medical Systems, Erlangen, Germany). We used an echo planar sequence (TR/TE = 3000/60 ms; FA = 90°; in-plane resolution = 4 mm^2) for the collection of functional data. Four runs of each subject were recorded in one session for each experiment. During each run, 128 volumes of 24 axial slices (5 mm thickness, spanning the cerebral cortex) were collected, resulting in a total of 512 volumes per subject and experiment. Structural 3D data sets were recorded in the same session using a T1-weighted sagittal MP-RAGE sequence (TR/TE = 10/4 ms; FA = 12°; TI = 100 ms; voxel size = 1 mm^3). One session lasted around 1.5 h. High-quality 3D structural data sets of each subject were recorded using a T1-weighted sagittal FLASH sequence (TR/TE = 38/5 ms, FA = 30°, voxel size = 1 mm^3) for reconstruction of their cortical surface.

Data analysis: FMRI data were analyzed using Brainvoyager software (Brain Innovation, Maastricht, The Netherlands, www.BrainVoyager.com). Reconstructions of individual cortical surfaces were generated on the basis of the high-quality 3D structural data sets and the surface reconstructions were inflated according to a method described elsewhere [9,11]. This procedure allowed for a surface-based ROI-definition. Functional volumes (i.e. packages of 24 slices recorded during one scan within a functional run) were co-registered with the three-dimensional structural data sets from the same session. Statistical activation maps for the ROI definition were computed by cross-correlating each voxel's time-courses from the multi-object experiment with a reference vector. This reference vector was generated by convolving a square-wave function representing the experimental protocol with a gamma-function ($\delta = 2.5$; $\tau = 1.25$) modeling the hemodynamic impulse response. The activation maps were thresholded at $p < 10^{-4}$ (uncorrected). The regions activated during conjuction were marked as ROIs on the eight reconstructed cortical surfaces. For each ROI, unsmoothed fMRI time-courses from the single object experiment were averaged across voxels. Mean amplitudes during conjunction were then computed by collapsing across repetitions of blocks (with 6 s delay for the hemodynamic response) and measurements within blocks.

RESULTS

Behavior: Saccades $> 1.5°$ of visual angle occurred in $< 3\%$ of the trials of both feature and conjunction. No significant differences between the numbers of saccades in both conditions were observed. Response times from the psychophysical control experiment ($n = 14$) are plotted as a function of set size for conjunction and feature in Fig. 1b. Regression analysis yielded a response time × set size function with a slope of 23.8 ms/object for conjunction and a flat function with a slope of −0.7 ms/object for feature. The difference of slopes between tasks was significant ($t(13) = 7.98$; $p < 0.01$). The main effects of the factors task (conjunction, feature) and set size (one, three, four) as well as their interaction were significant according to a two-way repeated measures ANOVA (task: $F(1,13) = 96.88$, $p < 0.01$; set size: $F(2,26) = 25.76$, $p < 0.01$; task × set size: $F(2,26) = 39.65$, $p < 0.01$]. *A priori* single comparisons revealed that within conjunction, response times were significantly longer for three than one ($t(13) = 5.91$, $p < 0.01$) and for four than three ($t(13) = 2.62$, $p < 0.05$). In sum, response times increased with set size in conjunction and were independent of set size in feature, implying higher difficulty of conjunction. At set size one response times were also significantly longer during conjunction than during feature ($t(13) = 7.1$, $p < 0.01$).

During fMRI, accuracy in task performance was high: subjects made errors in 3.1% of the feature trials and 4.6% of the conjunction trials. The difference between error rates did not attain significance ($t(3) = 1.56$, $p = 0.11$). Mean response times were 459.0 ms in feature and 500.4 ms in conjunction. The difference in response times was significant ($t(3) = 3.33$, $p < 0.05$).

Functional imaging: The ROIs of a representative subject are shown in Fig. 2a. The fMRI responses of these ROIs during conjunction, relative to feature, are shown in Fig. 2b. The amplitudes of differential responses were accepted as significant if the confidence interval did not include zero. IPTO was significantly modulated in six, the FEF and AIPS in three, and PIPS in only two of the eight hemispheres. In the group average, significant differential responses were found in AIPS and IPTO bilaterally and in the FEF and PIPS only in the right hemisphere. According to the 99% confidence criterion, significant responses were restricted to AIPS and IPTO of both hemispheres in the group average. Group average responses were compared between corresponding ROIs of both hemispheres. Responses were larger in the left than in the right hemisphere in AIPS (Wilcoxon's $T = 2$, $p < 0.05$) and in IPTO. This difference was only marginally significant in IPTO (Wilcoxon's $T = 5$, $p = 0.078$). The amplitudes of differential responses did not differ between both hemispheres in the FEF and in PIPS.

DISCUSSION

Differences between fMRI responses during two single object visual search tasks matched in sensory stimulation and motor requirements, but differing in difficulty, were found within (predominantly left) AIPS and IPTO. Activation of PIPS and the FEF was less reliable and failed to be significant in the group average. Eye movements are unlikely to account for the response differences in the present study: eye movements were rare and equally distributed across conditions outside the scanner. Moreover, no activation occurred in early visual areas, which would have resulted from retinal image displacements if saccade rates differed between conditions. The activations are also unlikely to reflect an increase of unspecific arousal effects during the more difficult experimental condition, since subregions of the IPS have been shown to be activated by tasks that demand visual attention, but not by task difficulty *per se* [16]. Thus, the present activations should reflect attention

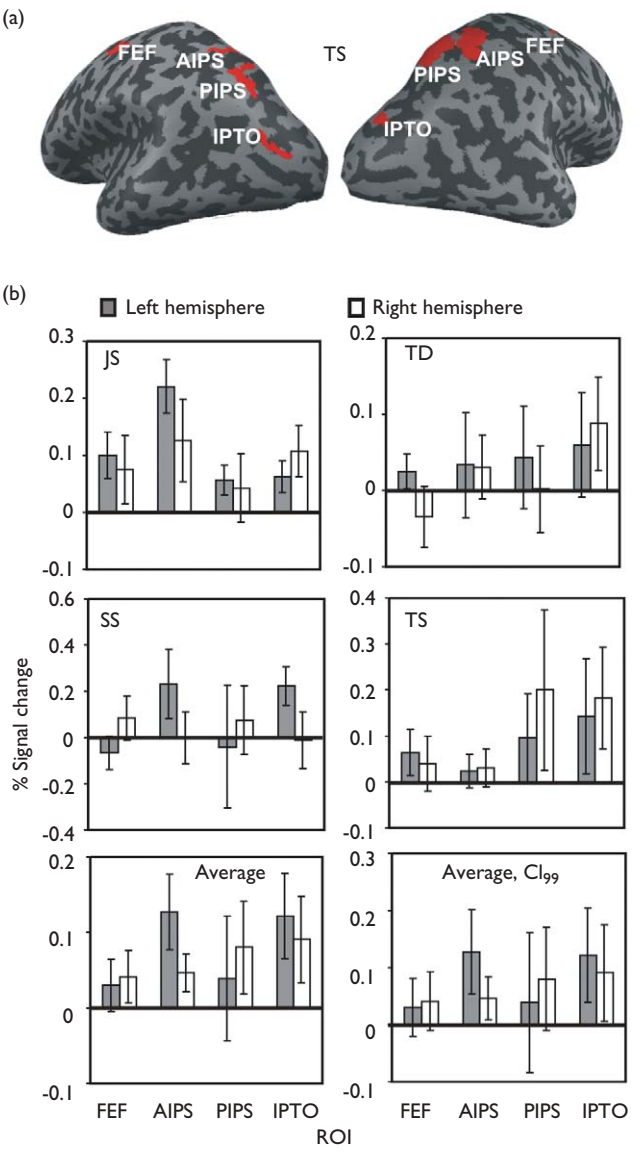

Fig. 2. (**a**) ROIs are marked in red on the inflated left and right hemisphere of subject TS. (**b**) ROI responses during conjunction in the single object experiment. The signal is normalized to the mean of feature. Results from subjects JS, SS, TD, and TS are given in the top and middle panel. Error bars represent 95% confidence intervals. Group averages are displayed in the bottom panel, with 99% confidence intervals on the right.

processes. It might be argued that the bar elements of the background texture constituted visual objects. However, visual scenes are segmented into figures and background as early as in primary visual cortex [23]. Moreover, visual selection during search is presumably carried out on a representation of perceptual groups or higher-level object representations [1,2,4,5] rather than on a representation of local elements. Accordingly, the present findings indicate that parts of the PPC are engaged in attentional control even if a single peripheral object has to be identified. Neither the presence of inter-object competition [22] nor the necessity for distractor inhibition [16] seems to be a prerequisite for their engagement.

Co-activation of multiple sub-regions appears to be a characteristic feature of parietal lobe function, complicating attempts to understand its functional organization [17]. By contrast, the present data point to a functional dissociation: AIPS and IPTO were consistently engaged while PIPS was not. In principle, separate parietal areas could be specialized in different selection mechanisms, such as spatial and feature-based attention, and their general co-activation could result from a blending of these mechanisms in the tasks commonly applied to probe parietal function. The contribution of neurons in macaque lateral intraparietal area to both spatial [6] and feature-based attention [20] argues against this hypothesis. Moreover, the failure to detect a reliable PIPS activation during single object search does not rule out an involvement of at least a sub-group of PIPS units. The co-existence of neuronal populations mediating different types of attentional control seems to be the more likely alternative. The sub-regions could merely differ in the proportion of these populations which would result in different degrees of activation in population measures such as fMRI. This scenario is more consistent with the general parcellation pattern in the macaque parietal cortex, where multiple neuronal populations with different functional properties related to attention and spatial representation co-exist within each of multiple areas [24]. Clearly, this issue cannot be resolved with the spatial resolution of current fMRI techniques.

What kind of attention mechanism does the PPC engagement in single object search reflect? At least, three types of mechanism are conceivable: (1) endogenous control of spatial attention shifts towards the peripheral object [2,3,7], (2) prolonged maintenance of the attentional focus at the peripheral location during the identification of the feature conjunction [1], and (3) the control of feature-based attention [1,2,4,5]. Interestingly, Shulman and co-workers observed a predominantly left-hemispheric activation in AIPS during the delay of a non-spatial feature matching task [21]. This finding contrasts with the reliable predominance of the right PPC in studies of spatial attention [15,18], but corresponds well with the present results.

CONCLUSIONS

Two sub-regions of the parietal cortex, AIPS and IPTO, are engaged in the attentional control of visual conjunction search irrespective of the presence of multiple distractors. By contrast, the engagement of another sub-region, PIPS, seems to presuppose the presence of distractors. Similar to non-spatial attention tasks, parietal activity during single object search predominates in the left hemisphere.

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