Orienting Attention to Locations in Perceptual Versus Mental Representations

A. C. Nobre[1], J. T. Coull[2,*], P. Maquet[2], C. D. Frith[2], R. Vandenberghe[3,†], and M. M. Mesulam[3]

Abstract

■ Extensive clinical and imaging research has characterized the neural networks mediating the adaptive distribution of spatial attention. In everyday behavior, the distribution of attention is guided not only by extrapersonal targets but also by mental representations of their spatial layout. We used event-related functional magnetic resonance imaging to identify the neural system involved in directing attention to locations in arrays held as mental representations, and to compare it with the system for directing spatial attention to locations in the external world. We found that these two crucial aspects of spatial cognition are subserved by extensively overlapping networks. However, we also found that a region of right parietal cortex selectively participated in orienting attention to the extrapersonal space, whereas several frontal lobe regions selectively participated in orienting attention within on-line mental representations. ■

INTRODUCTION

Attention biases the selection of targets according to changing motivation and volition to guide perception and action. To date, the extensive research on attention has focused on the selection of items located in the extrapersonal world. However, as humans, much of our world is internal. We constantly build and manipulate mental representations based upon experiences and expectations. It may be equally important, therefore, to direct attention within these internalized representations. Orienting to mental representations of extrapersonal space is a common aspect of our daily activities. Some examples are looking back at a relevant target in the room after having been distracted or reaching toward your coffee cup on the desk while not breaking gaze from the computer monitor.

Here we used event-related functional magnetic resonance imaging (efMRI) to investigate the neural system involved in orienting spatial attention to previous stimulus events held on-line within internalized memory representations, and to compare it with the neural system involved in orienting spatial attention to upcoming extrapersonal events. This investigation was stimulated by several lines of research that have emphasized the close interplay between attentional orienting and working memory, the function that mediates the on-line maintenance and manipulation of mental representations for guiding behavior.

Attentional orienting and working memory are subserved by partially overlapping distributed neural systems. Spatial orienting to external events is coordinated by a distributed network including areas in the posterior parietal, lateral premotor and dorsal prefrontal, and cingulate cortices (Nobre, 2001; Mesulam, 1981, 1999). Overlap with the neural system underlying working memory occurs in the intraparietal sulcus and frontal eye fields (Awh et al., 1999; LaBar, Gitelman, Parrish, & Mesulam, 1999; McCarthy, 1995). Prefrontal regions, anterior to these areas of overlap, are additionally engaged during tasks requiring working memory.

The known anatomical overlap between neural systems involved in orienting attention and in working memory supports the functional similarities between the two cognitive domains (Awh & Jonides, 2001). Downing has shown that the contents of working memory can guide the orienting of attention to optimize performance in behavioral tasks (Downing, 2000). Similar patterns of activation and modulation have been reported in posterior extrastriate visual areas by attention and working memory (Awh, Anllo Vento, & Hillyard, 2000; Awh et al., 1999; Chelazzi, Miller, Duncan, & Desimone, 1993). Based on these types of observations, influential theoretical models posit a close link between attention and working memory (Desimone & Duncan, 1995; Baddeley, 1993).

The overlap between spatial attention and working memory also supports the intuitive notion of the ability to scan a working memory scene in a spatially addressed fashion in a similar way as a perceptual scene

[1]University of Oxford, [2]Institute of Neurology, [3]Northwestern University Medical School

[*]Current address: Laboratoire de Neurobiologie de la Cognition, Centre National de la Recherche Scientifique, Marseille, France

[†]Current address: Neurology Department, University Hospital Gasthuisberg, Louvain, Belgium

in the extrapersonal world. The neural mechanisms for orienting attention to locations in mental representations has not yet been investigated systematically, but the influence of spatial attention upon the access to and manipulation of mental representations is illustrated by the deficits of patients with left hemispatial neglect, a neurological syndrome characterized by a severe deficit of spatial attention. Some patients with this syndrome are unable to direct attention to the left side of internal representations while others cannot introduce the relevant detail into the left side of newly compiled mental representations (Bisiach & Luzzatti, 1978; Bisiach, Luzzatti, & Perani, 1979). Neglect of internal representations can sometimes occur in the absence of neglect for the extrapersonal space (Ortigue et al., 2001; Beschin, Basso, & Della Sala, 2000; Coslett, 1997; Guariglia, Padovani, Pantano, & Pizzamiglio, 1993), suggesting that the neural systems for orienting attention to external versus internal representations may differ, at least in part.

We developed an experimental task to reveal brain areas involved in orienting attention toward locations in mental representations (Figure 1). The task required retrieving the color of an item from a briefly presented array, where each quadrant contained one stimulus. In some conditions, spatially informative cues occurred seconds after the array had appeared and disappeared, pointing to the relevant quadrant location of the internalized representation from which the color should be retrieved. These *retrocues* oriented attention toward a specific location in the array that existed only as a mental representation in working memory. In other conditions, spatially informative precues preceded arrays and directed attention to one quadrant of the extrapersonal array, as in traditional investigations of attentional orienting (Posner, 1980). Orienting attention to locations in mental representations of previously presented stimulus arrays was compared to orienting attention to locations in upcoming perceptual arrays. The experimental paradigm built upon the work of Sperling (1960), who used spatial cues to prompt retrieval of items from immediately preceding arrays held in very short-term iconic memory.

The fact that spatial retrocues do orient attention to locations within on-line representations of arrays held in working memory was confirmed by an independent set of behavioral investigations (Griffin & Nobre, 2003). In these experiments, subjects were asked to determine whether a specific colored item had been present anywhere in a four-item array. Stimulus arrays were similar to those used in the present experiment. In spatially cued trials, spatially informative precues or retrocues were presented seconds before or after the array, respectively, predicting the likely location of the relevant colored item with 80% validity. In noncued trials, neutral precues and retrocues provided no information regarding the likely location of the relevant colored item. Valid spatial cues pointing to a match optimized behavioral performance relative to noninformative neutral cues. Spatially misleading invalid cues led to behavioral costs. Attentional benefits and costs were equivalent whether cues appeared before or after the array, showing that retrocues were just as potent as precues in optimizing behavioral performance.

In our present efMRI experiment, the spatial precue specified a focused spatial orientation toward one quadrant of an upcoming rectangular array. The retrocue instructed an equally focused spatial orientation toward one quadrant of an internal representation of the array held in working memory. Event-related analysis of fMRI data revealed brain areas activated by spatially informative precues and retrocues within the trials, controlling for aspects of cue processing that were unrelated to their spatial orienting nature (see Methods). We compared activations associated with the precue and retrocue to identify areas of common and differential engagement by the two types of attentional orienting. Areas of common activation helped to determine the neural substrates shared by the two types of attentional orienting whereas areas of differential activation helped to identify regions potentially involved in selective functions supporting the orienting of attention to extrapersonal locations versus their internal representations.

RESULTS

Behavioral Performance

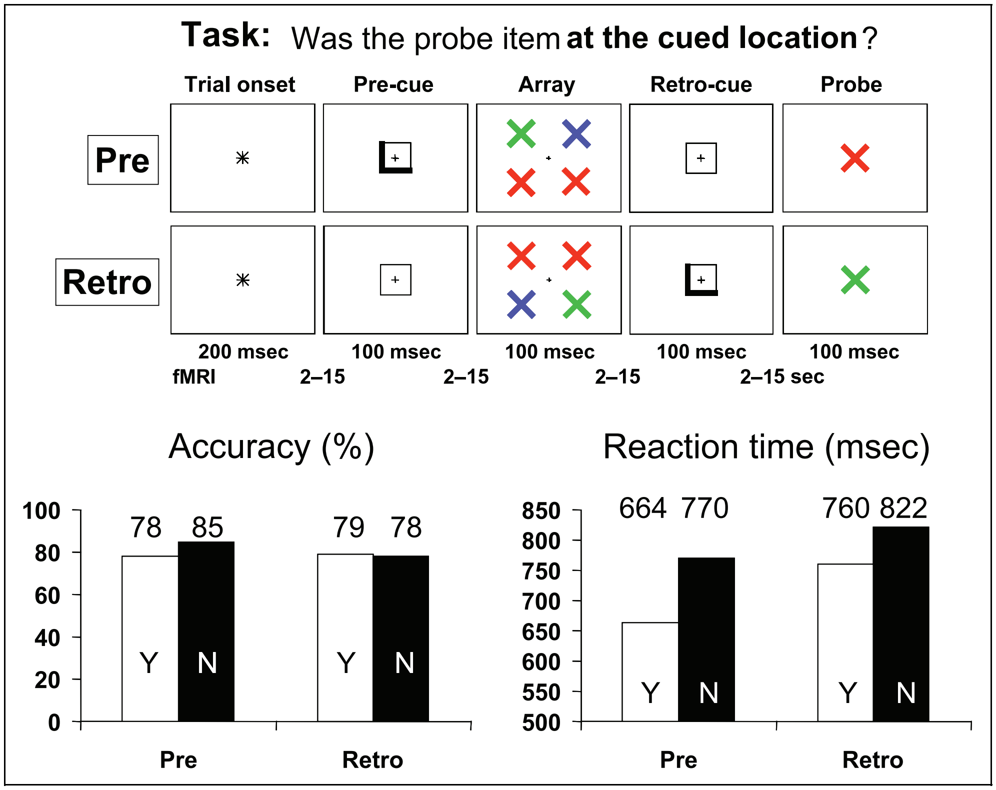
Participants performed the behavioral task adequately (see Figure 1). The average level of accuracy to decide whether the probe stimulus was the same color as the stimulus at the cued location was 80%. Accuracy during "yes" and "no" trials was statistically equivalent. The percentage of correctly identifying matching stimuli (hits in yes trials) was 79% and the percentage of correctly dismissing nonmatching probes was 81% (19% false alarms). Accuracy of task performance did not differ between precue (81%) and retrocue (79%) trials, in either yes or no trials. The location of the probe stimulus in the array during matching trials did not have a main effect on accuracy.

Reaction times were on average 754 msec. Participants were faster to identify matching probes in yes trials (712 msec) than to dismiss nonmatching probes in no trials (796 msec), $F(1,9) = 7.71$, $p < .05$. Reaction times appeared faster in precue trials (717 msec) than retrocue trials (791 msec), but this was not statistically significant, $F(1,9) = 4.36$, $p = .07$. Cue and response type did not interact. The location of the probe stimulus in the array during matching trials did not have a main effect on reaction times.

Brain Imaging

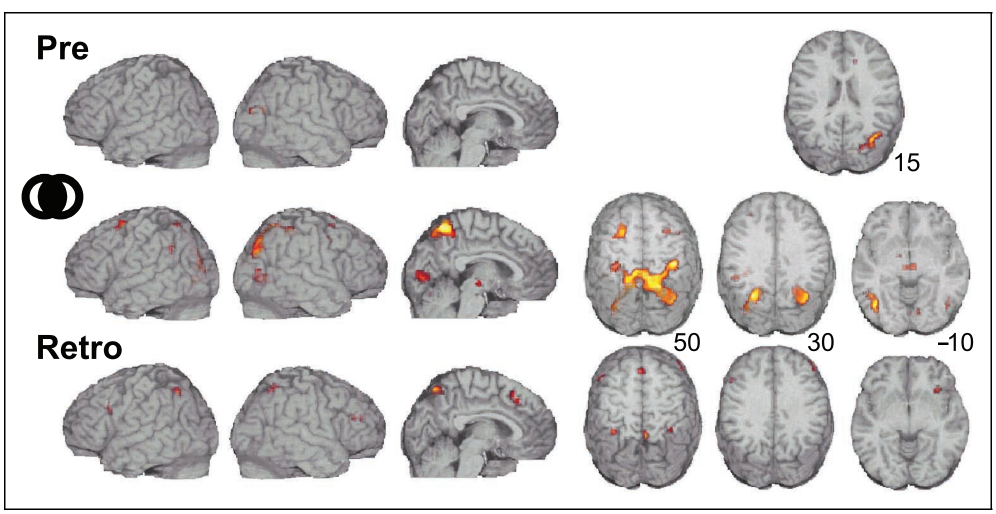
To isolate the brain activations related to the act of orienting spatial attention to an upcoming external

Figure 1. Top: Task schematic. All trials contained a stimulus that indicated the onset of a trial (200 msec), a precue (100 msec), an array of four differently colored crosses (100 msec), a retrocue (100 msec), and a probe stimulus (100 msec). In precue trials, the spatially informative orienting cue appeared 2–15 sec before the stimulus array. In retrocue trials, the spatially informative orienting cue appeared 2–15 sec after the stimulus array. In all trials, participants responded according to whether the probe stimulus had been present at the cued location (50% probability). Bottom: Behavioral results during brain scanning: accuracy and reaction-time measures in precue (pre) and retrocue (retro) trials when probe targets matched the item at the cued location (Y) and when probe targets differed from items at the cued location (N).



perceptual array or orienting spatial attention to the internal representation of a previous array, efMRI analysis concentrated on the hemodynamic response functions elicited by the precues and retrocues only. The brain activity engaged by the appearance of a spatially informative cue was, of course, not limited to activity specifically related to orienting spatial attention. The cue had to be perceived and its meaning decoded. It may have had alerting effects and engaged temporal expectancies. To minimize the contribution of brain activity unrelated to spatial orienting, the brain activity elicited by spatially uninformative neutral cues appearing at the equivalent phase of the trial was subtracted out (see Methods for fuller explanation). These neutral cues engaged similar nonspecific processes, such as visual analysis, decoding, alerting, and temporal expec-

Figure 2. Significant activations overlaid on different views of a standardized brain volume. From left to right, activations are shown on the left lateral surface, right lateral surface, midsagittal surface, and at progressively more inferior axial views. The numbers indicate the location of the axial slice in mm according to the atlas of Talairach and Tournoux (1988). The top row shows brain areas that were significantly more activated by precues than retrocues. The middle row shows the brain areas activated in common by both precues and retrocues. The bottom row shows brain areas that were significantly more activated by retrocues than precues.



tancies. The activations reported thus represent signal increases in brain areas tied to the spatially informative aspects of precues and retrocues.

Spatial precues and retrocues both triggered a shift toward or a zooming in on a relevant spatial location. In addition to the variable of interest, namely, the workspace of attentional orientation, spatial orienting by precues and retrocues also differed in some respects. In the case of spatial precues, orienting occurred with no items yet present. The spatial focus needed to be maintained in anticipation of the stimulus array. There might have been some biasing of neuronal activity in perceptual areas according to the spatial relevance or irrelevance of receptive fields. In the case of spatial retrocues, the spatial shift or zooming occurred already within a representational mnemonic context. The item at the relevant location could be selected, and items at irrelevant locations could be filtered. There was no need to maintain a spatial focus or to bias activity in perceptual areas in a sustained way. In this particular task, once the relevant object was selected, its identity or defining color feature had to be maintained on-line until the probe stimulus.

Spatial Orienting by Precues and Retrocues

Table 1 and Figure 2 summarize the results from analysis of common brain activations elicited by informative precues and retrocues relative to their neutral-cue controls. Orienting spatial attention to external perceptual and internal working-memory representations showed a large network of overlap involving the parietal, frontal, and visual cortices. Parietal activations were extensive and included the precuneus, superior parietal lobule, and several foci along the intraparietal sulcus bilaterally—from the intersection with postcentral sulcus to the intersection with the superior occipital gyrus. On the left hemisphere, activation also occurred in the inferior parietal lobule around the supramarginal gyrus. Frontal cortex was activated on the lateral dorsal prefrontal/premotor region bilaterally. Bilateral activation occurred at the intersection between the superior frontal sulcus and precentral sulcus, including the frontal eye fields (Petit, Clark, Ingeholm, & Haxby, 1997; Petit & Haxby, 1999; Paus, 1996) and the cortex just anterior to it (Haxby, Petit, Ungerleider, & Courtney, 2000; Postle, Zarahn, & D'Esposito, 2000; Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998). On the left hemisphere, an additional focus occurred ventrally in the precentral sulcus (Beauchamp, Petit, Ellmore, Ingeholm, & Haxby, 2001). Visual activation occurred bilaterally in the middle occipital gyrus. In the left hemisphere, additional foci occurred in the collateral sulcus. A focus was also observed in the posterior aspect of the calcarine sulcus, although this did not reach the $p < .001$ threshold for significance (corrected for false discovery rates).

Table 2 summarizes differences between activations elicited by informative precues and retrocues. Informative precues activated only one brain region in a specific manner. The focus was located in the posterior right angular gyrus, at the intersection of the inferior parietal lobule, superior temporal sulcus, and transverse occipital gyrus. This focus was adjacent to the overlapping parietal activations elicited by precues and retrocues.

Compared to precues, informative retrocues led to stronger activity in some of the commonly activated regions of parietal cortex—precuneus and the middle portion of the intraparietal sulcus bilaterally. Activations of brain areas that were specific for retrocue processing occurred in nonoverlapping regions of frontal cortex. Frontal activations occurred in the dorsomedial prefrontal/premotor cortex in the region of the pre-SMA, the intersection of the right mid-ventrolateral prefrontal cortex with anterior insula, right middle frontal gyrus, and left posterior inferior frontal sulcus.

DISCUSSION

The experimental design enabled us to investigate the neural system for orienting attention to spatial locations in internal representations and to compare it with the system for spatial orienting in the extrapersonal world. Participants were able to use retrocues, occurring seconds after the stimulus array disappeared, to orient attention to a specific location within an on-line representation of the array. Retrocues led to accuracy and reaction times that were equivalent to those associated with precues that oriented attention to a location in the extrapersonal space.

The behavioral results agree well with the initial findings of attentional orienting using retrocues (Griffin & Nobre, 2003). Participants found the task challenging, and did not perform at ceiling. Two factors may have contributed to the difficulty of this simple task. The participant must remember not only color, but also color–location conjunctions. Furthermore, the stimulus set was limited, and the same four colors occurred repeatedly over trials, causing strong proactive interference. Another possibly surprising outcome was the equivalent performance in precues and retrocue trials. One important factor contributing to this outcome may be that the number of items in the stimulus display was within the capacity of working memory (Wheeler & Treisman, 2002; Luck & Vogel, 1997). With arrays exceeding working memory capacity, it may not be possible to rely on retrocues for accurate performance. Studies manipulating the stimulus load in the array will yield useful knowledge about the constraints on attentional orienting to mental representations.

By separating each event within a trial by a long and variable time span, it was possible to measure the hemodynamic response functions triggered by individual precues and retrocues, and thus to identify brain activity that contributed to orienting attention to items in upcoming extrapersonal arrays versus previously seen arrays held in working memory.

Orienting attention to locations in external and internal representations activated a largely overlapping network of parietal, frontal, and occipital areas. The overlap occurred in brain areas where activations have previously

Table 1. Common Brain Activations to Precues and Retrocues

Brain Area	*x, y, z (mm)*	*z*	*k*
SPL and IPS			1123
Med SPL (precuneus)	+02, −57, +54	6.20	
	−09, −51, +51	5.27	
	−12, −54, +48	5.46	
R SPL (superior parietal gyrus)	+09, −60, +69	5.82	
	+12, −63, +60	5.83	
	+18, −72, +51	6.09	
R IPS (postcentral gyrus to superior occipital gyrus)	+39, −42, +51	6.14	
	+27, −54, +45	4.94	
	+27, −57, +60	4.71	
	+15, −60, +54	5.67	
	+27, −66, +39	4.27	
	+24, −72, +39	5.97	
	+33, −81, +24	5.07	
L SPL (superior parietal gyrus)	−21, −63, +54	5.24	
	−12, −72, +45	5.98	
L IPS (superior parietal lobule to superior occipital gyrus)	−15, −60, +54	5.09	
	−18, −75, +42	6.25	
	−30, −78, +30	5.90	
	−39, −75, +27	4.90	
	−33, −81, +27	5.68	
	−33, −84, +21	5.93	
L IPL (supramarginal gyrus)	−39, −48, +33	4.27	78
R PMC/PFC (precentral sulcus/superior frontal sulcus)	+30, +06, +57	4.27	24
L PMC/PFC (precentral sulcus/superior frontal sulcus)	−27, +00, +57	6.16	149
	−42, −03, +42	5.11	
R visual (middle occipital gyrus)	+48, −69, −03	4.34	72
L visual (middle occipital gyrus and collateral sulcus)	−45, −78, −03	6.12	109
	−45, −69, −09	5.70	
	−48, −57, −09	5.40	
Med visual (calcarine cortex, V1)*	+00, −87, −03	4.12	45
Brainstem	−06, −21, −09	4.21	19

($z > 4.20$, $p < .001$, FDR corrected).
FDR = false discovery rates, Med = medial, R = right, L = left, SPL = superior parietal lobule, IPS = intraparietal sulcus, IPL = inferior parietal lobule, PMC = premotor cortex, PFC = prefrontal cortex.
*Activation of V1 was not significant after correction for FDR.

Table 2. Differential Brain Activations to Precues and Retrocues

Brain Area	*x, y, z (mm)*	*z*	*k*
Precues > retrocues (z > 3.19, p < .05, FDR corrected; k > 5, p < .05, uncorrected)			
R IPTO (posterior angular gyrus)[a]	+33, −87, +15	4.24	62
	+33, −78, +15	3.90	
	+39, −72, +18	3.87	
Retrocues > precues (z > 3.19, p < .05, FDR corrected; k > 5, p < .05, uncorrected)			
Med SPL (precuneus)[b]	+03, −69, +51	4.89	21
R IPS[b]	+36, −57, +42	3.29	25
	+33, −57, +57	4.19	
L IPS[b]	−36, −63, +51	4.20	16
Med PMC/PFC (pre-SMA, superior frontal gyrus)[a]	−03, +24, +39	4.47	30
R ventral PFC/insula (inferior frontal gyrus/anterior insula)[a]	+36, +24, −12	4.37	11
R dorsolateral PFC (middle frontal gyrus)[a]	+51, +39, +21	4.23	6
	+48, +45, +21	3.68	6
L dorsolateral PFC (posterior inferior frontal sulcus)[a]	− 54, +21, +33	3.85	11

Precues > Retrocues = {[(spatial precue − neutral precue) − (spatial retrocue − neutral retrocue, p < .001)], masked by (spatial precue)}; Retrocues > Precues = {[(spatial retrocue − neutral retrocue) − (spatial precue − neutral precue)], masked by (spatial retrocue)}.

FDR = false discovery rates, Med = medial, R = right, L = left, SPL = superior parietal lobule, IPS = intraparietal sulcus, PFC = prefrontal cortex, IPTO = intersection of inferior parietal, posterior temporal, and occipital cortices, Pre-SMA = pre supplementary motor area.

[a]Selective activations. [b]Enhancements of common activations.

been reported during visual spatial orienting tasks (Yantis et al., 2002; Beauchamp et al., 2001; Hopfinger, Woldorff, Fletcher, & Mangun, 2001; Nobre, 2001; Kastner & Ungerleider, 2000; Gitelman et al., 1999; Corbetta, 1998; Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000). Selectivity occurred in the right inferior parietal cortex for orienting attention to locations in the external world, and in prefrontal cortex for orienting attention to locations in internal representations.

The extensive neuroanatomical overlap of activations may indicate that the orienting of attention in the perceptual and working-memory domains shares common substrates. One such area serving both types of orienting may be located in the posterior parietal region. In this part of the brain, activations common to the precue and retrocue were located mainly in superior parietal lobule and intraparietal sulcus, regions that have been proposed to mediate shifts of the attentional focus in spatial attention tasks (Yantis et al., 2002; Vandenberghe, Gitelman, Parrish, & Mesulam, 2001a).

A strong relationship between the networks for attention (spatial as well as nonspatial) and working memory has been shown previously (Awh et al., 1999; Awh & Jonides, 2001; LaBar et al., 1999). Many theories of attention or working memory acknowledge explicitly the interplay between these two cognitive domains (Awh & Jonides, 1998, 2001; Smith & Jonides, 1999; Desimone & Duncan, 1995; Baddeley, 1993). Working memory has been proposed to guide attentional selection of stimuli in the extrapersonal world (Downing, 2000; Desimone & Duncan, 1995). Shifts of attention have been proposed to sustain working memory (Awh & Jonides, 1998, 2001). Here we show a new sort of relationship where the contents of working memory are queried in a spatially directed way.

Differential activations by precues and retrocues helped to identify candidate areas that may be specialized for each mode of spatial orienting. The right inferior posterior parietal area, preferentially activated by the precues relative to the retrocues, could participate in maintaining the spatial focus of attention in a salience map and/or provide top–down signals to bias processing in more ventral visual areas where initial stimulus encoding occurs. The salience map and associated top–down signals could bolster processing of upcoming stimuli at relevant locations and/or inhibit processing from irrelevant locations (Wojciulik & Kanwisher, 1999). These functions would have been especially prominent in our task, in which the precue could precede the array by several seconds and therefore induced a relatively prolonged interval of directionally specific expectancy.

This interpretation is consistent with brain-imaging findings implicating this region in the maintenance of a spatial focus during tasks of attention (Vandenberghe, Gitelman, Parrish, & Mesulam, 2001b) and working memory (Awh & Jonides, 2001). Distorted salience maps or biasing functions could also contribute to the representational deficits associated with this brain area in neglect and extinction (Karnath, Himmelbach, & Kuker, 2003; Driver & Mattingley, 1998; Friedrich, Egly, Rafal, & Beck, 1998; Rafal, 1998; Vallar & Perani, 1986; Mesulam, 1981, 1999; Heilman & Van Den Abell, 1980). Further experiments should examine whether the role of this brain area is specific to the spatial domain or whether it serves a more general function for sustaining attentional foci and biasing processing along nonspatial stimulus attributes as well.

The retrocues selectively activated multiple frontal regions—dorsomedial prefrontal cortex in pre-SMA, right middle frontal gyrus, right ventrolateral prefrontal cortex adjacent to the anterior insula, and left posterior inferior frontal sulcus. This pattern of frontal areas is consistent with previous investigations of working memory (D'Esposito, Postle, & Rypma, 2000; Haxby et al., 2000; Owen, 2000; Smith & Jonides, 1999; McCarthy et al., 1996) and long-term memory (Ranganath, Johnson, & D'Esposito, 2003), and more generally in tasks that involve executive processes to achieve behavioral goals (Duncan et al., 2000; Miller, 2000; Miller & Cohen, 2001). In the present task, prefrontal activations could not have been related to decision-making or response selection. Decisions could only be made and responses selected upon the appearance of the final probe stimulus. Nor could the activity reflect the higher memory load in the retrocue trials, since we measured the signal increase elicited by the retrocue and not by the preceding delay (see also Rypma, Berger, & D'Esposito, 2002; Jha & McCarthy, 2000). Candidate functions, which characterized the act of orienting spatial attention within an on-line representation of the array, are selecting a target item from among distractors (Thompson Schill et al., 2002), possibly inhibiting the representations of distractors and holding on-line target identity or color of the target. Frontal regions may also have participated specifically in the act of shifting or zooming spatial attention to locations in internal representations per se. If so, this would suggest that shifting or zooming the spatial focus of attention in the absence versus presence of a memory context recruits highly overlapping but not coextensive systems. Further teasing apart of the exact functional contributions of the different prefrontal areas during orienting to internal representations will require future experimentation.

Orienting attention to locations in internal versus external representations also led to higher activity in some parietal areas commonly engaged by both precues and retrocues. Such activations occurred in the middle portion of the intraparietal sulcus bilaterally and in medial superior parietal lobule in the precuneus region. The cortex around the intraparietal sulcus is typically involved in visual spatial orienting to extrapersonal events (Yantis et al., 2002; Beauchamp et al., 2001; Corbetta et al., 2000; Corbetta, Kincade, & Shulman, 2002; Gitelman et al., 1999; Nobre et al., 1997). Enhanced activation of its middle portion during orientation to internal spatial representations points to functional heterogeneity in this large cortical region (Corbetta & Shulman, 2002; Donner et al., 2002). The intraparietal area that was more intensely activated by retrocues may be analogous to area LIP in the macaque, where individual neurons show sensitivity to intended eye movements, attentional monitoring, and working memory (Sereno, Pitzalis, & Martinez, 2001; Colby, Duhamel, & Goldberg, 1996).

The precuneus has been associated with mental imagery (Ishai, Ungerleider, & Haxby, 2000; Ghaem et al., 1997; Fletcher, Shallice, Frith, Frackowiak, & Dolan, 1996), a function highly related to attention both functionally (Frith & Dolan, 1997; Ishai & Sagi, 1995) and neuroanatomically (Ishai et al., 2000). Mental imagery may have played an important role during orienting to internalized representations in the present task, where retrocues might trigger the mental image of the previous array to serve as a substrate for attentional orienting. Greater activation of the precuneus in conditions that emphasize working memory relative to attentional orienting to perceptual arrays is consistent with previous observations (LaBar et al., 1999).

In summary, we have introduced a novel experimental paradigm to investigate the relationship between visual spatial attention to extrapersonal events and to their mental representations in working memory. Although these relationships have been acknowledged for a long time, there have been few efforts to dissociate attentional orienting functions from working memory functions by using matched stimulus and response parameters and in the same set of participants. In the present experiment, we have provided additional confirmation that attentional orienting is achieved by a network of posterior parietal and frontal areas. The frontal areas involved in orienting to extrapersonal events are located in premotor and dorsal prefrontal cortex. More anterior prefrontal regions become selectively engaged when the task involves the orienting of attention and selection of targets within on-line representations. Activity in a subset of parietal areas is also modulated specifically by this sort of attentional activity. These prefrontal and parietal activations were not linked to decision-making or response selection.

Further use of this experimental paradigm will help to explore how selective attention operates within internalized mental representations (Griffin & Nobre, 2003). Its variations will help to identify the selective anatomical substrates of attentional orienting subtypes and components of working memory. To our knowledge, this is the first description of the functional neuroanatomy linked to the orientation of attention with the "inner eye."

METHODS

Participants

Ten healthy young volunteers (aged 22–41; 5 women) performed a behavioral task involving shifts of attention to locations in extrapersonal arrays or their internal mental representations during brain scanning using fMRI. The study had approval from the local ethics committee. Participants gave written informed consent before the study.

Behavioral Tasks

Figure 1 illustrates the task. Participants viewed arrays of four differently colored crosses either preceded or followed by spatial cues, and made a delayed decision about the color of the item at the cued location in the array. There were two types of trial: precue and retrocue trials. In precue trials, informative spatial cues appeared before the array, enabling participants to orient covertly to the relevant location in the upcoming perceptual array. In the retrocue trials, informative spatial cues appeared after the array, requiring participants to orient toward the relevant location in the array held as a mental representation in working memory. Precue and retrocue trials were randomly intermixed.

The background display, consisting of a fixation point on a black screen, was present throughout the task. Participants were instructed to maintain central fixation throughout the experiment. Each trial contained the same general sequence of five events. Events were separated by a random interval ranging between 2 and 15 sec. (1) An asterisk presented at the center of the screen (200-msec duration) marked the start of a trial. (2) A central square (1° width) appeared foveally (100-msec duration). The brief highlighting of its sides provided the precue. In precue trials, two adjacent sides of the square brightened, forming an arrowhead pointing at one of the peripheral locations and indicating the relevant location in the upcoming array. In retrocue trials, all the sides brightened, providing no spatial information. (3) A visual array appeared briefly (100-msec duration), consisting of four differently colored crosses (1° height and width; red, blue, green, and yellow) presented simultaneously, each in one peripheral quadrant location (centered at 3° vertical and horizontal eccentricity). (4) The central square reappeared with highlighted sides (100-msec duration), providing the retrocue. In precue trials, all sides of the square brightened, providing no spatial information. In retrocue trials, two adjacent sides brightened, forming an arrowhead pointing at one of the peripheral locations and indicating the relevant location in the past array. (5) Finally, one colored cross (probe) appeared foveally (1° width and height; red, blue, green, or yellow), prompting the decision. Participants made a choice response indicating whether the probe item matched in color the item at the cued location in the array (yes) or not (no). There were an equal number of yes and no trials.

The key to the analysis and interpretation of this experiment was the ability to measure brain activity to the individual events within single trials. To achieve this, the intervals between events were of sufficient span and variability (2–15 sec) to enable the resolution of their individual hemodynamic response functions (Friston et al., 1998). To keep the total task duration to a reasonable length, the distribution of intervals was skewed toward the short interval trials. The median interval was of 5 sec. On average, a trial lasted 25 sec, with trial duration ranging from 10 to 70 sec depending on the randomized intervals between events.

The task was performed during fMRI scanning, after the participants had been instructed and had performed a few practice trials on a computer outside the scanning room to ensure understanding of the task. Precue and retrocue trials were intermixed during task performance. Four blocks of 24 trials each were performed successively over separate brain-imaging runs. Each experimental block lasted approximately 10 min. The four blocks contained different randomized orders of trial (12 precue, 12 retrocue) and response (12 yes, 12 no) types. The directions of informative precues or retrocues (top-left, top-right, bottom-left, bottom-right) were distributed as uniformly as possible between trial and response types. Each trial in a block contained a unique arrangement of the four colors in the array. Participants completed the four blocks, each in a different order.

Participants lay supine in the MRI scanner. Stimuli were back-projected onto a semiopaque screen placed 30 cm in front of them. Participants viewed the display through tilted mirrors placed over their eyes. They responded with their right index and middle fingers using an MRI-compatible response box.

Behavioral accuracy and reaction-time measures were analyzed using repeated-measures analysis of variance (ANOVA). The ANOVAs tested for possible effects of: trial type (precue, retrocue), response (yes, no), stimulus location along the horizontal axis (left, right), and stimulus location along the vertical axis (top, bottom).

Event-related Functional Magnetic Resonance Imaging

Magnetic resonance images were obtained with a 2-T Magnetom Vision whole-body scanner (Siemens, Erlangen, Germany). Functional measures sensitive to the blood oxygenation level-dependent contrast (Kwong et al., 1992; Ogawa et al., 1992) were obtained using single-shot echo planar T2*-weighted imaging (TE = 40 msec, TR = 2.13 sec). Twenty-eight 4-mm slices (64 × 64-voxel matrix, with 3 mm^2 in-plane resolution) covered the entire cortex. The cerebellum was not fully sampled in the image set. Participants completed four experimental runs, each containing 302 image sets. The first five image sets were collected in the absence of any task to allow the signal intensities to saturate and were discarded from subsequent analysis. Over the subsequent 297 images (633 sec), participants performed one block of 24 randomly intermixed trials. Structural magnetic resonance images were obtained during the same experimental session using a high-resolution T1-weighted sequence ($1 \times 1 \times 1.5$ mm resolution).

Data were processed and analyzed using Statistical Parametric Mapping (SPM 99, Wellcome Department of Cognitive Neurology, London, UK) implemented in MATLAB (MathWorks, Natick, MA). Functional scans were realigned with one another to correct for artifacts involving head movement. Structural scans were spatially coregistered with the realigned functional images (Friston, Frith, Frackowiak, & Turner, 1995) to enable the localization of functional activations relative to the structural anatomy. Functional and structural images were translated into a normalized and standardized anatomical framework, using the averaged-brain template of the Montreal Neurological Institute (Collins, Neelin, Peters, & Evans, 1994), which approximates the stereotactic atlas of Talairach and Tournoux (1988). Functional images were spatially smoothed using an 8-mm Gaussian kernel to conform the data to a Gaussian model and to accommodate for intersubject anatomical variability (Hopfinger, Buchel, Holmes, & Friston, 2000). The resulting spatial resolution was about 11 mm^3 at full width at half maximum. The time series was temporally filtered to remove artifactual sources of slow drift signals (high-pass filter: 231 sec) and high-frequency temporal autocorrelations between successive measurements (low-pass filter: 4 sec).

The neural response triggered by each trial event was modeled using a canonical hemodynamic response function and its temporal derivative. Statistical comparisons between experimental factors used linear contrasts in a random-effects analysis (Friston, Holmes, & Worsley, 1999), after scaling for global signal values in individual subjects. The random-effects model enables the results obtained over the sample of participants to be generalized to the population at large. Statistical parametric maps of the t statistic over voxels of brain images were generated and transformed into maps of corresponding z values. The resulting foci of activations were characterized in both peak height and spatial extent. The significance of each region was estimated using distributional approximations from the theory of Gaussian fields (Worsley, Evans, Marrett, & Neelin, 1992).

Statistical analyses of the cue stimuli identified brain areas participating in orienting spatial attention to locations in external space and/or to locations in internal representations in working memory. Brain areas participating in orienting spatial attention to locations in perceptual arrays were defined as the regions that were significantly more activated by informative spatial precues (in precue trials) than by uninformative neutral precues (in retrocue trials). To rule out contributions from brain areas of significantly increased deactivations to the uninformative neutral precues, only brain regions significantly activated by the informative spatial precue event were considered. This was achieved by creating a binary mask of the precue activations, where all voxels that were not significantly activated ($p < .001$ uncorrected) were set to zero. The contrast of interest was then multiplied by the binary mask, a procedure equivalent to the inclusive-masking option in SPM. Thus, the external orienting condition was calculated as: [(spatial precue − neutral precue), masked by spatial precue]. Brain areas participating in orienting spatial attention to locations in mental representations of the array were defined in an analogous fashion: [(spatial retrocue − neutral retrocue), masked by spatial retrocue]. Brain areas that were activated in common by both the external and internal spatial orienting conditions were calculated as the intersection of activations in the external and internal conditions: {[(spatial precue − neutral precue), masked by (spatial precue)] and [(spatial retrocue − neutral retrocue), masked by (spatial retrocue)]. Brain areas preferentially activated by external relative to internal orienting conditions were calculated as: {[(spatial precue − neutral precue) − (spatial retrocue − neutral retrocue, $p < .001$)], masked by (spatial precue)}. Brain areas preferentially activated by internal relative to external orienting conditions were calculated as: {[(spatial retrocue − neutral retrocue) − (spatial precue − neutral precue)], masked by (spatial retrocue)}.

An activation was considered significant if both its cluster size was significant ($p < .05$ uncorrected) and the magnitude of its peak value was significant at $p < .05$ corrected for false discovery rates (Genovese, Lazar, & Nichols, 2002). Also reported are activations with peak values significant at $p < .05$ corrected for multiple comparisons over the entire brain volume. In the case of conjunction analyses, there was no available cluster-size statistic, and a threshold of false discovery rate of $p < .001$ was used instead.

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Reprint requests should be sent to Anna Christina Nobre, Brain and Cognition Lab, Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, UK, or via e-mail: kia.nobre@psy.ox.ac.uk.

The data reported in this experiment have been deposited in the fMRI Data Center (http://www.fmridc.org). The accession number is 2-2004-115RA.

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