# Neural Systems for Visual Orienting and Their Relationships to Spatial Working Memory

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## Abstract

■ We investigated neural correlates of human visual orient-ing using event-related functional magnetic resonance imaging (fMRI). When subjects voluntarily directed attention to a peripheral location, we recorded robust and sustained signals uniquely from the intraparietal sulcus (IPs) and superior frontal cortex (near the frontal eye field, FEF). In the ventral IPs and FEF only, the blood oxygen level dependent signal was modulated by the direction of attention. The IPs and FEF also maintained the most sustained level of activation during a 7-sec delay, when subjects maintained attention at the peripheral cued location (working memory). Therefore, the IPs and FEF form a dorsal network that controls the endogenous allocation and maintenance of visuospatial attention. A separate right hemisphere network was activated by the detection of targets at unattended locations. Activation was largely independent of the target's location (visual field). This network included among other regions the right temporo-parietal junction and the inferior frontal gyrus. We propose that this cortical network is important for reorienting to sensory events. ■

## INTRODUCTION

In a recent study, we dissociated the function of differ-ent regions in the human parietal cortex during visual orienting (Corbetta, Kincade, Ollinger, McAvoy, & Shul-man, 2000). Regions along the intraparietal sulcus (IPs) were active when subjects selected a location indicated by a central arrow cue. In contrast, the right inferior parietal lobule and right superior temporal gyrus (STG) (temporo-parietal junction, TPJ) were active when sub-jects detected a target, particularly when that target appeared at an unexpected location. Hence, we pro-posed that the IPs is involved in the endogenous allocation of attention to a location, whereas the right TPJ is important for reorienting toward unattended visual stimuli. Interestingly, the right TPJ is the region most frequently involved in unilateral spatial neglect (Vallar & Perani, 1987), and patients with neglect are specifically impaired in reorienting to and detecting unattended targets (Friedrich, Egly, Rafal, & Beck, 1998; Posner, Walker, Friedrich, & Rafal, 1984).

In the present study, we present new analyses on the same data set to determine whether the distinction between neural systems for voluntary orienting and visual reorienting extends outside the parietal cortex, and whether other regions involved in reorienting are also lateralized to the right hemisphere similarly to the TPJ. Nobre, Coull, Frith, and Mesulam (1999) reported with positron emission tomography (PET) bilateral orbi-to-frontal activation during blocks of trials containing a high percentage of unattended targets and related this activity to changes in stimulus–response association. Arrington, Carr, Mayer, and Rao (2000) showed that a right hemisphere network including the right TPJ and right inferior/middle frontal gyrus is recruited during processing of stimuli at unattended locations as com-pared to stimuli at attended locations and proposed a role for this network in spatial reorienting.

A second issue addressed in this study is the relation-ship between neural systems for visuospatial attention and spatial working memory. Visuospatial attention tradi-tionally defines the capacity to select a location for focal visual processing. Spatial working memory defines the ability to encode, transform, and maintain spatial infor-mation for perception and action. These two functions may share common cognitive operations and neural substrates. Awh and Jonides (2001) proposed that visual selection is a key component of rehearsal in spatial working memory. This idea is supported by the strong overlap of foci of activation in the parietal and frontal cortex during tasks involving spatial selection and spatial working memory (Chelazzi & Corbetta, 2000; LaBar, Gitelman, Parrish, & Mesulam, 1999; Smith & Jonides, 1999). However, no functional imaging experiment has directly tested the anatomical overlap of the underlying neural systems using a design able to separate attentional and memory signals from low-level sensory and motor activity. Here, we use event-related functional magnetic resonance imaging (fMRI) and novel analytical techni-ques (Ollinger, Corbetta, & Shulman, 2001; Ollinger,

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Shulman, & Corbetta, 2001; Shulman et al., 1999a) to separate signals related to the endogenous allocation of attention from its maintenance on a location over a 7-sec interval. Some results on parietal cortex have been already reported in short form (Corbetta et al., 2000).

## Visual Orienting Task

Figure 1 shows the structure and timing of the different trials used during the visual orienting task. Each scan was a random mixture of four types of trials—Cue, Valid, Invalid, and Delay. In Cue trials, subjects were presented with a small arrow centered on the fixation point for 2.36 sec. The arrow pointed toward either a left or right box; the boxes were located at 3° on each side of the fixation point. The trial ended after the fixation point reverted to red. In Valid trials, an arrow was presented as in Cue trials; its offset was followed by a random 1.5- to 3.0-sec interval; then a target (an asterisk flashed for 100 msec) was presented in the box indicated by the arrow cue (left box for leftward arrow cue). In Invalid trials, the target appeared at the location opposite to that indicated by the cue (right box for leftward arrow cue). Subjects were instructed to fixate, pay attention to the arrow cue, and respond as fast and accurately as possible after the onset of the target by pressing a key with the right hand. In Delay trials, a 4.72-sec delay, but no target, followed the offset of the cue. Therefore, in Delay trials, subjects presumably maintained attention to the peripheral cued location for ≈ 7 sec (2.36 sec cue period + 4.72 sec delay period minus the brief time needed to shift attention to the box). The analysis described in the Methods sepa-

rates the fMRI signals for the four different types of trials (e.g., Cue, Valid, Invalid, and Delay trials) and for the different periods within a trials (e.g., cue period, delay period, valid target period, invalid target period).

## RESULTS

### Behavior

Reaction times (RTs) to valid targets were shorter than those to invalid targets [fMRI session: valid vs. invalid, 380 vs. 426 msec, $F(1,11) = 21.9$, $p = .001$]. Data from one subject were lost.

### fMRI: Cue-Related Signals

Regions in the occipital, parietal, and frontal cortex were active during the cue period (Figure 2, Cue, regions labeled in red; Table 1). Figure 2 (Cue) shows all areas that significantly modified their signal during the cue period. In the occipital cortex, they included the lateral occipital (LO) region, fusiform gyrus (Fus), and middle temporal complex (MT+), bilaterally. In the parietal cortex, several regions were active bilaterally along the IPs: a more ventral region (vIPs) near area V3A/V7 (Tootell et al., 1997), a more dorsal posterior region extending into the superior parietal lobule (pIPs), and a more anterior region deep within the IPs (aIPs). In the frontal cortex, activity was recorded from the intersection of the posterior end of the superior frontal sulcus and the medial end of the precentral sulcus (SF–PrCes), near the putative human homologue of the frontal eye field (FEF) (Paus, 1996), in the more lateral part of the precentral sulcus, and near the supplementary motor area (SMA) (Table 1).

Figure 3A shows the time course of the blood oxygen level dependent (BOLD) response in most cue-activated regions during the cue and target periods (valid target). Several important results can be noted. First, all regions that became active during the cue period responded during both cue (red–cyan) and target (blue–green) periods. Second, occipital regions such as the MT+ responded more transiently to the cue than did the parietal (vIPs, pIPs, aIPs) and frontal (SF–PrCes, SMA) regions. A significant Region (Fus, LO, MT+, vIPs, pIPs, aIPs, SF–PrCes, SMA) × Time interaction [$F(56,672) = 5.18$, $p = .0001$] supported this result. Pairwise comparisons between regions with similar peak magnitudes confirmed the difference, even when the comparison was restricted to Frames 3 and 4. For example, the signal was more sustained in aIPs than in MT+ [ANOVA Region × Time (Frames 3 and 4 only), $F(1,12) = 7.22$, $p = .02$], and it was also more sustained in pIPs than in LO [ANOVA Region × Time (Frames 3 and 4 only), $F(1,12) = 24.3$, $p = .0003$]. There was no significant difference between parietal and frontal time courses. Third, cue direction, generally, had a modest effect, though in vIPs
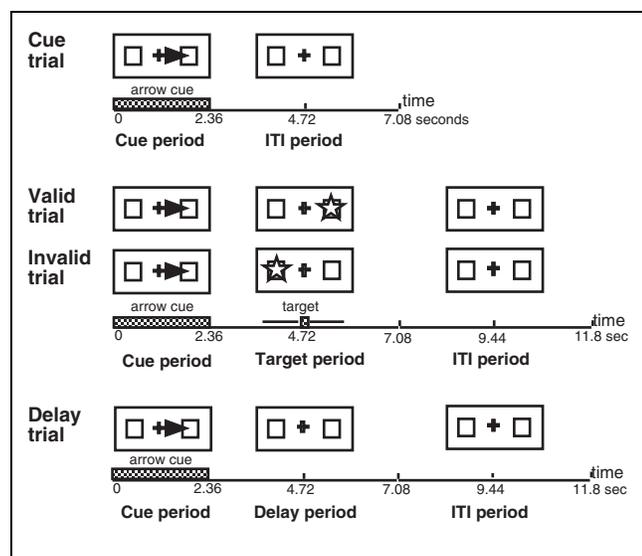


**Figure 1.** Task and MR design. For each panel: (top) visual display during each time interval; (bottom) timeline of each trial. Gray rectangles indicate duration of cue (2.36 sec) and target (100 msec) stimuli. The target stimulus was presented randomly between 3860 and 5360 msec after cue onset.

**Figure 2.** Statistical activation map (ANOVA $F$ map transformed to $z$ map, multiple-comparison corrected) showing regions of activation during cue, target, and delay periods, and differentially modulated by valid or invalid targets (Validity). Left and right visual field (cue, target) conditions are averaged. Cue regions labelled in red: SFs–PrCes = intersection of the superior frontal sulcus and precentral sulcus; SMA = supplementary motor area; aIPs = anterior intraparietal sulcus; pIPs = posterior intraparietal sulcus; vIPs = ventral intraparietal sulcus; LO = lateral occipital region; MT+ = middle temporal complex; Fus = fusiform gyrus. Cue regions also responded during target period. Target regions labelled in yellow: SMC = sensory–motor cortex; SMA = supplementary motor area; PC = precuneus; MFG = middle frontal gyrus; SMG = supramarginal gyrus; STG = superior temporal gyrus; INS = insula-frontal operculum; Calc = calcarine region; IFG = inferior frontal gyrus. Thalamus, basal ganglia, and cerebellum were also active. Regions uniquely reactivated at the end of delay period labelled in white: SM = sensory–motor cortex; aLing = anterior lingual. Transverse slices from $z = -20$ to $z = 46$ in atlas space. Color scale indicates $z$ scores.
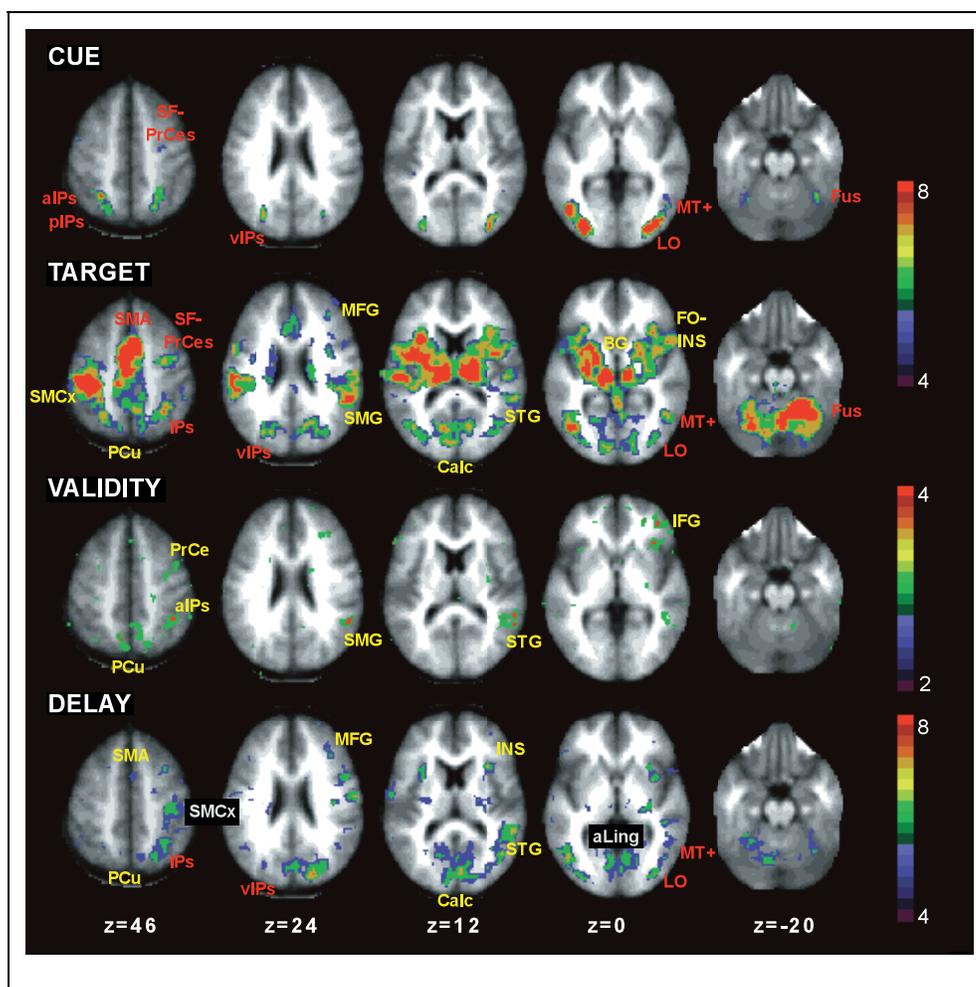


and SF–PrCes, there was a significant Cue Direction × Hemisphere interaction. This is best visualized in Figure 4A, which compares the responses in each hemisphere for leftward and rightward cues. In both regions, leftward cues produced stronger responses in the contralateral (right) hemisphere than did rightward cues, whereas rightward cues produced equally strong responses in both hemispheres (Figure 4A). This impression was confirmed by a significant Hemisphere × Region (Fus, LO, MT, vIPs, pIPs, aIPs, SF–PrCes, SMA) × Cue Direction × Time [$F(8,96) = 2.07, p = .049$] interaction, which was accounted for by a stronger directional effect in some regions (vIPs, SFs–PrCes) but not others. Moreover, we found a significant Hemisphere × Cue Direction × Time interaction in the vIPs and SFs–PrCes only [vIPs: $F(7,84) = 2.68, p = .015$; SFs–PrCes: $F(7,84) = 4.36, p = .0004$]. In all other areas, leftward and rightward cues evoked similar responses (see Figure 3A). There was no overall effect when cue direction was averaged over regions and no significant difference across regions [Cue Direction ×

Time: $F(7,84) = 0.429, p = ns$; Regions × Cue Direction × Time: $F(56,672) = .88, p = ns$]. Fourth, the responses of MT+ and pIPs were significantly stronger in the left hemisphere (Hemisphere × Time: MT+, $p = .001$; pIPs, $p = .008$), whereas the responses of other regions, such as fusiform, vIPs, and PrCe were stronger in the right hemisphere (Hemisphere × Time: Fus, $p = .0003$; vIPs, $p = .001$; PrCe, $p = .0007$).

## Target-Related Signals

All the regions that responded to the cue also responded to the target (Figure 2, Target, regions labeled in red, Table 1). Figure 2 (Target) shows all areas whose signal was significantly modulated during the target period. In general, most areas responded more strongly during the target period than during the cue period. Figure 3A shows the separation of the cue and target responses in several cue-activated regions. Many posterior regions, including MT+ (left, $p = .0001$; right,

**Table 1.** List of Anatomical Regions Activated during Cue, Target, and Delay Periods, and for Validity Effect

| | Cue | | | | Target | | | | Invalid > Valid | | | | Delay | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Regions | $x$ | $y$ | $z$ | Z Score | $x$ | $y$ | $z$ | Z Score | $x$ | $y$ | $z$ | Z Score | $x$ | $y$ | $z$ | Z Score |
| *Occipital* | | | | | | | | | | | | | | | | |
| L ant Fus | −31 | −55 | −16 | 5.47 | | | | | | | | | −25 | −53 | −18 | 5.87 |
| R ant Fus | 35 | −57 | −20 | 6.79 | 29 | −55 | −18 | 8.69 | | | | | 27 | −51 | −14 | 6.37 |
| L pos Fus | −27 | −65 | −14 | 6.07 | −27 | −69 | −22 | 8.23 | | | | | | | | |
| R pos Fus | 35 | −67 | −12 | 5.99 | 35 | −69 | −18 | 7.73 | | | | | 31 | −65 | −16 | 6.54 |
| L MT+ | −45 | −69 | −2 | 9.3 | −47 | −69 | 6 | 8.02 | | | | | −47 | −69 | 4 | 7.21 |
| R MT+ | 45 | −69 | −4 | 6.51 | 47 | −65 | 8 | 6.29 | | | | | 45 | −65 | 12 | 6.76 |
| L LO | −31 | −83 | 0 | 9.08 | −29 | −85 | 0 | 5.52 | | | | | −35 | −85 | 0 | 6.22 |
| R LO | 27 | −87 | 0 | 8.87 | 29 | −87 | −2 | 6.26 | | | | | 33 | −87 | 4 | 6.58 |
| L CalcS | | | | | −5 | −89 | 0 | 6.78 | | | | | | | | |
| R CalcS | | | | | 5 | −91 | 0 | 5.71 | | | | | | | | |
| L Calc/Pos | | | | | −11 | −71 | 8 | 7.65 | | | | | −3 | −71 | 16 | 5.71 |
| R Calc/Pos | | | | | 15 | −79 | 6 | 7.1 | | | | | 3 | −81 | 8 | 6.68 |
| R SOG | | | | | | | | | | | | | 19 | −83 | 24 | 6.96 |
| L LingG | | | | | | | | | | | | | −7 | −67 | −2 | 6.65 |
| R LingG | | | | | | | | | | | | | 9 | −71 | −8 | 6.62 |
| *Parietal* | | | | | | | | | | | | | | | | |
| L vIPs | −27 | −75 | 26 | 7.23 | −27 | −77 | 20 | 7.16 | | | | | −27 | −77 | 18 | 5.76 |
| R vIPs | 29 | −71 | 22 | 6.01 | 23 | −71 | 30 | 6.63 | | | | | 31 | −75 | 18 | 6.4 |
| L ant IPs | −25 | −57 | 46 | 7.55 | −29 | −47 | 42 | 7.58 | | | | | −25 | −55 | 42 | 6.16 |
| L pos IPs | −25 | −67 | 48 | 7.58 | −25 | −65 | 48 | 6.94 | | | | | | | | |
| R ant IPs | 27 | −59 | 52 | 6.75 | 33 | −51 | 48 | 7.6 | 39 | −47 | 48 | 4.09 | 27 | −49 | 38 | 6.3 |
| R pos IPs | 21 | −65 | 52 | 6.62 | 23 | −63 | 46 | 5.81 | | | | | 33 | −61 | 46 | 6.37 |
| L SMG | | | | | −51 | −37 | 34 | 8.23 | | | | | | | | |
| R SMG | | | | | 53 | −45 | 20 | 8.53 | 53 | −49 | 30 | 5.12 | 57 | −41 | 30 | 6.53 |
| R Precun | | | | | 7 | −73 | 34 | 7.71 | 7 | −75 | 34 | 4.28 | 9 | −69 | 38 | 6.48 |
| L Precun | | | | | 11 | −67 | 38 | 7.46 | −5 | −71 | 34 | 4.27 | −3 | −79 | 26 | 6.17 |
| L PoCeG | | | | | −31 | −31 | 52 | 10.8 | | | | | | | | |
| L PoCeG | | | | | −25 | −43 | 58 | 8.63 | | | | | | | | |
| R PoCeG | | | | | 51 | −25 | 40 | 6.01 | | | | | 51 | −23 | 40 | 6.09 |
| L ParOperc | | | | | −55 | −27 | 28 | 8.51 | | | | | | | | |
| R ParOperc | | | | | 53 | −31 | 28 | 7.65 | | | | | | | | |
| R PoCeG | | | | | | | | | | | | | 39 | −23 | 40 | 6.86 |
| R PoCeG | | | | | | | | | | | | | 43 | −37 | 56 | 6.07 |

*(continued)*

**Table 1** (continued)

| Regions | Cue | | | | Target | | | | Invalid > Valid | | | | Delay | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *x* | *y* | *z* | *Z Score* | *x* | *y* | *z* | *Z Score* | *x* | *y* | *z* | *Z Score* | *x* | *y* | *z* | *Z Score* |
| *Temporal* | | | | | | | | | | | | | | | | |
| R STG | 51 | −55 | 4 | 5.41 | Activity w/o independent peak | | | | 57 | −45 | 12 | 4.44 | 55 | −41 | 12 | 7.01 |
| R mid STG | | | | | | | | | | | | | 47 | −39 | 8 | 6.28 |
| L Parahipp | | | | | | | | | | | | | −19 | −57 | −8 | 6.16 |
| L ant STG | | | | | | | | | | | | | −63 | −11 | 14 | 6.13 |
| *Frontal* | | | | | | | | | | | | | | | | |
| L PrCe | −49 | −3 | 46 | 5.44 | −39 | −7 | 44 | 6.43 | | | | | 41 | −1 | 32 | 6.23 |
| R PrCe | 39 | −9 | 56 | 5.27 | | | | | 37 | −3 | 52 | 4.05 | −41 | −15 | 30 | 6.01 |
| L SFs–PrCes | −23 | −11 | 50 | 5.14 | −29 | −15 | 58 | 7.7 | | | | | | | | |
| R SFs–PrCes | 25 | −13 | 50 | 5.49 | 31 | −11 | 54 | 7.51 | | | | | | | | |
| L SMA | −9 | −1 | 54 | 4.95 | −3 | −11 | 54 | 10.5 | | | | | | | | |
| R SMA | 7 | 3 | 52 | 4.9 | 7 | 1 | 48 | 9.27 | | | | | | | | |
| L Ant Cing | | | | | −3 | −9 | 46 | 10.1 | | | | | | | | |
| R ACing | | | | | 7 | 9 | 42 | 9.69 | | | | | | | | |
| L PCing | | | | | −13 | −29 | 44 | 8.51 | | | | | | | | |
| L Ces | | | | | −41 | −31 | 50 | 10.9 | | | | | | | | |
| R ant INS-FO | | | | | 33 | 15 | 8 | 7.9 | 33 | 23 | −2 | 4.15 | 29 | 15 | 8 | 7.25 |
| L aINS-FO | | | | | −33 | 13 | 8 | 8.42 | | | | | −31 | 15 | 8 | 6 |
| L MFG | | | | | −31 | 25 | 28 | 6.24 | | | | | | | | |
| R MFG | | | | | 33 | 27 | 32 | 6.14 | 35 | 31 | 24 | 3.5 | 33 | 23 | 30 | 6.38 |
| L IFG | | | | | | | | | −39 | 43 | −6 | 4.28 | −37 | 29 | −8 | 6.86 |
| R IFG | | | | | | | | | 37 | 39 | −4 | 4.47 | | | | |
| R SFs | | | | | | | | | | | | | 23 | 3 | 56 | 6.3 |
| R Ces | | | | | | | | | | | | | 55 | −13 | 30 | 6.23 |
| R Ces | | | | | | | | | | | | | 33 | −31 | 60 | 6.29 |

This table includes the large majority of all activated regions and all the regions discussed in the text. Contact the corresponding author for a complete listing.

$p = .0001$), right LO ($p = .000001$), vIPs (left, $p = .002$; right, $p = .002$), and right aIPs ($p = .0001$) showed a significant contralateral bias, exhibiting stronger responses to contralateral than to ipsilateral targets. In Figure 3A, for instance, left MT+ responded more strongly to targets presented in the right visual field than to those presented than in the left visual field, whereas right MT+ had the opposite response. This contralateral field bias was not observed in frontal regions SF–PrCes and SMA. However, the SMA response was determined by which hand pressed the key. The activation in the left SMA, which was contralateral to the responding hand, was significantly stronger than the activation in the right SMA (compare the left and right SMA for valid targets in Figure 3A). SF–PrCes, which was modulated by cue direction, showed neither a target position bias nor a response bias.

Several other regions (Figure 2, Target; Table 1) were recruited only during the target period. Some of these regions are labeled in yellow in Figure 2 (Target). Some areas presumably were involved in preparing and executing the right-handed key-press response. These included left sensory–motor cortex, bilateral parietal operculum near SII (Burton, Videen, & Raichle, 1993), right antero-superior cerebellum, basal ganglia, and thalami. Other regions were localized in frontal, parietal, and temporal cortex: middle frontal gyrus (MFG), precentral region (PrCe), anterior insula-frontal operculum

**Figure 3.** (A) Time course analysis of BOLD signal during cue and target periods in several cue-activated regions (see Figure 2 for anatomical labels); $y$ axis = % change MR signal; $x$ axis = time. Each data point corresponds to the mean BOLD amplitude recorded in each MR frame. The cue stimulus (C) was presented on Frame 1, the target stimulus (T) on Frame 3. The cue response peaks two frames later (4.72 sec), as expected based on the standard hemodynamic delay of the BOLD response (4–6 sec). The target response peaks on Frame 5, two frames after the onset of the target that occurs with some temporal uncertainty on Frame 3. Signal evoked by cue stimuli in red (leftward cue) and cyan (rightward cue). Signal evoked by valid target stimuli in green (left valid) and blue (right valid). (B) Time course during cue and delay period in several cue-activated regions. The end of the delay period, or beginning of ITI, occurred on Frame 4 (ITI). Frames 4 and 5 (black arrow marks Frame 4) were time-locked (after the appropriate hemodynamic lag) to the delay period. The reactivation on Frame 6 was time-locked (after the appropriate hemodynamic lag ) to the end of the delay, or beginning of ITI, on Frame 4.
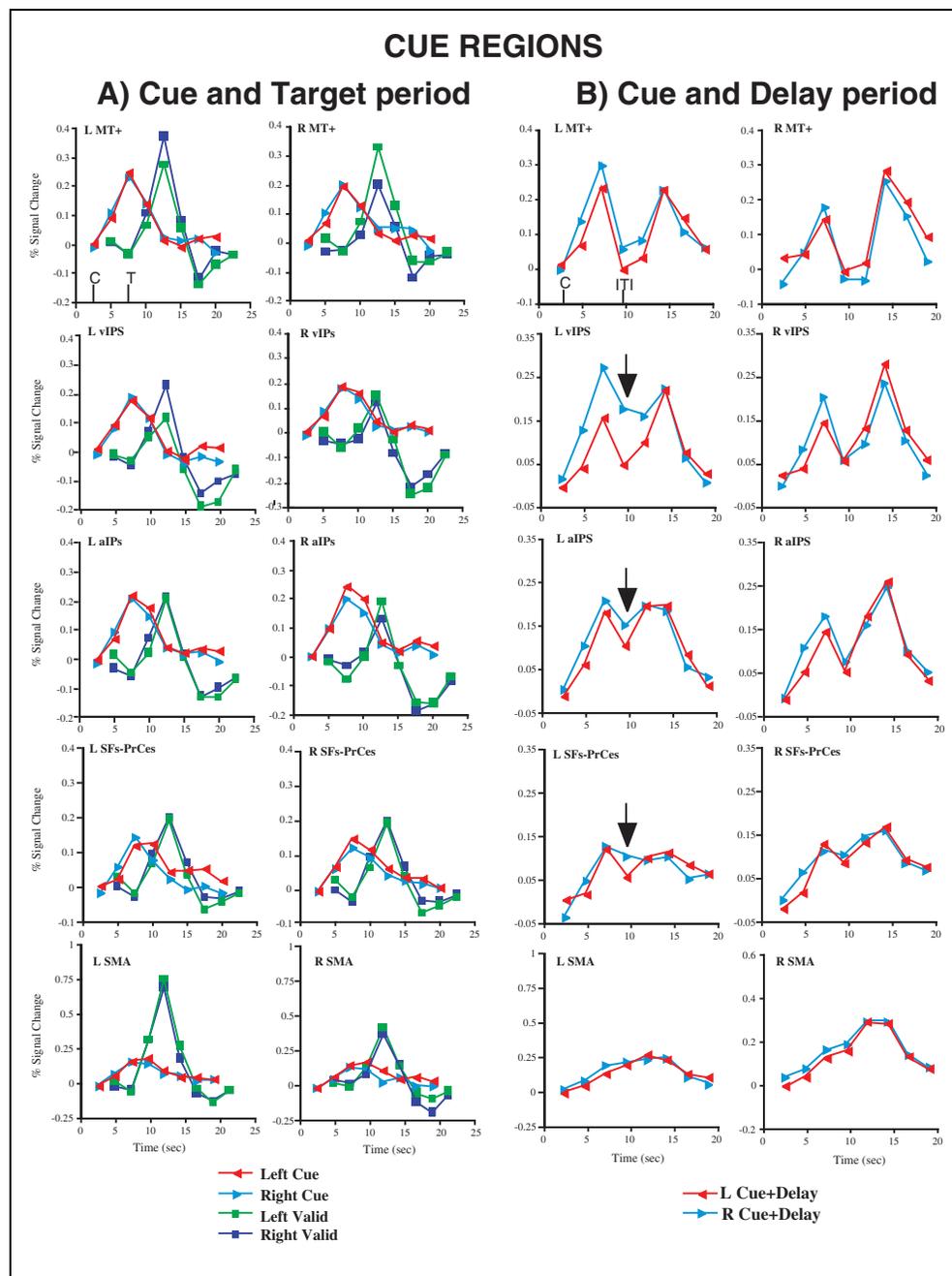
(INS), precuneus (PC), supramarginal gyrus (SMG), and the STG in the temporal cortex. Figure 5 shows cue- and target-related time courses in some regions that were active predominantly during the target period. Target responses in other regions are shown in Figure 4. All these regions responded weakly or not at all to the cue stimulus, but became robustly active when detecting or responding to the target (Figure 5).

## Valid versus Invalid Target-Related Signals

Both regional and voxel-wise ANOVAs indicated that a set of regions predominantly located in the right hemi-

sphere was significantly modulated by target validity. Figure 2 (Validity) shows the results of a voxel-wise ANOVA that identifies regions in which the BOLD signal was significantly different for valid and invalid targets. These regions included the right SMG, right STG, right aIPS (adjacent but separate from the region active during the cue period), right PrCe, right MFG, and—bilaterally but still stronger in the right hemisphere—the precuneus and inferior frontal gyrus (IFG) (Figure 2; Table 1).

Figure 4B shows that all these regions responded more strongly to invalid than to valid targets. In most regions, moreover, the signal was not significantly

**Figure 4.** (A) Directional modulation during cue period. Time course for leftward or rightward cues in areas SFs–PrCes (top) and vIPs (bottom). Green = signal from left hemisphere; red = signal from right hemisphere. (B) Validity effect. Time course for target stimuli in several areas that show a BOLD validity effect (significantly stronger response for invalid than for valid targets). Blue = valid targets (left, right); red = invalid targets (left, right).
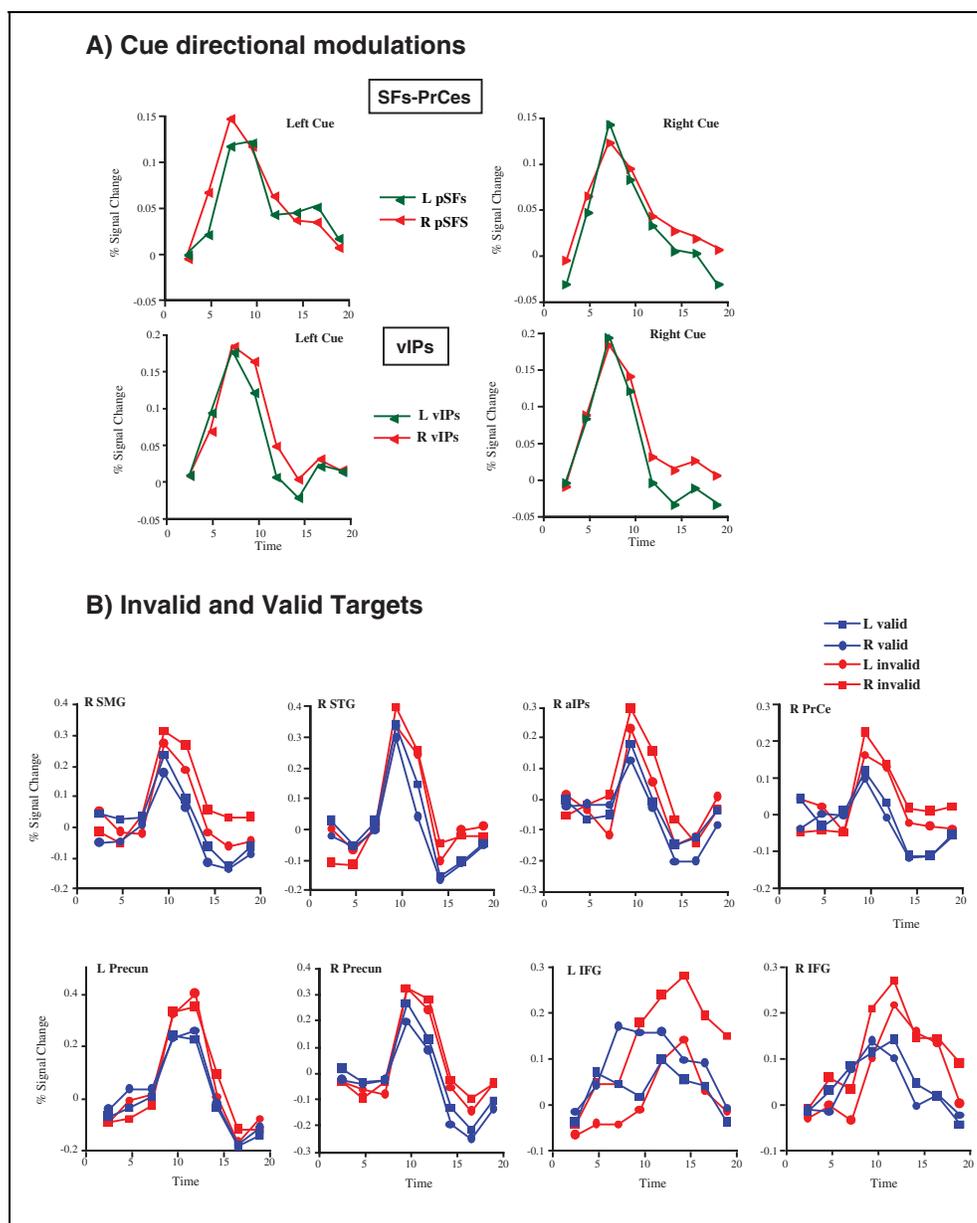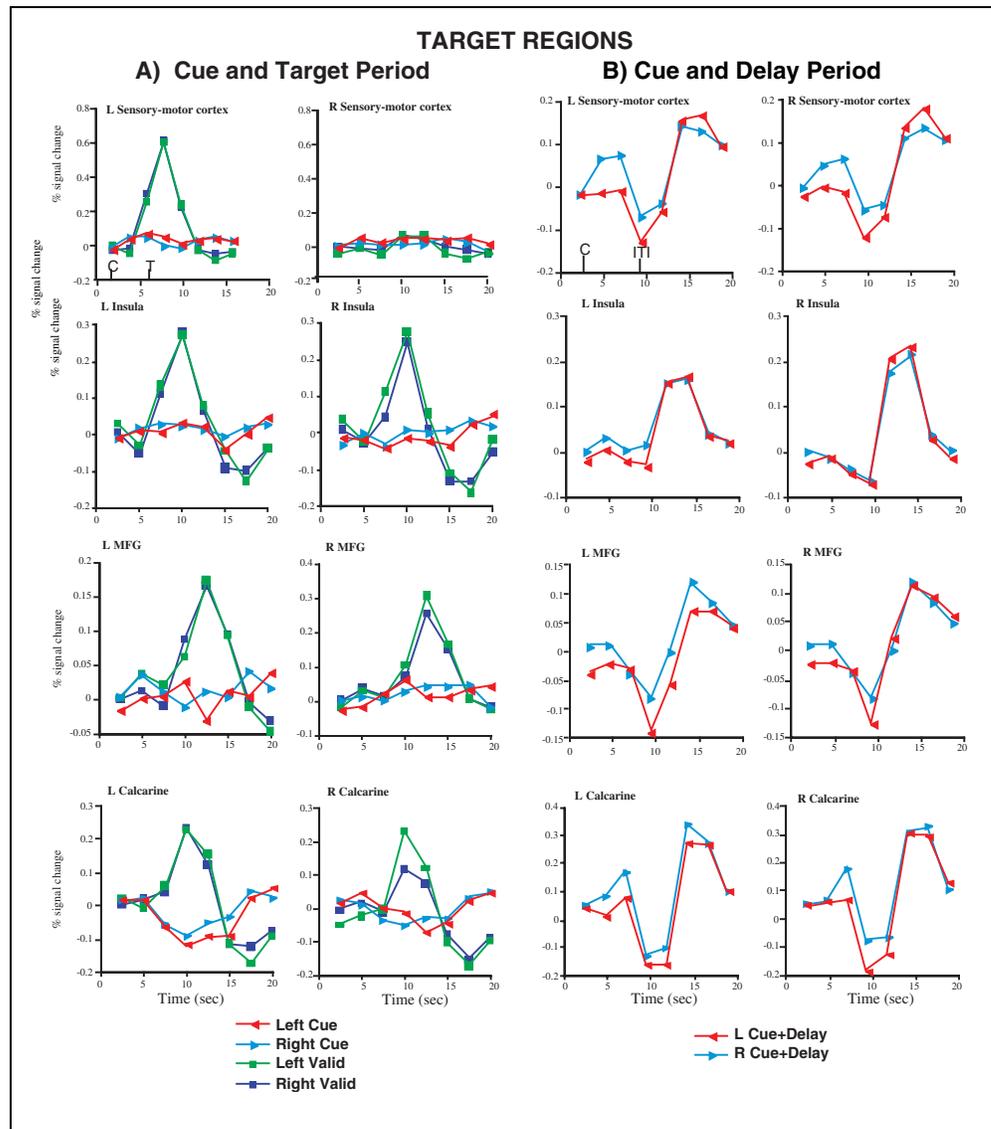
modulated by target location (left or right). In the right aIPs only, the response to targets in the left visual field was significantly stronger than the response to targets in the right visual field [$F(117,84) = 2.79$, $p < .052$]. Finally, the response in the IFG differed from the other areas modulated by invalid targets. The peak of the response in the IFG was significantly extended in time as compared to the other regions. Figure 4B shows that, in most regions, the BOLD response peaks on Frames 4–5, being locked to the onset of the target stimulus; it then returns to baseline on Frames 6–7. In contrast, the IFG signal peaks on Frames 5–6 and is still elevated on Frame 7. This impression was confirmed by a significant Region × Time interaction over the whole time course [Frames 1–8, $F(35,420) = 4.01$, $p = .000001$] or just on the second half of the response

[Frames 5–8, $F(10,120) = 5.61$, $p < .000001$]. Surprisingly, no region was significantly more active during valid than during invalid trials.

## Delay-Related Signals

The voxel-wise ANOVA in Figure 2 (Delay) isolates areas active during the delay period. Interestingly, both cue- and target-related regions were active. Several regions that were active during the cue period, including MT+, LO, vIPs, aIPs, and SMA (delay-related activity in SF–PrCes did not reach significance), were also active during the delay (regions labeled in red). Several regions that were active only during the target period, including the insula-frontal operculum, MFG, and STG, also responded significantly during the delay

**Figure 5.** (A) Time course during cue and target periods in several target-activated regions. (B) Time course during cue and delay periods in several target-activated regions or regions uniquely reactivated at the end of the delay (e.g., right sensory–motor cortex). Note the absence of delay activity on Frames 4 and 5; note the strong reactivation on Frame 6.



**TARGET REGIONS**

**A) Cue and Target Period**   **B) Cue and Delay Period**

Legend:
- Left Cue
- Right Cue
- Left Valid
- Right Valid
- L Cue+Delay
- R Cue+Delay

(labeled in yellow). Finally, some new regions, including the right motor cortex or anterior lingual gyrus, were uniquely recruited during the delay period (labeled in white). Analysis of the signal time course revealed different temporal patterns in each set of regions.

Figure 3B shows the time course of the response in cue-related regions. To clarify the relationship between cue- and delay-related signals, the time course is plotted over the whole trial (cue + delay period). Consider first the signal in the left or right MT+. The response in MT+ was characterized by a first peak on Frame 3 that was time-locked to the onset of the cue stimulus two frames earlier. The signal returned to baseline within one frame (Frame 4) and remained at baseline for an additional frame (Frame 5). Frames 4 and 5 were time-locked to the delay period, which began at Frame 2. The signal peaked again on Frame 6, corresponding in time to either the end of the delay period

or the beginning of the intertrial interval (ITI). Thus, the MT+ response in the ANOVA map (Figure 2, Delay) predominantly reflects reactivation of the signal at the end of the delay period (or beginning of the ITI). The reactivated signal on Frame 6 was observed in all cue- and target-related areas identified during the delay period (see below and Figures 3B and 5B). This reactivation is endogenous, and its physiological characteristics are discussed in a separate report (Shulman et al., in press).

Consider now the responses in intraparietal (e.g., vIPs and aIPs, Figure 3B) and superior frontal cortex (SF–PrCes, Figure 3B), which were more sustained during the cue period. After the initial peak in Frame 3, which corresponded to the onset of the cue, the signal was sustained during the delay (Frames 4–5) and was reactivated on Frame 6. There was a trend for more sustained activity moving dorsally into parietal and frontal regions. For example, the time course in vIPs is

intermediate between the transient response in the MT+ and the more sustained responses observed in the aIPs and SF–PrCes. This impression was confirmed by a significant Region (MT+, LO, vIPs, aIPs, pIPs, PrCe, SFs–PrCe, SMA) × Time interaction on Frames 3–5 $[F(14,168) = 16.4, p = .0001]$ and Frames 4–5 $[F(7,98) = 8.078, p = .0001]$. The signal during the delay (Frames 4–5) was significantly stronger in the aIPs and SFs–PrCe than in occipital regions (aIPs vs. LO, $p = .05$; aIPs vs. MT+, $p = .0008$; aIPs vs. Fus, $p = .0008$; SF–PrCes vs. LO, $p = .001$; SF–PrCes vs. MT+, $p = .0001$; SF–PrCes vs. Fus, $p = .0001$). There was no significant difference, however, between aIPs and SFs–PrCe ($p = .17$). The response in SMA grew during the delay and blended into the reactivation (Figure 3B).

The direction of attention modulated the response during the delay period, as during the cue period. Inspection of Figure 3B suggests that regions in the left hemisphere that responded during the cue period did so more strongly when attention was directed to the right visual field than to the left visual field. In contrast, right hemisphere regions responded equally well when attention was directed toward either visual field. This was confirmed by a significant Hemisphere × Delay × Direction interaction [Frames 4–5, $F(1,12) = 12.6$, $p = .004$; Frames 4–5, $F(1,12) = 17.3$, $p = .001$]. $F$ tests on individual regions confirmed that several left hemisphere intraparietal and superior frontal regions responded more strongly to delay signals for rightward attention than to those for leftward attention [L pIPs, $F(1,12) = 4.98$, $p = .05$; L aIPs, $F(1,12) = 6.23$, $p = .03$; L vIPs, $F(1,12) = 7.58$, $p = .02$; L SFs–PrCes, $F(1,12) = 5.70$, $p = .03$; L PrCes, $F(1,12) = 8.46$, $p = .02$], whereas no directional difference was observed in the homologous regions of the right hemisphere. Furthermore, the response of left hemisphere regions, including occipital regions (e.g., left MT+ in Figure 3B), was more sustained than that of homologous regions in the right hemisphere, as indicated by a significant Hemisphere × Time interaction [Frames 4–5, $F(2, 24) = 6.18$, $p = .007$; Frames 4–5, $F(1,14) = 2.76$, $p = .11$].

The time course of the response in some target-responsive regions (left sensory–motor cortex, insula, MFG, calcarine) during the cue and delay periods is shown in Figure 5. To clarify the relationship between cue- and delay-related signals, the time course is plotted over the whole trial (cue + delay period). Figure 5B also shows the time course in a region that was uniquely active during the delay (right sensory–motor cortex). In most regions, the response to the cue is small or absent, decreases during the delay (Frames 4–5), and reactivates on Frame 6 (left motor cortex, MFG, calcarine). The decreased signal during the delay period in MFG is particularly striking in light of the positive sustained activity in the more dorsal SF–PrCes region (see Figure 2B).

## DISCUSSION

### Eye Movements

Eye movements were not monitored in the scanner. However, critical results like the asymmetrical response in the vIPs and SFs–PrCes during the cue period, or the lateralization of activity to the right hemisphere for invalid targets, cannot be explained by eye movements. Furthermore, it is unlikely that subjects moved their eyes during the fMRI session. All subjects maintained accurate fixation during the behavioral session in agreement with a large psychological literature, indicating that subjects avoid moving their eyes during covert orienting involving detection tasks (Posner & Cohen, 1980). In previous PET experiments, we used the same procedure of training subjects in a prior psychophysical session, and then measured eye movements in the course of the experiment on analogous spatial detection tasks (Corbetta, Miezin, Shulman, & Petersen, 1993; Corbetta, Shulman, Miezin, & Petersen, 1995). We never eliminated any subject because of inaccurate fixation. Finally, we have recently rerun similar experiments with an eye tracker and confirmed that the MR environment does not encourage eye movements in appropriately screened subjects (Astafiev, Shulman, & Corbetta, unpublished observations).

### The Dorsal Frontal Parietal Network and Endogenous Visual Attention

This study provides novel anatomical and functional information on a frontal parietal network consistently associated with the control of visual attention (Corbetta, 1998; Kanwisher & Wojciulik, 2000; Kastner & Ungerleider, 2000). In the posterior parietal cortex, three separate regions were recruited when subjects voluntarily paid attention to a location (cue period): (1) vIPs, at the junction of the ventral ramus of the IPs and the transverse occipital sulcus, which corresponds to V3A/V7 as identified in retinotopic mapping studies by Tootell et al. (1997); (2) the more dorsal pIPs, which lies more at the posterior end of the IPs and extends into SPL; and (3) aIPs, which is more anterior and extends deep into the IPs. The anterior IPs may be homologous of monkey LIP/VIP based on a recent comparison of activation foci from human studies of visuospatial attention and eye movements with functional areas in macaque, after multidimensional warping of human and macaque brains (Van Essen et al., in press). This focus is also active during attention to motion and passive stimulation with radial motion (Shulman et al., 1999; Culham et al., 1998), consistent with the presence of directionally selective signals in VIP (Colby, Duhamel, & Goldberg, 1993) and LIP (Eskandar & Assad, 1999).

In the frontal cortex, three areas were modulated during the cue period. One area, SF–PrCes, lies at the intersection of the posterior end of the superior frontal

sulcus and precentral sulcus. The other, PrCes, lies more laterally along the precentral sulcus and extends, in some studies, more ventrally. A number of reports have proposed that SF–PrCes is homologous with macaque FEF (Paus, 1996; Corbetta et al., 1998; Luna et al., 1998), but in blocked design studies, both areas are typically active. In more recent event-related studies that separate more precisely cognitive from sensory signals, we have observed unique coactivation of SF–PrCes and IPs regions without recruitment of the more lateral precentral region. In this experiment, the ventral IPs and SF–PrCes were uniquely modulated by the direction of attention (see below). In Shulman, Ollinger, Akbudak, et al. (1999a) and Shulman, Ollinger, Petersen, et al. (1999b), the anterior and posterior IPs and SFs–PrCes were coactive as subjects attended to the direction of motion. If coactivation reflects anatomical connectivity, and the aIPs is partly homologous with LIP, then SF–PrCes should be the human homologue of FEF given the strong reciprocal connectivity between LIP and FEF in macaque (Blatt, Andersen, & Stoner, 1990). In the rest of the paper, we will use the term human FEF (or FEF for short) to indicate the SF–PrCes region, but this homology is tentative. The third area corresponds to the SMA in the medial frontal cortex. While activity in the FEF and IPs (vIPs) was spatially selective (see below), SMA activity did not show location selectivity. Rather, it greatly increased during the target period, particularly contralaterally to the responding hand, when subjects prepared and executed a key-press. Therefore, based on its temporal profile of activation, we can conclude that SMA frequently considered part of a spatial attention system based on blocked design studies (Mesulam, 1999) relates more to response preparation than to spatial expectation.

The temporal analysis of the BOLD signal indicates that regions in the IPs and FEF represent critical cortical components of an endogenous spatial orienting system. The BOLD signal in these regions was time-locked to the presentation of an endogenous cue, indicating a likely target location, and it remained sustained while subjects paid attention to that location. In contrast, other occipital regions (e.g., MT+, LO) responded only transiently to the onset of the cue. There was a trend for more sustained signals in more dorsal visual areas. For example, signals in vIPs (V3/V7, Tootell et al., 1997) were intermediate between MT+ and the more dorsal aIPs (putative LIP) or FEF. Our interpretation is that transient signals in the occipital cortex reflect the initial encoding of the arrow cue (perhaps analysis of its shape), whereas more sustained signals in the frontal and parietal cortex underlie the shift and maintenance of attention to the cued location.

Furthermore, the BOLD signal in vIPs and in FEF were modulated by the direction of attention. Leftward cues, producing a shift of attention to a location in the left visual field, evoked stronger responses in the right hemisphere. Rightward cues, producing a shift of

attention to a location in the right visual field, evoked similar responses in the two hemispheres (Figure 4A). This directional modulation was specific to the cue period; during the target period, vIPs activation was stronger for contralateral targets, whereas FEF activation was not modulated by where the target was presented. The directional modulation in the vIPs and FEF and the related hemispheric asymmetry cannot be explained by sensory differences because the cue stimuli were identical except for the direction in which each arrow pointed. These areas may contain a spatial map where the coordinates of an attention shift are calculated. These maps may code visual space asymmetrically in the two hemispheres, with the left hemisphere coding predominantly for contralateral locations and the right hemisphere coding for bilateral locations. This arrangement is consistent with the theoretical proposal that space is represented bilaterally in the right posterior parietal cortex (Mesulam, 1999; Heilman & Watson, 1977) and the view that the fronto-parietal network is right hemisphere dominant (Mesulam, 1999).

However, our results indicate a more complex functional organization and pattern of asymmetry in the human posterior parietal cortex. First, in contrast to the small vIPs region modulated by the direction of the cue, other regions in the IPs (aIPs, pIPs) did not show any directional modulation during the cue period and responded bilaterally to cues in either direction. Second, during the target period, all IPs regions showed a stronger response in the hemisphere contralateral to the target, as other visual regions (e.g., MT+ or LO, see Figure 3A). Third, a much stronger right hemisphere asymmetry is evident during the target period in more ventral IPL and STG regions (see below). Therefore, the separate temporal analysis of cue- and target-related signals may explain why previous blocked design studies, in which cue- and target-related signals were mixed, have reported either no lateralization (Corbetta et al., 1998; Vandenberghe et al., 1997, 2000), a relative contralateral advantage (Nobre et al., 1997; Corbetta et al., 1993) or an absolute right hemisphere advantage (Gitelman et al., 1996). Our event-related analysis indicates a mostly symmetrical response in the IPs (with the exception of the vIPs) during endogenous spatial orienting (cue period) and a mostly contralateral response to target stimuli. However, a review of the imaging literature suggests that the exogenous allocation of attention may predominantly recruit right IPs (Corbetta, Kincade, & Shulman, in press).

The specialization of a dorsal frontal parietal network for endogenous visual selection is consistent with other imaging studies that find IPs and FEF activation following the presentation of symbolic cues instructing location (Hopfinger, Buonocore, & Mangun, 2000) or motion direction (Shulman et al., 1999a) or complex patterns (Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999). Also, frontal lesions that include FEF

specifically slow down voluntary saccades toward the contralateral visual field (Henik, Rafal, & Rhodes, 1994). In addition, posterior parietal lesions, centered in IPs–SPL, specifically impair the ability to shift attention endogenously (Friedrich et al., 1998).

It is not understood how neural signals in the dorsal fronto-parietal network contribute to visual selection. A general organizing principle has been that these regions are critical for spatial selection (Colby & Goldberg, 1999). Accordingly, many theories have emphasized the importance of location codes in visual selection (Rizzolatti & Camarda, 1987; Posner, 1980). Recent imaging work, however, clearly indicates that human intraparietal cortex is also active during nonspatial visual selection. For example, Le, Pardo, and Hu (1998) reported IPs activation during blocks of trials in which subjects select alternatively between the shape and color of an object, as compared to when they tonically select either its shape or color. Since the object was presented at the fovea, and did not change location during the experiment, this type of modulation is not easily explained in terms of covert motor planning or simple selection of location codes.

One way to reconcile spatial and nonspatial selection is to consider IPs cortex as an area that dynamically links multiple maps of an object (e.g., representations of its features) by linking similar locations in each map. This scheme is similar to Treisman's (1986) master map of location except that we propose that the IPs cortex controls not only switches between locations in the master map, but also switches between functional areas that encode different attributes of the same object. Therefore, the parietal cortex would control a switch from a motion area to a color area, if the task calls for attending (and reporting) in sequence first motion and then color information. This hypothesis predicts that damage to the parietal cortex should create problems with both spatial and nonspatial selection. The IPs is in a strategic position to switch between representations or locations within a representation because of its extensive connectivity, both intracortically and subcortically with many different levels of the visual system (Lewis & Van Essen, 2000; Blatt et al., 1990).

Control and switching are functions traditionally associated with the prefrontal cortex (Desimone & Duncan, 1995). The prefrontal cortex, however, is reciprocally connected only with the highest levels of the ventral and dorsal visual system (Felleman & Van Essen, 1991) and is not in the position to influence in parallel multiple levels of the visual system. Widespread parallel connectivity between the source and site of attention is necessary to explain why attentional modulations occur with similar latencies over multiple levels in the visual hierarchy (Luck, Chelazzi, Hillyard, & Desimone, 1997). The function of prefrontal areas may be to retrieve stored information and provide the content of an expectation that is then linked to visual areas via the parietal cortex.

In the case of a purely spatial task, the content signal (where to attend to) may be represented by an oculo-motor program stored in FEF or a reaching program stored in the premotor cortex. In the case of an identification task, the content signal (what to attend to) may be generated by the reactivation of object representations stored in the temporal cortex.

## The Dorsal Frontal Parietal Network and Spatial Working Memory

A second important result of this study is the demonstration that the frontal parietal network involved in endogenous visual attention is also specifically recruited during a memory interval, in which subjects maintain attention on a peripheral location. Whereas some degree of delay activity was observed throughout the dorsal visual system, delay signals were most sustained and robust in the IPs and FEF. As during the cue period, we observed a graded increase of sustained activity going from occipital to parietal and frontal areas (see Figure 3B). For example, the delay response in the left vIPs was intermediate between that of MT+ and that of the aIPs or FEF. No delay activity was observed in ventral visual regions like LO or fusiform, indicating that these regions were not involved in spatial memory.

The IPs and FEF were also uniquely modulated by the direction of attention during the delay period. This is consistent with their spatial selectivity during the cue period and confirms the special roles of these regions in spatial coding. However, the response in the two hemispheres was differentially modulated for left and right visual field attention during the two temporal intervals (cue, delay). During the cue period, attention to the left visual field produced relatively stronger activation of the right IPs and FEF than their left hemisphere counterparts. In contrast, attention to the right visual field evoked similar responses in the two hemispheres. During the delay period, maintaining attention to the right visual field produced relatively stronger activation of the left IPs and FEF, whereas maintaining attention to the left visual field did not produce any significant hemispheric difference. In addition, we observed an overall stronger response during the delay period in other left hemisphere regions that was independent of the direction of attention (Figure 3B). We offer two possible explanations for the relative left hemisphere lateralization during the delay. It is possible that the left hemisphere bias reflects an intentional code of the attended location. As the time for response approaches in the course of the delay period, motor preparation signals related to the right-handed key-press may emerge throughout the brain. Alternatively, locations might be coded more verbally during the delay, and verbal codes are known to preferentially recruit the left hemisphere.

These results provide direct support for the claim that spatial attention and spatial working memory (rehearsal)

share common processes and neural substrates (Awh & Jonides, 2001). Behavioral results indicate that spatial memory is impaired when attention is shifted away from the remembered location. Previous meta-analyses of brain imaging studies (Chelazzi & Corbetta, 2000; Smith & Jonides, 1999) and one blocked design study (LaBar et al., 1999) noted anatomical overlap in the posterior parietal and superior frontal cortex of activation foci during spatial attention and spatial working memory tasks. Here, we show that identical IPs and FEF regions are modulated by the initial allocation of attention to a location and by its maintenance over a 7-sec delay interval in a design that separates attentional and memory signals from low-level sensory or motor signals. Therefore, spatial rehearsal, namely, the operation necessary to maintain a location in working memory, recruits the same regions involved in shifting attention to a location. Accordingly, at the neuronal level, several studies have reported co-localization of spatial attention and spatial memory signals in several areas of the macaque brain that are potentially homologous to those active in humans (LIP; Colby, Duhamel, & Goldberg, 1996), area 7a (Andersen, Bracewell, Barash, Gnadt, & Fogassi, 1990; Bushnell, Goldberg, & Robinson, 1981), and FEF (Kodaka, Mikami, & Kubota, 1997; Funahashi, Chafee, & Goldman-Rakic, 1993).

The IPs and FEF are also recruited during maintenance of other visual attributes like faces (Courtney, Ungerleider, Keil, & Haxby, 1997) and direction of motion (Shulman et al., 1999b). Memory-related activity for attributes other than location is not surprising in light of the involvement of the frontal parietal network in their selection (Shulman et al., 1999a; Le et al., 1998).

## A Right Hemisphere Network for Visual Reorienting

The final main result of this study was the identification of a right hemisphere cortical system, which was not active during the cue period, responded during target detection, and more strongly for invalid than valid targets. These regions included the right TPJ (separate SMG and STG regions, as reported in Corbetta et al., 2000), right MFG, right anterior insula, IFG, and precuneus. Arrington et al. (2000) described a very similar right hemisphere system (including the right TPJ, right IFG, and right MFG), which was also modulated by the detection of invalid targets during spatial orienting. Since valid and invalid targets do not differ in sensory terms, the most straightforward interpretation is that this right hemisphere network is involved in visual reorienting. Based on current evidence, the right TPJ and right ventral frontal cortex (IFG and orbito-frontal cortex) represent core regions of this network, which is anatomically and functionally separate from the more dorsal FEF–IPs system involved in visual selection and working memory.

Several processes help reorient attention and may contribute to activation of this right hemisphere network. Some regions may be involved in "disengaging" attention from the attended location and/or in computing the novel location of the target. Classic work by Posner, Rafal, et al. (Friedrich et al., 1998; Posner et al., 1984) shows that patients with TPJ lesions are impaired in redirecting attention toward targets presented in the contralesional visual field, when attention is occupied elsewhere in the ipsilesional visual field. However, TPJ-damaged patients can normally use probabilistic (endogenous) cues to direct attention, consistent with the activation of more dorsal IPs regions during endogenous spatial selection. Conversely, IPs–SPL lesions impair endogenous spatial orienting (Friedrich et al., 1998). Recent single unit studies show that neurons in area 7a in macaque respond to behaviorally relevant salient stimuli, particularly when they occur at novel unattended locations (Constantinidis & Steinmetz, 2001a, 2001b), consistent with a role of 7a in reorienting attention. Macaque area 7a may be homologous to the human TPJ (the dorsal component) based on recent warping studies by Van Essen et al. (in press). Therefore, imaging, lesion, and single unit data strongly support a division of labor in the posterior parietal cortex, with the IPs involved in endogenous selection, and the right TPJ involved in visual reorienting.

Reorienting is also associated with changes in alerting, and possibly vigilance. Alerting defines short-term changes in responsiveness associated with the presentation of warning stimuli or oddball targets during steady state stimulation. Vigilance defines a state of readiness to detect and respond to sensory events. A growing literature indicates that the neural and psychological processes of alerting and vigilance may be closely related (Parasuraman, Warm, & See, 1998). An alternative interpretation for the cortical modulation produced by invalid targets is that it relates not to their spatial position, but to changes in alerting/vigilance produced by the detection of low frequency events. Hence, the right hemisphere lateralization reflects a lateralization of alerting/vigilance processes, rather than spatial processes. This interpretation is supported by a number of observations. In our study, the response to targets was modulated by their validity, but not by their position in the visual field. Target position, which strongly modulated the FEF–IPs network both during cue and target period, did not significantly influence the right hemisphere reorienting network, possibly indicating that these regions do not code spatial locations.[1] Accordingly, a growing number of studies have reported modulation of the TPJ and ventral frontal cortex during the detection of low frequency oddball stimuli, independently of their modality (Downar, Crawley, D.J., & Davis, 2000), location, or identity (Marois, Leung, & Gore, 2000). Furthermore, damage of the TPJ and frontal cortex abolishes evoked electrical potential (P300b)

triggered by the detection of infrequent or novel stimuli embedded in a temporal stream of standard stimuli (Daffner et al., 2000; Knight & Scabini, 1998). Finally, vigilance activates right inferior parietal and right frontal regions that are overlapping with those modulated by invalid targets (Pardo, Fox, & Raichle, 1991); and lesions of the right frontal cortex specifically impair vigilance (Wilkins, Shallice, & McCarthy, 1987).

In summary, the reviewed evidence suggests that a ventral right frontal parietal network may act as a ''sentinel'' to detect salient events in the environment. Necessarily, the detection of a salient event must lead to the secondary recruitment of the more dorsal FEF–IPs system for spatial localization and attentional selection. This functional interaction may be reflected in the recruitment of dorsal frontal and parietal regions (right precentral and right IPs) during the detection of invalid targets.

## Two Neural Systems for Orienting and the Pathophysiology of Neglect

One of the puzzles of the last decade has been the apparent mismatch between imaging results showing dorsal (IPs–SPL) parietal activation during shifts of spatial attention, and the localization of unilateral spatial neglect, and related deficits in attentional shifting, to the more ventral TPJ (SMG and STG) (Corbetta et al., in press; Friedrich et al., 1998; Vallar & Perani, 1987). This paradox has been recently exacerbated by a recent report that localizes spatial deficits in neglect, in the absence of visual field deficits, to the STG (Karnath, Ferber, & Himmelbach, 2001). A similar problem may exist in the frontal cortex, where imaging has consistently reported superior frontal activation during attentional tasks, whereas lesions causing neglect map more ventrally (Corbetta et al., in press; Husain & Kennard, 1996; Vallar & Perani, 1987).

This experiment provides some novel information on the functional anatomy and pathophysiology of neglect. First, the location and hemispheric asymmetry of the reorienting network match the anatomy of neglect much better than the more dorsal FEF–IPs regions, postulated by Mesulam (1999) as the core areas of damage in neglect. As discussed earlier, this network may mediate alerting/vigilance processes. Therefore, neglect must reflect, in large part, the dysfunction of these mechanisms. Indeed, the clinical literature indicates that neglect patients have nonlateralized problems of detection and vigilance (Heilman, Bowers, Valenstein, & Watson, 1987), and that frontal lesions impair vigilance and detection (Wilkins et al., 1987). Second, neglect patients have a characteristic sensory–motor bias toward the right side, that is, they tend to orient more easily ipsilesionally than contralesionally, particularly when stimuli appear simultaneously in both visual fields. We suggest that this spatial deficit relates to biases within the more dorsal IPs–FEF system, caused by functional inactivation

of the ipsilateral IPs by more ventral TPJ damage. Specifically, we propose that alerting signals in the TPJ triggered by the detection of a novel event activate the ipsilateral IPs. As both IPs contain a contralateral map of space, inactivation of the ipsilesional map would lower the threshold for orienting toward stimuli coded in the contralesional map, creating a spatial imbalance (Kinsbourne, 1977). Third, this effect may be compounded by damage or inactivation of areas like the right vIPs and right FEF, which code for bilateral visual field locations. Fourth, behavioral interactions exist between vigilance and endogenous spatial orienting in neglect patients. Therapists use verbal cues and ''cognitive anchoring'' as a way to retrain left inattention, since neglect patients are more impaired with sensory-driven than cognitive-driven orienting (Weinberg et al., 1977), while Robertson (1999) demonstrated that vigilance training and phasic alerting improve spatial orienting of neglect patients. These behavioral modulations may well depend on the functional interactions of the dorsal IPs–FEF orienting network with the ventral TPJ–IFG alerting network. Cognitive cues may drive the dorsal system and rebalance attention, but this effect is transient in the absence of a normal alerting system. Conversely, vigilance training or alerting may increase activation of the right TPJ and improve orienting of the ipsilateral IPs–FEF system.

## Conclusions

Our study shows that multiple neural systems in the human brain mediate different varieties of attention. The intraparietal and superior frontal cortex mediate the voluntary (endogenous) allocation of visual attention. These same areas are involved in maintaining selection on a relevant location during a delay period (working memory). They constitute a ''dorsal'' fronto-parietal network for the endogenous, cognitively driven, allocation of attention, and directed visuomotor behavior. A separate ''ventral'' network that is strongly lateralized to the right hemisphere is recruited when we reorient toward unattended visual stimuli. The two systems interact during normal behavior and can be selectively damaged by different lesions in the brain. IPs and FEF lesions impair voluntary directed orienting, whereas the TPJ and inferior frontal lesions impair sensory orienting and vigilance. We suggest that unilateral spatial neglect reflects malfunctioning of both orienting networks.

## METHODS

### Subjects

Thirteen subjects (6 women and 7 men, age 18–38 years) were recruited from the Washington University (WU) community. All subjects were strongly right-handed as measured by the Edinburgh handedness inventory, had no significant abnormal neurological history, and had

normal or corrected-to-normal visual acuity. Each subject gave informed consent following guidelines set by the WU Institutional Review Board.

## Apparatus, Stimulus, and Task

Stimuli were generated by an Apple Power Macintosh computer. During the imaging session, stimuli were projected onto a screen at the head of the scanner's bore by a Sharp LCD projector. Subjects viewed the screen through a mirror attached to the head coil. Behavioral responses (accuracy and RTs) were recorded by a fiber-optic light-sensitive key-press held in the subject's right hand. The display consisted of a fixation cross (16 min of visual angle) flanked on either side by two square boxes (box size 1°, eccentricity 3.3°). The cross was green during a trial and red during the ITI. At the beginning of a trial, an arrow cue was superimposed on the fixation cross. The arrow cue could point to the left or right box with equal probability, and it remained on the screen for one MR frame (2360 msec). Twenty percent of the trials (all the Cue trials) ended immediately after the cue was presented. Otherwise, the cue period was followed by a target period of two MR frames (4720 msec). In 20% of those trials, no target was presented during the test period (Delay trials). In 44%, a target appeared at the location indicated by the cue (Valid trials). In 16%, a target appeared at the uncued location (Invalid trials). The target was a white asterisk that appeared in one of the square boxes for 100 msec. Target onset varied randomly between 3860 and 5360 msec after the onset of the arrow cue (approximately between Frames 2 and 3). Subjects were asked to press a button with the right hand as quickly as possible after they detected the target, or to withhold a response on cue and delay trials. They were aware that the direction of the arrow would indicate the most likely location of the target. Accurate fixation was emphasized throughout the experiment. Eye movements were not recorded during the fMRI session since an eye tracker was not available at the time this experiment was run. However, eye movements were measured with electro-oculography in a prior psychophysical session, in which the visual display was identical to the one in the scanner.

## fMRI Acquisition and Data Analysis

An asymmetric spin–echo, echoplanar imaging sequence was used to measure BOLD contrast (TR = 2.36 sec, TE = 50 msec, flip angle = 90°). Each scan consisted of 128 frames during which 16 contiguous 8-mm axial slices were acquired ($3.75 \times 3.75$ mm in-plane resolution). Sixteen scans were acquired in each subject. Each scan contained approximately 22 trials, or approximately 352 trials per experiment per subject. Anatomical images were acquired using a sagittal MP-RAGE sequence

(TR = 97 msec, TE = 40 msec, flip angle = 12°, inversion time T1 = 300 msec). Functional data were realigned within and across runs to correct for head movement, and they were coregistered with the anatomical data. Whole-brain normalization was applied to equate signal intensity across subjects. In each subject, each time point of the BOLD response (eight frames long) was estimated using a basis set of delayed delta functions (fixed impulse response) within the general linear model (Ollinger, Corbetta, et al., 2001). This estimate was performed voxel-wise for each trial type (Cue, Delay, Valid, Invalid) and each trial period (cue period, delay period, valid target period, invalid target period). This basis set of functions spans the space of all possible responses and is therefore insensitive to changes in the shape of the response. It only assumes that the same BOLD response is measured for each event of the same type. The time courses from the linear model were transformed into atlas space and smoothed by a filter with a full width at half maximum of 2 mm. Group analyses were conducted on the time courses using voxel-level and regional ANOVAs. Each subject contributed only a single parameter for each time point to the group analysis. Hence, subjects were treated as a random effect so that all results generalized across the population. The voxel-wise $F$ maps were corrected for multiple comparisons and transformed into equivalent $z$ statistics for display purposes. Regions modulated in each period (cue, delay, target) were identified on the main effect of Time (Frames 1–8) voxel-wise $F$ map (Figure 2, Cue, Target, Delay). Regions that were more active for invalid than valid targets were identified on the interaction of Time (Frames 1–8) × Target Type (valid, invalid) voxel-wise $F$ map (Figure 2, Validity). The effect of cue direction (left, right), delay direction (left, right), visual field of the target (left, right), and target validity (valid, invalid) was assessed using regional ANOVAs on regions selected on the appropriate voxel-wise $F$ maps with a cut-off of $z = 4.0$.

## Note

1. An alternative interpretation is that these cortical regions code for locations in both visual fields (see Perry & Zeki, 2000).

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