Biasing the Organism for Novelty: A Pervasive Property of the Attention System

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Abstract: Although the functional and anatomical independences between the orienting and the executive attention networks have been well established, surprisingly little is known about the potential neural interaction between them. Recent studies point out that spatial inhibition of return (IOR), a mechanism associated with the orienting network, and nonspatial inhibition of return, a mechanism associated with the executive

such as when a person allocates attention to a predefined spatial location before a target appears. The orienting attention network has been associated with areas of dorsal frontoparietal cortex [Corbetta et al., 2000; Fan et al., 2005; Kincade et al., 2005; Yantis et al., 2002]. Executive attention is needed in situations that involve resolving conflicts [Botvinick et al., 2001; MacDonald et al., 2000], top-down suppression of task-irrelevant representations in working memory [Gazzaley et al., 2005, 2007], and implementation of task sets [Dosenbach et al., 2006] etc. The executive network has been associated with prefrontal regions [Botvinick et al., 2001; Fan et al., 2003a, 2005]. Although there has been extensive evidence suggesting the functional and anatomical independences between the executive and the orienting networks, it remains an outstanding and critical issue how the attentional networks interact for coherent, goal-directed behavior. In this fMRI study, we aim at investigating the neural interaction between the executive and orienting networks.

The orienting network of the attention system counts with a spatial inhibitory mechanism that helps the organism to avoid reexamining previously attended locations and biases the organism to novel locations. This mechanism manifests in the Posner's spatial cuing task, in which a peripheral cue is first presented to attract spatial attention to the cue location. Responses to a target immediately appearing at the cued location, compared to responses to a target at an uncued location, are both faster and more accurate. However, if the cue-target stimulus onset asynchrony (SOA) is longer than 300 ms and the cue is not informative with regard to target location, responses to the target at the cued location are delayed, compared with responses to the target at an uncued location [Klein, 2000; Posner and Cohen, 1984; Posner et al., 1985]. This inhibitory effect is termed inhibition of return (IOR), which slows down attentional reorienting to the previously attended (cued) location and thus increases the efficiency of visual search. Neurally, previous human brain imaging studies reveal that a dorsal frontoparietal network, including bilateral frontal eye field (FEF) and superior parietal cortex, is activated by spatial IOR at long SOA, representing the spatial inhibitory mechanism in the orienting network [Lepsien and Pollmann, 2002; Mayer et al., 2004a,b; Muller and Kleinschmidt, 2007; Rosen, 1999; Zhou and Chen, 2008].

Attention can also be addressed to non-spatial target features and this process may involve the executive network. For instance, in comparison with passive viewing, selectively attending to one attribute of multidimensional targets, which could vary in shape, color and movement, increases neural activity not only in brain areas specialized to process the attribute, but also in areas of the executive attention network [Corbetta et al., 1991]. Thus, the executive network is involved in top-down control of selecting nonspatial properties of objects. Moreover, the executive network exhibits, in the nonspatial domain, inhibitory functions that mimic what IOR does in the spatial domain [Fuentes and Santiago, 1999; Fuentes et al., 1999a; Zhou

and Chen, 2008]. For example, in a semantic priming task in which an intervening stimulus is presented between a prime and a target and the target is related or unrelated to the prime, the priming effect can be either facilitatory or inhibitory, depending on the properties of the intervening stimulus. When the intervening stimulus is a string of letter X, related targets produced *shorter* RTs than unrelated targets. When the intervening stimulus is a word of a different category from that of the prime and target, related targets produced *longer* RTs than unrelated targets. The latter *semantic inhibition* is sort of inhibition of return in the semantic space [Fuentes et al., 1999a]. The intervening stimulus serves as a neutral cue to attract attention away from the semantic category of the cue, making attention difficult to return to the category of the cue. Similarly, in a color discrimination task in which three consecutive color patch stimuli are presented at the same, central location, the first color patch (the cue) and the third color patch (the target) could have either the same or different colors. The intervening color patch has a color different from that of either the cue or the target, serving as a "neutral attractor" to draw attention away from the color of the cue. It is found that the response time to the target is significantly slower when the cue and the target have the same color than when they have different colors [Law et al., 1995]. This color-based IOR corresponds to neural activity in left prefrontal cortex [Zhou and Chen, 2008], indicating the involvement of the executive network in nonspatial IOR.

It has been broadly accepted that *episodic retrieval of inhibitory label* underlies a variety of executive attentional processes, including nonspatial IOR [Grison et al., 2005; Tipper et al., 2003] and negative priming [Egner and Hirsch, 2005; Neill, 1997; Neill et al., 1992]. With regard to nonspatial IOR, for example, the onset of a cue in a visual scene is represented as a coherent episode or object file [Kahneman et al., 1992; Lupiañez and Milliken, 1999]. If there is an intervening stimulus between the cue and the target, attention shifts away from the episodic representation of the cue to a new episodic representation of the intervening stimulus. More importantly, the episodic representation of the cue is then tagged with an inhibitory label [Grison et al., 2005; Tipper et al., 2003]. The subsequent onset of a target, which is similar to the cue, cues the retrieval of the episodic representation of the cue together with its associated inhibitory label. The episodic retrieval of the inhibitory label causes interference between two episodes with conflicting contextual information. Thus, responses to the old (repeated) object are slowed down and the attention system is biased to encode novel information. Since the episodic retrieval process and the postretrieval evaluating process of episodic memory implicate prefrontal cortex [Eldridge et al., 2000; Henson et al., 1999, 2000; Rugg et al., 2002, 2003], the episodic retrieval of inhibitory label underlying the nonspatial IOR effect can be attributed to the prefrontal executive network; the bias for novelty is thus also a property of the executive network [Fuentes and Santiago, 1999].
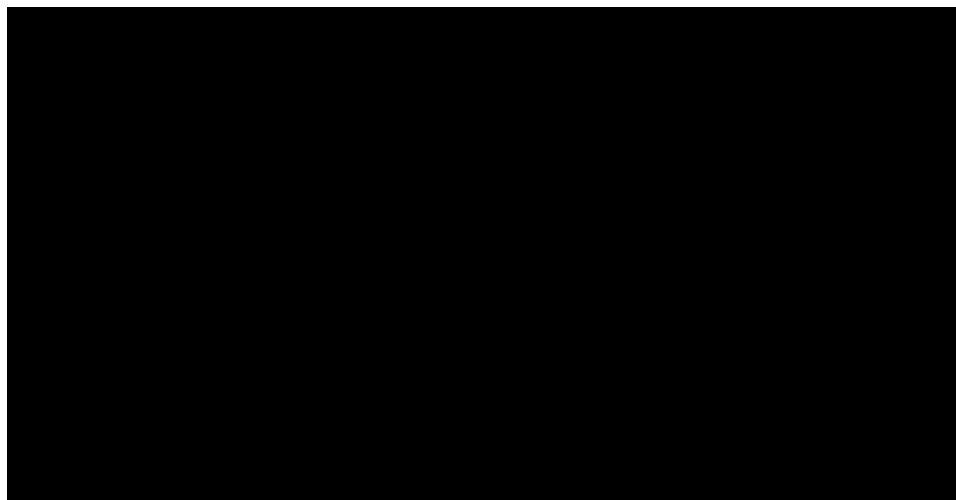
Figure 1.

Sequence of the stimuli and the orthogonal cross between location and color cue validity. A colored peripheral cue was first presented to exogenously attract attention to a peripheral spatial location and a color representation. It was uninformative with regard to either the spatial location or the color of the subsequent target. An intervening neutral stimulus between the cue and the target was then presented at the central location, attracting attention away from the spatial location and the color representation of the cue. A target of either the same (old) or different (novel) color from the cue was then presented at either the old (cued) or the novel (uncued) spatial location.

By combining behavioral and neuroimaging techniques here we investigate how spatial and nonspatial IOR, associated to the orienting and executive attention networks respectively, coactivate and interact to select novel information. We combined the spatial and nonspatial (color) IOR paradigms and manipulated orthogonally the cue-target correspondence along both spatial and color dimensions (see Fig. 1). To further control the task-relevance of spatial and nonspatial features, we asked participants to perform a spatial (localization) task and a nonspatial (color discrimination) task on the same visual inputs. Evidence from previous behavioral studies shows that in a spatial tasks, only spatial IOR, but no nonspatial IOR, occurs. In contrast, in a nonspatial tasks, spatial IOR and nonspatial IOR coexist and interact [Chen et al., 2007; Fuentes et al., 1999a]. Moreover, in nonspatial tasks, spatial IOR occurs only when the nonspatial identity of the target is novel with regard to the cue, and nonspatial IOR occurs only when the spatial location of the target is novel with regard to the cue. These behavioral results suggest that spatial IOR and nonspatial IOR complement each other in biasing the attention system for novelty under specific task demands. When nonspatial IOR is not operative, i.e., when a novel object appears, spatial IOR slows down responses to the object if it appears at the old (cued) spatial location. When spatial IOR is not functioning, i.e., when an object appears at a novel (uncued) spatial location, nonspatial IOR slows down responses to the object if it is an old (repeated) object. We thus predict that in the nonspatial,

color discrimination task, the orienting neural network is involved in slowing down responses to the previously attended spatial location only when the cue and the target differ in nonspatial features (i.e., when the nonspatial IOR mechanism in the executive network is not functioning), and the executive network is involved in slowing down responses to the previously attended nonspatial representations only when the cue and the target differ in spatial locations (i.e., when the spatial IOR mechanism in the orienting network is not functioning). On the other hand, in the spatial, localization task, since there exists only spatial IOR, but not nonspatial IOR, we predict that the orienting network is involved in spatial IOR, independently of the cue-target correspondence along the nonspatial dimension.

MATERIALS AND METHODS

Participants

Twelve undergraduate and graduate students (six females, 21–25 years old) participated in the study. They were all right handed and had normal or corrected-to-normal vision without color blindness or weakness. Color vision was assessed by the Ishihara Color Test when the participants were recruited [Ishihara, 1917]. All the participants gave written informed consent before fMRI scanning in accordance with the Helsinki declaration. None of them had history of neurological or psychiatric disorders. This

study was approved by the Academic Committee of the Department of Psychology, Peking University.

Stimuli and Experimental Design

The stimuli were presented through a LCD projector onto a rear projection screen located behind the participants' head. Participants viewed the screen through an angled mirror on the head-coil. Each trial consisted of a serial of displays of black boxes which were presented on a white background (see Fig. 1). Each box measured 1.5 × 1.5° in visual angle. The center-to-center distance between two adjacent boxes was 5° in visual angle.

For each trial, a red or blue patch was first presented in one of the peripheral boxes for 100 ms, serving as a cue along both the spatial and the color dimensions. The cue was uninformative with regard to either the location or the color of the target, in the sense that the target shared color or spatial location with the cue in 50% of the total trials. After an interval of 200 ms, a green color patch was presented in the central box for 100 ms, which served on the one hand as a central cue in the spatial dimension to attract participants' attention away from the cued peripheral location and on the other hand as a neutral cue in the color dimension to attract participants' attention away from the color representation of the cue. After another interval of 250 ms, 350 ms or 450 ms, a red or blue target patch appeared for 300 ms in either the old (cued) or the novel (uncued) peripheral box. The cue and the target could be either a red or a blue square, and they could have either the same or different color. The neutral central cue between the cue and the target was always a green square. Participants were asked to perform a localization task (left/right) or a color discrimination task (red/blue) on the target. The purpose of using variable SOAs between the cue and the target at the long SOAs was to prevent participants from forming time-based expectations towards the target. Since the three levels of SOA were applied for all the experimental conditions, any potential confound evoked by the variable SOAs should be cancelled out when the experimental conditions were directly compared.

Participants were asked to fixate the central box all the time. The timing and procedure of events, i.e., the bottom-up input stimuli, were the same in the localization and color discrimination blocks. Participants used their index and middle fingers to make responses. To make sure that the behavioral and neural effects we observed are independent of the response hands, we asked half of the participants to respond with their right hand and the other half with the left hand. The arrangement of the two response buttons on the response pad was vertical along the Y axis, i.e., orthogonal to the left-right X axis of stimuli, in order to avoid possible confounds with the Simon effect [Lu and Proctor, 1995; Simon, 1969]. In the localization task, participants were asked to localize the target as quickly and as accurately as possible, irrespective of the color of the target, by pressing one button with one finger if the target was

presented at the left peripheral location, and the other button with another finger if the target was presented at the right peripheral location. In the color discrimination task, participants were instructed to discriminate the color of the target, irrespective of the location of the target, by pressing one button with one finger if the color of the target was red, and the other button with the other finger if the color of the target was blue. The mapping between the two response buttons and spatial (left-right) and nonspatial (red-blue) attributes of the target was counterbalanced across participants. Since two buttons on the response pad were used to respond to both the position and the color of the targets, and participants alternated between localization and color discrimination tasks within a session of fMRI scanning, there existed an overlap of stimulus–response mapping in the color and location domains. However, the correspondence between color-related and location-related response assignments (congruent vs. incongruent) was fully counterbalanced within each of the four experimental conditions (Supporting Information, Fig. 1).

Therefore the experiment used a 2 (type of task: localization vs. color discrimination) × 2 (location cue validity: old vs. novel) × 2 (color cue validity: old vs. novel) mixed within-participant design. Participants alternated between localization and color discrimination blocks. Furthermore, event-related procedures, including the jittering of sequential trials, were embedded within each block. Each block began with a 3-s visual instruction, telling participants the type of task in that block. There were 8 experimental conditions in the factorial design and 48 trials for each condition. In total, there were 512 trials, consisting of 384 experimental trials and 128 null trials. In the null trials, only a frame of three horizontally arranged boxes was displayed. For the localization and the color discrimination tasks, respectively, null trials and trials from different conditions were randomly mixed and then divided into different test blocks. The temporal order of trials was randomized for each participant individually in order to avoid potential problems of unbalanced transition probabilities. Within each block, 16 trials were randomly mixed together. The intertrial-intervals (ITIs) were jittered from 2,000 to 3,000 ms (2,000 ms, 2,250 ms, 2,500 ms, 2,750 ms, 3,000 ms). The duration of each block was 40 seconds. There were 16 localization blocks and 16 color discrimination blocks alternating with each other. All the participants completed a training section of 15 min outside the scanner before the scanning.

fMRI Data Acquisition

A 3T Siemens Trio system with a standard head coil at Beijing MRI Center for Brain Research was used to obtain T2*-weighted echo-planar images (EPI) with blood oxygenation level-dependent (BOLD) contrast (matrix size: 64 × 64, pixel size: 3.4 × 3.4 × 5 mm³). Twenty-four transversal slices of 4 mm thickness that covered the whole brain

were acquired sequentially with a 1-mm gap (TR = 1.5 s, TE = 30 ms, FOV = 220 mm, flip angle = 90°). There was one run of functional scanning which included 945 EPI volumes. The first five volumes were discarded to allow for T1 equilibration effects. No additional high-resolution anatomical images were acquired.

Statistical Analysis of Imaging Data

Data were preprocessed with Statistical Parametric Mapping software SPM5 (Wellcome Department of Imaging Neuroscience, London, http://www.fil.ion.ucl.ac.uk). Images were realigned to the first volume to correct for interscan head movements. For each participant, the extent of head movements did not exceed one voxel size (2 mm × 2 mm × 2 mm). Then, the mean EPI image of each participant was computed and spatially normalized to the MNI space [Collins et al., 1994; Evans et al., 1994; Holmes et al., 1998], using the "unified segmentation" function in SPM5. This algorithm is based on a probabilistic framework that enables image registration, tissue classification, and bias correction to be combined within the same generative model. The resulting parameters of a discrete cosine transform, which define the deformation field necessary to move individual data into the space of the MNI tissue probability maps [Evans et al., 1994], were then combined with the deformation field transforming between the latter and the MNI single participant template. The ensuing deformation was subsequently applied to individual EPI volumes. All images were thus transformed into standard MNI space and re-sampled to 2 × 2 × 2 mm^3 voxel size. The data were then smoothed with a Gaussian kernel of 8 mm full-width half-maximum to accommodate inter-participant anatomical variability.

Data were analyzed employing a general linear model (GLM) as implemented in SPM5. At the first level, the GLM was used to construct a multiple regression design matrix that included the eight experimental conditions. We had four experimental conditions in the localization and the color discrimination tasks, respectively: a target with the same (old) color as the cue appeared in the cued (old) location (Location_Old & Color_Old: "LO_CO"), a target with a different (novel) color from the cue appeared in the cued (old) location (Location_Old & Color_Novel: "LO_CN"), a target with the same (old) color as the cue appeared in the uncued (novel) location (Location_Novel & Color_Old: "LN_CO"), and a target with a different (novel) color from the cue appeared in the uncued (novel) location (Location_Novel & Color_Novel: "LN_CN"). All the neural events were time-locked to the onset of the target of each trial by a canonical synthetic haemodynamic response function (HRF) and its time and dispersion derivatives, with event duration of 0 s. Since three levels of SOAs were used within each of the eight experimental conditions, theoretically, any potential confounds evoked by the varying SOAs should be equivalent across experimental conditions, and should be accordingly cancelled

out when the experimental conditions were directly contrasted. Practically, the inclusion of the dispersion derivatives in the statistical model took account the different durations of neural processes induced by the variable SOAs and allowed for changes in dispersion of the BOLD responses induced by different SOAs. Also, we locked neural events to the appearance of targets because the physical stimuli and underlying neural processes were essentially the same across the experimental conditions in each task and any differential neural activity between the experimental conditions should be evoked by the appearance of targets.

Moreover, it has been suggested that there exist variations of transient neural activity at the onset and offset of task blocks [Fox et al., 2005; Konishi et al., 2001]. Since experimental trials were blocked in the present hybrid fMRI design, in order to account for different levels of neural activity evoked by the varying temporal positions of the same type of trials in different task blocks, one parametric modulation regressor, coding the temporal positions (from 1 to 16) of trials of the same condition in different task blocks, was included for each of the eight types of trials. The relative temporal position of a certain trial in a task block was measured as the mean-corrected score: The temporal position of that trial minus the mean temporal order of all the trials of the same type. Because the average of any distribution from which the mean is subtracted is zero, this parametric modulation regressor of the temporal position was orthogonal to the regressor that coded for the average BOLD signal, i.e., the dot product of the corresponding columns in the linear model was zero. Thus, the HRF regressors and the parametric regressors of the temporal position could independently explain their variances: the parametric regressor of the temporal position can model the degree to which the BOLD response evoked by a trial type varied with the different temporal positions of trials of the same type in different task blocks without changing the estimate of the average BOLD response. Therefore, the differential effects of variable temporal positions of trials in the task block can be effectively regressed out. Our results showed that the later the temporal position of a trial in the task block, the higher the neural activity in the so called "default brain network," the lower the neural activity in the parietal cortex ($P < 0.05$, corrected at the cluster level; $P < 0.001$, uncorrected at the voxel level; see Supporting Information, Fig. 2).

Additionally, all the instructions were included as confounds. All the error trials were separately modeled as another regressor of no interest. The six head movement parameters derived from the realignment procedure were also included as confounds. Data were highpass-filtered at 1/128 Hz. Temporal autocorrelation was modeled using an AR(1) process. Parameter estimates were calculated for each voxel using weighted least squares to provide maximum likelihood estimators based on the temporal autocorrelation of the data. No global scaling was applied. For each participant, simple main effects for

each of the eight experimental conditions were computed by applying the "experimental condition vs. implicit baseline (null trials)" contrasts. The eight first-level individual contrast images were then fed to the $2 \times 2 \times 2$ within-participants ANOVA at the second group level employing a random-effects model (flexible factorial design in SPM5, including an additional factor modeling the participant means). In modeling variance components, we allowed for violations of sphericity by modeling nonindependence across parameter estimates from the same participant and allowing unequal variances between conditions and participants using the standard implementation in SPM5. Areas of activation were identified as significant only if they passed the threshold of $P < 0.01$, *corrected* for multiple comparisons at the cluster level with an underlying voxel level of $P < 0.005$ (uncorrected) [Poline et al., 1997].

To test for common neural activations, we used conjunction analysis to test the conjunction null hypothesis [Friston et al., 2005]. As cluster-level inference can validly be applied to single statistic images only and not to image intersections like in a conjunction, we used a threshold of $P < 0.005$ uncorrected (equivalent to a conjoint $P < 2.5 \times 10^{-5}$) and a cluster threshold of 50 contiguous voxels when reporting the results of the conjunction analysis.

RESULTS

Behavioral Results

Error trials and trials with reaction times (RTs) outside mean ± 3 SD (1.7% of the overall data points) were excluded. To check whether the color discrimination and the localization tasks differed in general task difficulty, we first examined the main effect of task type. There was no significant difference between the localization and the color discrimination tasks in either RTs (619 vs. 596 ms), $F_{(1,11)} = 1.76$, MSE $= 7390$, $P = 0.21$, or error rates (4.5 vs. 3.4%), $F < 1$, indicating that the two tasks were equivalent in general task difficulty. Since we were most interested in whether spatial and nonspatial IOR interacted differently in the two tasks, we subsequently submitted mean RTs and error rates in the localization and the color discrimination tasks to a 2 (location cue validity: old vs. novel) $\times$ 2 (color cue validity: old vs. novel) repeated-measures ANOVA, respectively.

For the localization task, the main effect of location cue validity was the only significant effect in the RT analysis, $F_{(1,11)} = 22.43$, MSE $= 940$, $P < 0.001$, suggesting that responses to the target at the old (cued) location (617 ms) were significantly slower than responses at the novel (uncued) location (575 ms), i.e., a typical location-based IOR effect (Fig. 2A, left). Neither the main effect of color cue validity, $F < 1$, nor the two-way interaction, $F < 1$, was significant. For the color discrimination task, the main effect of location cue validity was significant, $F_{(1,11)} =$
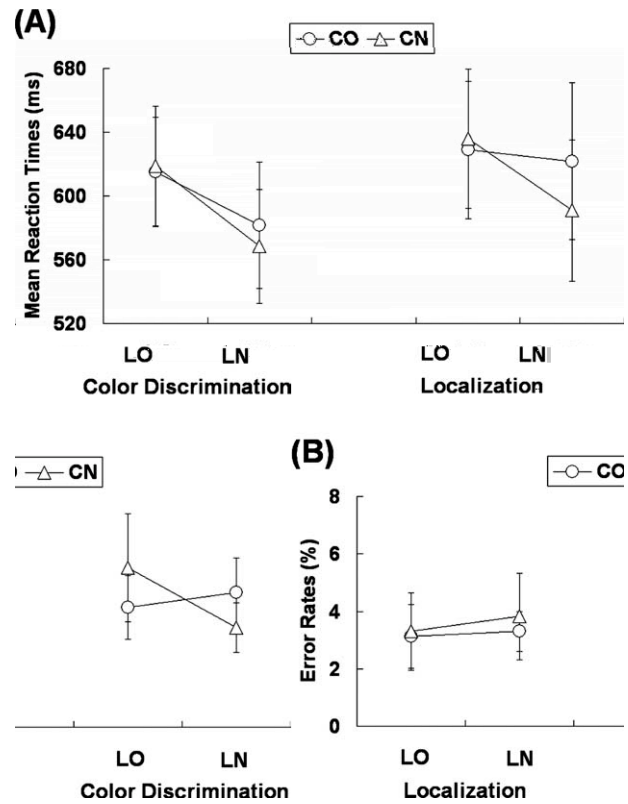

Figure 2.

Behavioral performance. (**A**) RTs (ms) with standard errors in the localization and color discrimination tasks as a function of the location and the color cue validity. (**B**) Error rates (%) with standard errors. LO, location_old; LN, location_novel; CO, color_old; CN, color_novel.

15.06, MSE $= 538$, $P < 0.005$, so was the main effect of color cue validity, $F_{(1,11)} = 4.93$, MSE $= 351$, $P < 0.05$. These effects demonstrated a significant location-based IOR effect (26 ms) and a color-based IOR effect (12 ms) (Fig. 2A, right). More importantly, the two-way interaction between location cue validity and color cue validity was significant, $F_{(1,11)} = 5.04$, MSE $= 853$, $P < 0.05$. Further planned *t*-tests on simple effects, with Bonferroni-correction when appropriate, showed that responses to the target at the old (cued) location were slower, compared to responses to the target at the novel (uncued) location, but only when the color of the target was *novel* with regard to the color of the cue, $t_{(11)} = 3.70$, $P < 0.005$, not when the color of the target was old, $t_{(11)} < 1$ (Fig. 2A, right). Responses to the target with the same color as the cue were slower, compared to responses to the target with novel (different) color, only when the target was presented at a *novel (uncued)* location, $t_{(11)} = 3.25$, $P < 0.01$, not when the target was presented at the old (cued) location, $t_{(11)} <$

1 (Fig. 2A, right). Although the pattern of error rates showed a similar trend as that of RTs in the color discrimination task (Fig. 2B, right), analysis of error rates did not reveal statistically significant effects either in the color discrimination task, all $P > 0.1$, or in the localization task (Fig. 2B, left), all $P > 0.1$.

Imaging Results

The behavioral results suggested that whether spatial and nonspatial IOR interact depends on task demands. In the spatial localization task, there existed only spatial IOR but no nonspatial IOR. At the neural level, we accordingly predicted the involvement of the orienting network in slowing down responses to the old (cued) location, i.e., the main effect of location cue validity in the contrast "Localization task: Location_Old (Color_Old + Color_Novel) > Location_Novel (Color_Old + Color_Novel)". In the nonspatial color discrimination task, spatial IOR and nonspatial IOR interacted behaviorally. Location-based IOR occurred only when the target and the cue differed in color, but not when they had the same color. At the neural level, we accordingly predicted that the orienting network would be involved in spatial IOR only when the color of the target was novel with respect to the cue but not when the color of the target was old. Similarly, nonspatial IOR occurred only when the target was presented at a novel (uncued) location but not when the target was presented at the old (cued) location. At the neural level, we accordingly predicted that the executive network would be involved in nonspatial IOR only when the spatial location of the target was novel with respect to the cue, but not when the location of the target was old.

The main effect of task type: "Localization vs. Color Discrimination"

Compared with "null events", trials with the localization and the color discrimination tasks activated similar brain regions, including bilateral premotor cortex, supplementary motor cortex, bilateral parietal cortex, bilateral posterior visual processing cortex, bilateral cerebellum and some subcortical regions (data not shown here). Direct comparisons between the two tasks, however, revealed differential neural networks, even though visual inputs in the two tasks were the same. Compared with the nonspatial color discrimination task, the spatial localization task significantly activated a bilateral dorsal frontoparietal network whereas compared with the spatial localization task, the color discrimination task significantly activated bilateral hippocampus extending to bilateral putamen, bilateral middle cingulate cortex extending to anterior cingulate cortex, bilateral superior occipital gyrus and bilateral cerebellum (Fig. 3 and Supporting Information, Table I).

The spatial task: The orienting network was involved in spatial IOR irrespective of the color cue validity

We calculated the main effect of location cue validity in the localization task, i.e., "Localization: Location_Old (Color_Old + Color_Novel) > Location_Novel (Color_Old + Color_Novel)." An extended dorsal frontoparietal network showed significantly higher neural activity to targets at old (cued) than novel (uncued) spatial locations (see Fig. 4). The local maxima in this network were located in left dorsal precentral gyrus and left superior parietal cortex (Table I).

We further extracted parameter estimates for the eight experimental conditions from the peak voxel of the activated clusters (see Fig. 4), and submitted the parameter estimates of the four conditions in the localization task to a 2 (location cue validity: old vs. novel) × 2 (color cue validity: old vs. novel) repeated-measures ANOVA. For left dorsal precentral gyrus, the main effect of location cue validity was the only significant effect, $F_{(1,11)} = 23.54$, $P < 0.001$, indicating that left dorsal precentral gyrus showed higher neural activity whenever the target appeared at the old (cued) location, irrespective of the color cue validity. Similarly for left superior parietal cortex, only the main effect of location cue validity reached significance, $F_{(1,11)} = 22.34$, $P < 0.001$, suggesting significant involvement of left superior parietal cortex in spatial IOR in the localization task.

The color discrimination task: The orienting network was involved in spatial IOR only when the color of the target was novel

For the nonspatial color discrimination task, we first checked whether there was differential neural activity between the old (cued) and novel (uncued) locations when the color of the target was old, by conducting the following contrast, "Color_Old (Location_Old > Location_Novel)." No effect was found in this contrast when the activation defined at the threshold of $P < 0.005$, uncorrected at voxel level, and $P < 0.05$, corrected at cluster level. Even at a very loose threshold of $P < 0.05$, uncorrected at voxel level, cluster size more than 10 voxels, there were no significant activations in the dorsal frontoparietal orienting network in this contrast (Supporting Information, Table II and Supporting Information, Fig. 3A).

To isolate brain regions that were significantly involved in slowing down responses to the old spatial location when the color of the target was novel but not when the color of the target was old, the contrast "Color_Novel (Location_Old > Location_Novel)" was exclusively masked by the mask contrast "Color_Old (Location_Old > Location_Novel)" at a liberal threshold of $P < 0.05$, uncorrected for multiple comparisons. In this way, those voxels that reached a level of significance at $P < 0.05$ (uncorrected) in the mask contrast were excluded from the analysis. It was found that

Figure 3.

Direct comparisons between the spatial localization (in green) and the color discrimination (in red) tasks.

the orienting network in bilateral superior parietal cortex and some posterior regions including bilateral middle occipital gyrus, left fusiform gyrus and right hippocampus was significantly activated in this contrast (Fig. 5A and Table II, color_novel (location_old > location_novel) masked excl. by color_old (location_old > location_novel).

To further test whether the orienting network involved in the current contrast (Fig. 5A) overlaps with the orienting network activated by spatial IOR in the localization task (see Fig. 4), we performed a statistical conjunction analysis between the two contrasts. Results suggested that the orienting network in left superior parietal cortex (MNI: $-20, -42, 48, z = 3.24$, 59 voxels), right superior parietal cortex (MNI: $22, -68, 54, z = 3.35$, 174 voxels), and left dorsal precentral gyrus (MNI: $-24, -6, 52, z = 3.52$, 140 voxels), and two posterior regions in left middle temporal gyrus (MNI: $-54, -66, 6, z = 3.67$, 109 voxels) and right superior occipital gyrus (MNI: $28, -66, 26, z = 3.48$, 108 voxels) were commonly involved in the two contrasts
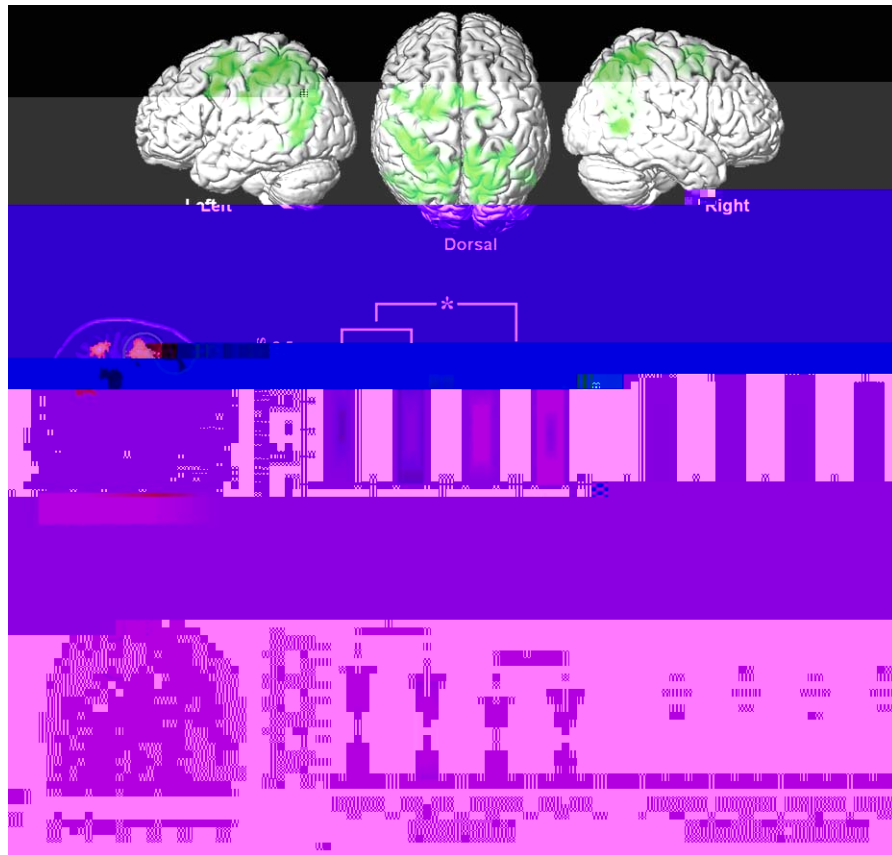

Figure 4.

The main effect of location cue validity in the localization task, i.e., "Localization: Location_Old (Color_Old + Color_Novel) > Location_Novel (Color_Old + Color_Novel)". In the localization task, an extended dorsal frontoparietal network showed higher neural activity to the target at the old (cued) location than at a novel (uncued) spatial location. Parameter estimates were extracted from the peak voxels in left dorsal precentral gyrus and left superior parietal cortex, respectively, and are displayed as a function of the experimental conditions (*, $P < 0.05$, corrected).

depicted in Figures 4 and 5A. Parameter estimates were extracted from peak voxels in the three regions of the orienting network and were shown as a function of the eight experimental conditions (Fig. 5B). For each region, parameter estimates in the localization and color discrimination tasks were submitted to a 2 (spatial cue validity: old vs. novel) $\times$
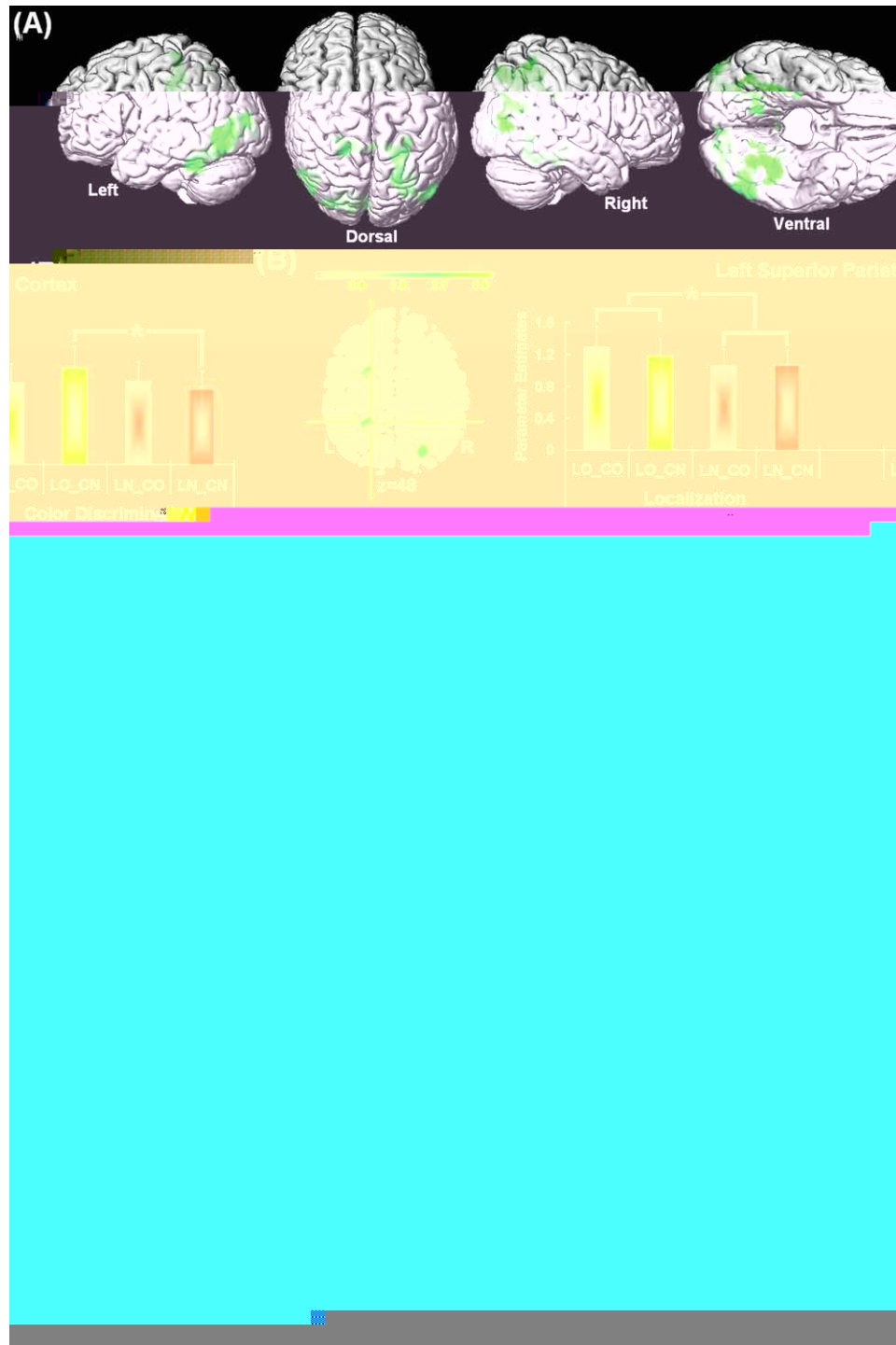
Figure 5.

(**A**) In the color discrimination task, the contrast "Color_Novel (Location_Old > Location_Novel)" was exclusively masked by the mask contrast "Color_Old (Location_Old > Location_Novel)". Bilateral superior parietal cortex, bilateral middle occipital gyrus, left fusiform and right hippocampus showed higher neural activity to the target at the old (cued) location than to the target at the novel (uncued) location, but only when the color of the target was novel compared to the cue, not when the color of the target was old. (**B**) A conjunction between the contrasts in Figures 4 and 5A suggested that the orienting network acti-vated in the color discrimination task overlapped with the orienting network activated in the localization task in left dorsal precentral gyrus and bilateral superior parietal cortex. Parameter estimates were extracted from the peak voxels in regions of the common orienting network, and are displayed as a function of the experimental conditions (*, $P < 0.05$, corrected). (**C**) In right hippocampus, the pattern of neural interaction in the color discrimination task was different from those in the other significantly activated areas.

TABLE II. Neural interaction between the orienting and executive networks in the color discrimination task

Anatomical regions	Cluster peak (mm)	Z score	No. of voxels
A. Color_novel (location_old > location_novel) masked excl. by color_old (location_old > location_novel)			
Right superior parietal cortex (BA 5)	22, −62, 52	3.52	695
Left superior parietal cortex (BA 2)	−22, −42, 46	4.23	328
Right hippocampus (BA 37)	26, −28, −6	3.68	339
Right middle occipital gyrus (BA 18)	50, −82, 14	4.11	414
Left middle occipital gyrus (BA 18)	−36, −90, 14	3.82	342
Left fusiform gyrus (BA 37)	−36, −48, −18	4.63	1,258
B. Location_novel (color_old > color_novel) masked excl. by location_old (color_old > color_novel)			
Right middle frontal gyrus (BA 45)	52, 28, 32	3.98	666
Right inferior frontal gyrus (BA 47)	38, 44, −10	4.21	546
Left inferior frontal gyrus (BA 47)	−34, 38, −8	4.22	419
Left Putamen (BA 48)	−26, −14, 14	4.5	422
Right inferior temporal gyrus (BA 37)	52, −62, −10	3.82	388
Left fusiform gyrus (BA 37)	−26, −52, −14	4.30	1,705

The coordinates (x, y, z) correspond to MNI coordinates.

trials when the target was presented at the old location by conducting the contrast "Location_Old (Color_Old > Color_Novel)." No effect was found in this contrast when the activation defined at the threshold of $P < 0.005$, uncorrected at voxel level, and $P < 0.05$, corrected at cluster level. Even at a very liberal threshold of $P < 0.05$, uncorrected at voxel level, cluster size more than 10 voxels, there were no significant activations in the executive network in this contrast (Supporting Information, Table II and Supporting Information, Fig. 3B).

To reveal brain regions that were involved in slowing down responses to old color representations when the target was presented at the novel (uncued) location, but not when the target was presented at the old (cued) location, the contrast "Location_Old (Color_Old > Color_Novel)" was used to exclusively mask the contrast "Location_Novel (Color_-Old > Color_Novel)" at a liberal threshold of $P < 0.05$, uncorrected for multiple comparisons. In this way, those voxels that reached a level of significance of $P < 0.05$ (uncorrected) in the mask contrast were excluded from analysis. The executive network in bilateral prefrontal cortex and left basal ganglia and some posterior regions including left fusiform and right inferior temporal gyrus was revealed in this analysis, suggesting that it was involved in slowing down responses to the previously attended (old) color representation only when the target was presented at a novel (uncued) spatial location, but not when the target was presented at the old (cued) spatial location (Fig. 6 and Table II, location_novel (color_old > color_novel) masked excl. by location_old (color_old > color_novel)).

Parameter estimates were extracted from the peak voxels in the activated regions and were shown as a function of the experimental conditions. Since the posterior regions showed the same pattern of neural activity as the prefrontal executive regions, we presented parameter estimates only for the prefrontal executive regions in Figure 6. For each region, parameter estimates in the color discrimination task were submitted to a 2 (location cue validity: old vs. novel) × 2 (color cue validity: old vs. novel) repeated-measures ANOVA. For right middle frontal gyrus, the only significant effect was the two-way interaction, $F_{(1,11)} = 6.98$, $P < 0.05$. Planned t-tests suggested that right middle frontal gyrus showed higher neural activity to the target with old color than to the target with novel color, but only when the target appeared at the *novel* location, $t_{(11)} = 3.12$, $P < 0.05$, not when the target appeared at the old location, $t_{(11)} = 0.38$, $P = 0.71$. For right inferior frontal gyrus, again, the only significant effect was the two-way interaction, $F_{(1,11)} = 7.10$, $P < 0.05$. Planned t-tests suggested that this region showed significantly higher neural activity to the target with old color than to the target with novel color only when the target was presented at the *novel* location, $t_{(11)} = 2.69$, $P < 0.05$, not when the target was presented at the old location, $t_{(11)} = 0.95$, $P = 0.36$. For left inferior frontal gyrus, the only significant effect was the two-way interaction, $F_{(1,11)} = 7.42$, $P < 0.05$. Planned t-tests suggested that this region showed significantly higher neural activity to the target with old color than to the target with novel color only when the target appeared at the *novel* location, $t_{(11)} = 2.84$, $P < 0.05$, not when the target was presented at the old location, $t_{(11)} = 0.05$, $P = 0.96$. Similarly for left putamen, the two-way interaction was also significant, $F_{(1,11)} = 5.22$, $P < 0.05$. Planned t-tests suggested that it showed higher neural activity to the target with old color than to the target with novel color only when the target was presented at the *novel* location, $t_{(11)} = 3.28$, $P < 0.01$, not when the target was presented at the old location, $t_{(11)} = 0.4$, $P = 0.70$.

DISCUSSION

Preference for novelty plays a fundamental role in survival. If organisms can keep track of which locations or objects having been examined when the exploration

Figure 6.

In the color discrimination task, the contrast "Location_Novel (Color_Old > Color_Novel)" was exclusively masked by the mask contrast "Location_Old (Color_Old > Color_Novel)." Bilateral inferior frontal gyrus, right middle frontal gyrus, left putamen, right inferior temporal gyrus, and left fusiform showed higher neural activity to the target with the same (old) color as the cue than to the target with a different (novel) color, but only when the target was presented at a novel (uncued) location, not when the target was presented at the old (cued) location. Parameter estimates were extracted from the peak voxels in the anterior executive areas and are plotted as a function of the experimental conditions (*, $P < 0.05$, corrected).

behavior (e.g., foraging) is suddenly interrupted (e.g., by the presence of a competitor), they may increase the chance of finding the desirable target (e.g., food) by avoiding reiterative reexaminations [Tipper et al., 2003]. In this fMRI study, we showed that depending on the task demand, the spatial and nonspatial IOR mechanisms in the orienting and the executive networks work either independently or cooperatively to bias the organisms for novelty.

Previous studies have shown that even the exogenous attentional orienting can be modulated by the dynamic interaction between the perceptual salience of visual stimuli and their behavioral relevance [Folk et al., 1992, 2002; Kincade et al., 2005; Serences et al., 2005; Wei and Zhou, 2006]. For example, salient sensory stimuli attract attention more effectively when they are relevant to task demand than when they are not. This form of stimulus-driven orienting has been labeled "contingent" to emphasize its dependence on the underlying task set [Folk et al., 1992]. Therefore, the potential interaction between spatial and nonspatial IOR mechanisms in the orienting and the executive networks may be determined not only by the physical correspondence between the cue and the target, but also by the task set that participants adopt in a particular task context [Lupiañez et al., 1997, 2001; Wei and Zhou, 2006]. In our color discrimination task, because color was the task-relevant dimension, the cue color was able to attract and initiate the exogenous shifts of attention in the color space. Meanwhile, because spatial location plays a very special role in guiding visuo-spatial selective attention [Triesman and Gelade, 1980; Tsal and Lavie, 1988], the location and color features of the stimuli may be codominant in guiding selective attention in the color discrimination task, inducing interaction between spatial and nonspatial IOR mechanisms at the behavioral and the neural levels. In contrast, in the localization task, color is not able to reflexively attract attention and location alone is dominant in guiding selective attention. Thus, the spatial IOR mechanism in the orienting network dominates in the spatial localization task. Below we discuss the neural activations in the spatial and nonspatial tasks, respectively.

In the spatial localization task, i.e., when the spatial dimension, rather than the nonspatial dimension, is task-relevant, the spatial IOR mechanisms in the orienting network work independently and solely to slow down attentional orienting to previously examined spatial locations and bias spatial attention to novel locations. Behaviorally, participants responded significantly slower to the target at the old (cued) location than to the target at the novel (uncued) location irrespective of the cue-target correspondence in the nonspatial color dimension (Fig. 2A, left). Neurally, the dorsal frontoparietal orienting network, which is involved in orienting spatial attention [Corbetta et al., 2000; Corbetta and Shulman, 2002], showed significantly higher neural activity to the target at the old (cued) location than to the target at the novel (uncued) location

both when the color of the target was novel and when the color of the target was old (see Fig. 4).

In the nonspatial color discrimination task, i.e., when the nonspatial dimension is task-relevant, the orienting network and the executive network complement each other in biasing attention to novel objects at novel spatial locations. Behaviorally, there was a significant location-based IOR effect only when the color of the target was novel, and there existed a significant color-based IOR effect only when the location of target was novel (Fig. 2A, right). A similar response pattern has been found in a previous study on the interaction between visual dimension changes and response changes [Pollmann et al., 2006]. It was suggested that behaviorally, there exists a dimension nonchange cost when the response changes, and there exists a response nonchange cost when the dimension changes.

Although the interaction between the orienting and the executive attentional networks has been barely investigated at the neural level [Chen et al., 2006], evidence from previous behavioral studies suggests that the two networks might interact, depending on processing demands on each network [Fuentes, 2004]. For example, Posner et al. [1987] combined a spatial orienting task and a demanding executive task (counting back from a three-digit number), and found that increasing processing demands in the executive network modulated the functioning of the orienting network. On the other hand, attentional orienting may also affect the resolution of perceptual and response conflicts in the executive network. For example, when the Stroop or flanker interference tasks are combined in the manipulation of IOR such that conflicting information can be presented at either the cued or the uncued location, the interference effects are reduced, eliminated or even reversed at the cued location [Chen et al., 2006; Fuentes et al., 1999b; Vivas and Fuentes, 2001]. Our behavioral results in the color discrimination task suggest further a third possibility: the orienting and the executive network can also mutually influence each other in a reciprocal way, probably because the processing demands on the two attentional networks are equivalent in the color discrimination task [Fuentes, 2004].

The pattern of neural activity in the orienting and the executive networks was, in general, consistent with the behavioral performance in the color discrimination task. The orienting network in bilateral superior parietal cortex was involved in slowing down responses to the target at the old (cued) spatial location, but only when the color of the target was *novel* (i.e., when the nonspatial IOR mechanism in the executive network was not operative; Fig. 5), not when the color of the target was old (i.e., when the nonspatial IOR mechanism in the executive network was implicated; see Supporting Information, Table II and Supporting Information, Fig. 3A). The prefrontal executive network in bilateral prefrontal cortex and left basal ganglia, two main brain regions involved in the executive attention [Fan et al., 2003a, 2005; Posner and Petersen, 1990], was

involved in slowing down responses to the previously attended (old) color representation, but only when the target was presented at the *novel (uncued)* spatial location (i.e., when the spatial IOR mechanism in the orienting network was not operative; Fig. 6), not when the target was presented at the old (cued) spatial location (i.e., when the spatial IOR mechanism in the orienting network was implicated; see Supporting Information, Table II and Supporting Information, Fig. 3B). Moreover, the activated dorsal and ventral parts of the inferior frontal gyrus in this study overlap very well with the prefrontal areas involved in the episodic retrieval process in the previous literature [Otten et al., 2002; Rugg et al., 2002], suggesting the involvement of the episodic retrieval of inhibitory label in nonspatial IOR.

Our results in the color discrimination task show clearly how the interacting spatial and nonspatial IOR mechanisms in the two attentional networks complement each other. When a novel object appears at the old spatial location, compared with the same object at a novel spatial location, the *nonspatial* IOR mechanism in the executive network cannot tell the difference between the two conditions since the nonspatial identity of the object is novel in both conditions. The *spatial* IOR mechanism in the orienting network, however, is capable of slowing down attentional orienting to the old location in the former condition (see Fig. 5B). Thus, spatial attention can be more rapidly oriented to novel objects appearing at novel spatial locations. The involvement of the bilateral occipitotemporal cortex may reflect the top-down attentional modulation from bilateral parietal cortex [Fu et al., 2001; Grent-'t-Jong and Woldorff, 2007; Kastner and Ungerleider, 2000; Kastner et al., 1999]. On the other hand, when an old object appears at a novel spatial location, compared to a novel object at a novel spatial location, the spatial IOR mechanism in the orienting network cannot tell the difference between the two conditions since the spatial location of the object is novel in both conditions. The nonspatial IOR mechanism in the prefrontal executive network, however, is able to slow down responses to the old object representation even at novel spatial locations in the former condition (see Fig. 6).

Interestingly, our results also suggested that right hippocampus showed higher neural activity both when a novel object appeared at the old spatial location and when an old object appeared at a novel spatial location (Fig. 5C). These results are in good accordance with previous evidence suggesting that the hippocampus may function as an associative match-mismatch comparator, generating mismatch signals whenever perceptual inputs contain a novel and an old associative components [Kumaran and Maguire, 2006, 2007a,b]. However, when a new object appears at a new spatial location, this associative novelty detection mechanism may not be highly activated.

Additionally, one may argue that the color-based repetition disadvantage effect in our study may represent an effect of repetition blindness (RB) rather than the nonspa-

tial IOR [Fox and de Fockert, 2001; Taylor and Klein, 1998]. RB is a relative inability to detect repetitions of items that occur in a rapid serial visual presentation [Kanwisher, 1987, 1991]. For example, Kanwisher (1991) presented a sequence of colored symbols one after another for 117 ms each at the same location. When a symbol was presented in the same color as an earlier symbol, RB occurred. In contrast to the classical RB effect, however, in the color-based IOR paradigm of the present study, between the cue and the target, we presented a neutral distract, whose color was different from either the color of the cue or the color of the target. The time intervals between the cue and the target (950 ms/1,050 ms/1,150 ms) were also much longer than those in the RB paradigm. Moreover, instead of being presented at the same central location, the three consecutive stimuli in one trial were in different spatial positions in this study. Consequently, it is unlikely that the color-based repetition disadvantage effect in our study reflects the inability at the perceptual level to detect repeated items. Instead, this effect represents an attentional inhibitory bias toward previously attended object representations once attention has been shifted away in the color space, i.e., the color-based IOR.

CONCLUSIONS

Organisms deal with multiple locations and objects over time and space in their natural life. It is important for them to keep track of the locations and objects that have become irrelevant in order to avoid useless re-examinations and maximize the chance of survival. Here we show that the underlying mechanisms can be understood at both the behavioral and the neural levels by putting together three important pieces of information: the orienting network slows down responses to objects at old locations when nonspatial IOR in the executive network is not necessary, the executive network slows down responses to an old object when spatial IOR in the orienting network is not necessary, and the hippocampus provides information to the attention system of what is novel or old in terms of both spatial location and nonspatial object identity. Together with previous work, the present study supports the view that biasing the organisms for novelty and change is a pervasive property of the attention system.

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