Cue validity modulates the neural correlates of covert endogenous orienting of attention in parietal and frontal cortex

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Received 24 February 2006; revised 3 May 2006; accepted 8 May 2006

Parietal brain regions have been implicated in reorienting of visuospatial attention in location-cueing paradigms when misleading advance information is provided in form of a spatially invalid cue. The difference in reaction times to invalidly and validly cued targets is termed the ‘validity effect’ and used as a behavioral measure for attentional reorienting. Behavioral studies suggest that the magnitude of the validity effect depends on the ratio of validly to invalidly cued targets (termed cue validity), i.e., on the amount of top–down information provided. Using fMRI, we investigated the effects of a cue validity manipulation upon the neural mechanisms underlying attentional reorienting using valid and invalid spatial cues in the context of 90% and 60% cue validity, respectively. We hypothesized that increased parietal activation would be elicited when subjects need to reorient their attention in a context of high cue validity. Behaviorally, subjects showed significantly higher validity effects in the high as compared to the low cue validity condition, indicating slower reorienting. The neuroimaging data revealed higher activation of right inferior parietal and right frontal cortex in the 90% than in the 60% cue validity condition. We conclude that the amount of top–down information provided by predictive cues influences the neural correlates of reorienting of visuospatial attention by modulating activation of a right fronto-parietal attentional network.

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Keywords: Visuospatial attention; Cue validity; fMRI

Introduction

Attention can be allocated in space covertly without accompanying movements of the head or the eyes (Helmholtz, 1866/1924; James, 1890). Orienting and reorienting of covert visuospatial attention can be investigated with location-cueing paradigms in which a cue provides either correct or misleading information about the location of an upcoming target. Stimulus detection is facilitated when the target appears at the expected, i.e., the validly cued location. The difference in reaction times to invalidly and validly cued targets is referred to as the ‘validity effect’; it is regarded as an indicator for the costs of disengaging and shifting of attention from the cued to the uncued location (Posner, 1980).

Regarding the neural correlates of attentional reorienting, neuropsychological data as well as neuroimaging studies attribute particular importance to parietal cortex. Spatial neglect constitutes a complex neuropsychological syndrome caused by focal cerebral lesions in which patients fail to attend to, respond adequately to or orient voluntarily to stimuli in contralateral space (Halligan et al., 2003; Fink and Heide, 2004). It is most commonly observed in patients with right hemispheric lesions, particularly after damage to the inferior parietal cortex and the temporo-parietal junction (Vallar and Perani, 1986; Vallar, 2001; Mort et al., 2003). Posner et al. (1984) observed that patients with right parietal lesions show an abnormal contralesional delay when attention has to be redirected from a location on the ipsilesional (i.e., intact) side to the contralesional side of space. This suggests that a specific impairment of the disengagement operation of attention contributes to the spatial neglect syndrome and emphasizes the importance of right hemispheric parietal brain structures for this cognitive process.

Consistent with patient data, neuroimaging studies using location-cueing paradigms have shown that the inferior parietal cortex and the temporo-parietal junction are activated by attentional shifts (Corbetta et al., 2000; Kincade et al., 2005; Thiel et al., 2004, 2005). Corbetta and Shulman (2002), however, postulate two separable neural attentional systems with distinct functions and anatomical locations: one system is supposed to be involved in the endogenous allocation of attention in response to an informative cue (top–down control). This system comprises the intraparietal sulcus and the frontal eye fields (dorsal fronto-parietal network) and is organized bilaterally. In contrast, the ventral fronto-parietal

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Available online on ScienceDirect (www.sciencedirect.com).

1053-8119/$ - see front matter © 2006 Elsevier Inc. All rights reserved. doi:10.1016/j.neuroimage.2006.05.019
network comprises the temporo-parietal junction and the ventral frontal cortex and is activated by events that require redirecting of attention to stimuli that have been outside the focus of processing (i.e., unexpected events like, e.g., invalidly cued targets). This reorienting network is supposed to be lateralized to the right hemisphere.

Behavioral studies suggest that orienting and reorienting of attention are modulated by the amount of top–down information that can be derived from an informative cue. In particular, it has been shown that the ratio of validly to invalidly cued targets (i.e., cue validity) influences attentional allocation with high cue validities increasing the magnitude of the validity effect (Jonides, 1980, 1983; Eriksen and Yeh, 1985; Madden, 1992; Riggio and Kirsner, 1997). In other words, if the information provided by the cue is highly valid, reaction times to valid targets decrease, while reaction times to invalid targets increase.

Space-based theories of attention comprising spotlight, zoomlens and gradient models, ascribe this effect to a differential distribution of attentional resources in response to validity manipulations (Jonides, 1980, 1983; Eriksen and Yeh, 1985, Madden, 1992). While the first two approaches can account for faster processing of targets preceded by a highly valid cue, they cannot easily explain why performance declines at an initially unattended location (i.e., in invalid trials). Hence, a gradient model was suggested as the appropriate framework for the characterization of the effects of different cue validities (Madden, 1992). According to this model, the distribution of attentional resources in response to a highly valid cue would have a higher peak at the cued and a lower tail at the unattended location than in a condition with low validity of the cue. This would make attentional reorienting more difficult and hence increase the validity effect for highly valid cues.

A different approach for explaining the effects of different cue validities is taken by Yu and Dayan (2005) who propose a computational model which specifies the role of different neurotransmitters for the balance of top–down expectation and bottom–up sensory input. In this model, behavioral data from location-cueing paradigms are successfully simulated by uncertainty computations according to Bayesian statistical theory. Cue validity in this framework represents ‘expected uncertainty’ which is defined as the degree of unreliability of predictive relationships. Thus, expected uncertainty would be high in low cue validity conditions. Expected uncertainty is supposed to suppress the use of the spatial cue for making inferences about the upcoming target location.

To our knowledge, no functional imaging study has systematically addressed the influence of a cue validity manipulation on the neural activation patterns related to reorienting in cued target detection tasks. One study (Gliessing et al., 2005) investigated the neural activity in a low, middle and high cue validity condition. However, by using 100% cue validity in the high cue validity condition, the authors did not compare differential neural activation in invalid trials. Given the involvement of parietal cortex in reorienting visuospatial attention and the effects of top–down expectations on attentional reorienting, we accordingly investigated whether parietal cortex activity is modulated by cue validity. To address this issue, we designed a modified Posner type task with 90% and 60% cue validity and hypothesized that parietal activation related to reorienting (invalid trials vs. valid trials) would be increased in the high as opposed to the low cue validity condition.

Materials and methods

Subjects

Thirteen subjects with no history of neurological or psychiatric disease gave informed consent to participate in the study. All subjects were right handed as indexed by a handedness inventory (Oldfield, 1971). One subject was excluded from further analysis due to excessive head movement (>3 mm) during fMRI scanning. Therefore, data from twelve subjects were analyzed (6 males, 6 females; age range 19–33 years; mean age 25.7 years). The subjects were investigated in the context of a pharmacological (between-subject design) fMRI study. The analyses presented here focuses on those subjects who belonged to the placebo group only.

Stimuli and experimental paradigm

We used a cued target detection task with central predictive cueing (Posner, 1980; see Fig. 1). Stimuli were projected onto a screen in front of the participant in the MR scanner. Viewing distance was approximately 29 cm. Subjects were presented with two horizontally arranged boxes (4.9° wide and 13.9° eccentric in each visual field). A central diamond (2.5° eccentric in each visual field) was placed in between serving as a fixation point. Cues consisted of a colored 100 ms brightening of one side of the diamond depicting an arrowhead pointing to one of the peripheral boxes. The cue was followed by the presentation of the target appearing for 100 ms in one of the boxes. To prevent temporal orienting, we used two cue–target intervals (400 and 700 ms). Subjects were asked to respond as quickly as possible to the target by a button press with the index finger of their right hand. Trials were presented every 1800 ms. One third of the trials were ‘null events’ (Josephs and Henson, 1999) where a baseline stimulus was displayed, leading effectively to variable stimulus onset asynchronies (SOAs) (i.e., 1800 ms, 3600 ms, 5400 ms, etc.).

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differed from those employed in prior behavioral studies where cue validity was changed only between different experimental blocks. Subjects were informed about the different cue validities and completed a practice session of 8 min prior to performing the task in the MR scanner. The assignment of cue color (green or blue) and cue validity (90% or 60%) was counterbalanced across subjects. In addition to validly and invalidly cued trials, we included catch trials in which the cue was not followed by any target. The experiment consisted of 756 trials including 252 null events and lasted for 24 min. The scanning session included two rest periods of approximately 1 min during which the word ‘pause’ was shown on the display, and the subjects were allowed to close their eyes. This was done to prevent deterioration of fixation ability due to exertion of the eyes. Restart of the task was indicated by a tone.

**Data acquisition**

T2*-weighted echoplanar (EPI) images with blood oxygen level-dependent (BOLD) contrast (matrix size 64 × 64, pixel size 3.12 × 3.12 × 5 mm³) were obtained using a 1.5 T Sonata MRI System (Siemens, Erlangen, Germany). Seven hundred forty-five volumes of twenty-one 4 mm-thick axial slices were acquired sequentially with a 1.0 mm gap (repetition time 2.0 s, echo time 60 ms). The first 5 volumes were discarded to allow for T1 equilibration effects. To correct for interscan movement, images were spatially realigned to the first volume. Images were synchronized to the middle slice correcting for differences in slice acquisition time and normalized to a standard EPI template volume (resampled to 3 × 3 × 3 mm³ voxels). The data were smoothed with a Gaussian kernel of 8 mm full-width half-maximum to accommodate intersubject anatomical variability.

**Statistical analysis of imaging data**

Data were analyzed with Statistic Parametric Mapping software SPM2 (Wellcome Department of Imaging Neuroscience, London, Friston et al., 1995, http://www.fil.ion.ucl.ac.uk/ spm2.html) employing a random effects model. Seven regressors were defined at the single-subject level comprising four events of interest (validly cued targets with 90% cue validity; invalidly cued targets in the context of 90% cue validity, validly cued targets with 60% cue validity, invalidly cued targets in the context of 60% cue validity) and 2 events of no interest (catch trials, incorrect responses). The event types were time locked to the onset of the target by a canonical synthetic hemodynamic response function (hrf). The pauses were modeled as blocks (convolved with the hrf) in a third regressor of no interest. The six movement parameters were included in the design matrix as additional regressors. Data were scan-wise scaled to reduce globally distributed confounding effects (Kiebel and Holmes, 2004) and high-pass filtered at 1/128 Hz. Due to the low correlation between global mean and the contrast-weighted design matrices for both validity effects and the interaction contrast (see below), we can rule out that global scaling might have produced artificial deactivations (Aguirre et al., 1998; validity effect 90% cue validity: averaged absolute values of correlations $r = 0.05$; validity effect 60% cue validity: $r = 0.04$; interaction contrast (validity effect 90% > validity effect 60%); $r = 0.04$).

The respective 4 contrast images (each trial type vs. baseline) were entered into a 1 × 4 within-subjects ANOVA. Homogeneity of variance and correlation of measurements were estimated with a Restricted Maximum Likelihood (ReML) algorithm. We used the following directed $t$ contrasts to test our hypotheses. To assess neural activity related to attentional reorienting under 90% and 60% cue validity, we contrasted invalidly with validly cued trials ([invalid > valid] for each validity condition. For the comparison of different reorienting processes in response to different cue validities, we contrasted the two validity effects ([90% cue validity [invalid > valid] > 60% cue validity [invalid > valid]]) with each other. Activations and figures from these analyses are reported at a level of $P < 0.001$ uncorrected and a cluster threshold of more than five contiguous voxels.

To compare the brain regions related to reorienting in the present experiment to previous studies, we additionally conducted region of interest (ROI) analyses using the coordinates reported by Corbetta et al. (2000). We defined two spheres with a radius of 16 mm, each, centered at the voxel of peak activation in the inferior parietal cortex (Talairach coordinates: $x = 53$, $y = -49$, $z = 30$) and superior temporal gyrus ($x = 57$, $y = -45$, $z = 12$) (WFU PickAtlas; Maldjian et al., 2003). Statistical images from these analyses were corrected for multiple comparisons across the search volume by using false discovery rate (FDR) inference to control for the expected proportion of false positives among suprathreshold voxels ($P_{FDR} < 0.05$) (Genovese et al., 2002).

**Statistical analysis of behavioral data**

Reaction times (RTs) faster than 100 ms (i.e., anticipations) were excluded from the analyses. As RT data usually contain slow outlying values resulting in positively skewed distributions, traditional RT analysis can cause misinterpretations (Heathcote et al., 1991). For this reason, we used a distributional analysis fitting ex-Gauss distributions to individual RT data (Heathcote et al., 2004). This technique has already been applied to RT data obtained from location-cueing paradigms (Gottlob, 2004) as well as the Stroop task (Heathcote et al., 1991). Ex-Gauss functions consist of a Gaussian component (with the mean $\mu$ and the standard deviation $\sigma$) and an exponential component $\tau$. Probability density functions were plotted for the four experimental conditions according to the following formula:

$$f(RT) = \frac{1}{\sqrt{\tau \pi} \sigma} \int_{-\infty}^{\infty} \left[ e^{-\frac{(x - \mu)^2}{2\sigma^2}} - e^{-\frac{x^2}{2\tau}} \right] dx$$

The means of the Gaussian component ($\mu$) for each subject were entered into a $2 \times 2$ repeated measures ANOVA with the factors cueing (valid; invalid) and cue validity (90%; 60%). In case of significant interactions, we conducted post hoc paired $t$ tests to elucidate the origin of these effects. Moreover, validity effects of the 90% and the 60% cue validity condition (RT invalid trials – RT valid trials) were post hoc compared with a paired $t$ test. Additionally, these results were compared to a traditional RT analysis in which median RTs were calculated for all four trial types in each subject and tested with the same statistical tests as described above.

**Eye movement control**

Eye position was monitored during scanning with an MR-compatible infrared eye tracker (ASL Model 540, Applied Science Group Co., Bedford, MA). Eye data were analyzed with ILAB software (Gitelman, 2002). Artefacts related to blinking were...
filtered out. A region of interest subtending 25% of the cue–target distance from the center was defined as fixation zone. For each subject and cue validity condition, the amount of time spent in this central region between cue and target presentation was calculated.

Results

Behavioral data

Misses, anticipations and false alarms (catch trials) amounted 4.3%, 0.7% and 6.2%, respectively. There were no significant differences in incorrect responses between the two cue validity conditions. The results of the distributional RT analysis are shown in Fig. 2.

The 2 × 2 ANOVA for repeated measurements of the Gaussian components (μ) revealed a significant main effect of cueing (valid; invalid) (F(1,11) = 33.32; P < 0.001) reflecting faster reaction times to validly than to invalidly cued targets. Additionally, we observed a significant main effect of cue validity (90%; 60%) (F(1,11) = 13.56; P < 0.01) and a cueing × cue validity interaction (F(1,11) = 37.76; P < 0.001). Post hoc t tests revealed that subjects responded significantly faster to validly cued targets in the 90% than in the 60% cue validity condition (t(11) = −2.30; P < 0.05). Conversely, reaction times to invalidly cued targets in the 90% cue validity condition were significantly slower than to invalidly cued targets in the 60% cue validity condition (t(11) = 4.88; P < 0.001). There was a significant difference in the two validity effects (RT invalid minus RT valid) (t(11) = 6.145; P < 0.001; see Fig. 3). The traditional RT analysis using individual median RTs yielded similar results. RT data from both analyses are summarized in Table 1.

Eye movement data

For technical reasons, eye position data were not reliably recordable in six subjects. Analysis of the available eye data revealed that the participants spent on average 96.6 ± 1.8% and 96.8 ± 1.9% of the time during the cue–target interval within the central region of interest in the 90% and the 60% cue validity condition, respectively.

Neural data

Neural correlates of attentional reorienting were determined by contrasting invalid and valid trials separately for the two cue validity conditions. In the 90% cue validity condition stronger frontal activity in invalid as compared to valid trials was evident in the right inferior frontal gyrus close to the inferior frontal sulcus (x = 51, y = 24, z = 33; Z = 3.40, 9 voxels). Three foci of activity were found in the right middle and superior temporal gyrus adjacent to the superior temporal sulcus (x = 60, y = −9, z = 15; Z = 3.66, 6 voxels; x = 63, y = −27, z = −9; Z = 3.56, 5 voxels) with one cluster centered at the posterior part of the sulcus near the temporo-parieto-occipital junction (x = 57, y = −57, z = 15; Z = 3.56, 18 voxels). Parietal activation was observed bilaterally along the intraparietal sulcus (x = 54, y = −45, z = 45; Z = 3.92, 36 voxels; x = −42, y = −54, z = 57; Z = 3.86, 10 voxels). The activation in the right hemisphere extended into the supramarginal gyrus. Additionally, regions in the right parahippocampal gyrus (x = 33, y = 3, z = −21; Z = 4.53, 8 voxels; x = 36, y = −9, z = −18; Z = 3.53, 5 voxels) and the left thalamus (x = −21, y = −15, z = 9; Z = 3.83; 6 voxels) showed higher activation for invalidly than for validly cued targets.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Distributional analysis</th>
<th>Traditional analysis</th>
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<tbody>
<tr>
<td></td>
<td>Valid trials</td>
<td>Invalid trials</td>
</tr>
<tr>
<td>90% Cue validity</td>
<td>233.0 (6.7)</td>
<td>308.0 (15.9)</td>
</tr>
<tr>
<td>60% Cue validity</td>
<td>236.9 (7.2)</td>
<td>277.1 (13.3)</td>
</tr>
<tr>
<td>Means of the ex-Gaussian parameter μ (distributional analysis) and averaged median reaction times (traditional analysis) for the four experimental conditions. Reaction times are reported in milliseconds. Standard errors of the mean are shown in parenthesis.</td>
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validly cued targets. Activations related to reorienting (invalid > valid) in the 60% cue validity condition were located in the left middle frontal gyrus ($x = -33, y = 36, z = 24; Z = 4.24, 10 voxels$) and the left intraparietal cortex ($x = -36, y = -48, z = 48; Z = 3.41, 8 voxels$).

To identify areas that were differentially activated during reorienting processes dependent upon cue validity we compared the two validity effects (90% cue validity [invalid > valid] > 60% cue validity [invalid > valid]) with each other. A list of all activations is provided in Table 2. This contrast yielded two frontal clusters of activation located in the right middle frontal gyrus and the right inferior frontal gyrus nearby the inferior frontal sulcus. Additionally, a cluster in the right inferior parietal cortex, comprising parts of the intraparietal cortex as well as the supramarginal and the angular gyrus showed higher activation in the 90% cue validity condition (see Fig. 4). The parameter estimates at the voxel of peak activation revealed that this effect mainly resulted from differential activity in invalid trials. Further activation was observed in the right lingual gyrus.

**ROI analyses**

The ROI analyses of areas related to attentional reorienting in the 90% cue validity condition revealed that four foci of activation were located adjacent to the inferior parietal cortex activation of Corbetta et al. (2000) whereof two foci were also enclosed in the ROI of the superior temporal gyrus (see Table 3). However, the largest cluster of activation was located at the posterior part of the superior temporal sulcus near the temporo-parieto-occipital junction. Neither the right inferior parietal cortex nor the right superior temporal gyrus showed suprathreshold activation in the 60% cue validity condition.

A ROI analysis of the interaction contrast comparing reorienting in the 90% to the 60% cue validity condition illustrated that parts of the parietal activation fell into the inferior parietal area reported by Corbetta et al. (2000) ($x = 51, y = -54, z = 45; Z = 4.14, 83 voxels; x = 57, y = -57, z = 15; Z = 3.05, 8 voxels; x = 21$).

![Fig. 4. Brain areas showing higher activation to invalidly cued targets under the high validity as compared to the low validity condition.](image-url)
Our results are also consistent with the model of Yu and Dayan (2005) postulating a relationship between the certainty of the information that can be derived from the spatial cue and the validity effect.

In the present fMRI study, we manipulated cue validity in a cued target detection paradigm and investigated its effect upon the neural mechanisms underlying reorienting of attention. At the behavioral level, high cue validity increased and low cue validity decreased the validity effect. Our imaging data show that cue validity influences the neural correlates of reorienting visuospatial attention by modulating the activation of a right fronto-parietal attentional network.

Behavioral data

Our behavioral data revealed that cue validity significantly modulates the magnitude of the validity effect which is conceived as a measure for the costs of attentional reorienting. This result is in accordance with previous behavioral studies and additionally demonstrates that this effect can be observed even when trials are presented in a truly random fashion. The significant difference between the validity effects of the two cue validity conditions was evident in a distributional reaction time analysis in which ex-Gauss distributions were fitted for each subject and each experimental condition as well as in a traditional analysis of individual median reaction times. The responses to validly cued targets differed significantly between the two validity conditions corroborating that the subjects used the spatial cues for allocating attention, which employed cue validities of 75–80% (Corbetta et al., 2000; Kincade et al., 2005; Thiel et al., 2004, 2005). Thiel et al. (2004) found bilateral activation of the intraparietal cortex in response to invalidly as opposed to validly cued targets. Corbetta et al. (2000) separated cue- and target-related neural activity by using long cue–target intervals. They observed that the right hemispheric intraparietal cortex showed a significant validity effect.

In contrast to the parietal activations under 90% cue validity, reorienting in the 60% condition did not elicit suprathreshold activation of the right parietal cortex in the present study, though subjects exhibited a significant validity effect as indexed by behavioral data. When comparing activity in the 90% and 60% condition, we found clear evidence that neural activity in right parietal cortex was dependent on the validity of the spatial cue. In particular, this analysis yielded stronger activation of the intraparietal cortex as well as parts of the supramarginal and the angular gyrus in conditions of high top–down expectation. This result confirms the importance of this region for attentional reorienting processes. Consistent with this, the area activated in the present experiment represents one of the core regions for the manifestation of spatial neglect which according to the work of Posner et al. (1984) is characterized by a pronounced disengagement deficit. Particularly, a study of Mort et al. (2003) using high-resolution MRI demonstrated that the area most commonly involved in neglect resulting from middle cerebral artery stroke is located in the anteroventral part of the angular gyrus of the inferior parietal cortex. Other studies consider the adjacent region of the supramarginal gyrus as a key region for the manifestation of the neglect syndrome (Vallar, 2001; for a review, see Halligan et al., 2003). A patient study by Friedrich et al. (1998) demonstrated that inferior regions of the parietal cortex play a more crucial role for performance in location-cueing tasks than superior parietal structures.

The ROI analysis demonstrated that the observed parietal activation in this study is close to the temporoparietal part of the ventral fronto-parietal network which is supposed to be involved in reorienting processes in response to unexpected events (Corbetta et al., 2000; Corbetta and Shulman, 2002). Note that it was assumed that this network should predominantly be engaged in reflexive, stimulus-driven (i.e., exogenous) orienting of attention which is

**Table 3**

<table>
<thead>
<tr>
<th>Region</th>
<th>Side</th>
<th>MNI coordinates</th>
<th>Voxels</th>
<th>Z score</th>
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<tbody>
<tr>
<td>Inferior parietal cortex</td>
<td>R</td>
<td>x = 54, y = -48, z = 45</td>
<td>19</td>
<td>3.57</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>x = 57, y = -57, z = 15</td>
<td>33</td>
<td>3.56</td>
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<tr>
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<tr>
<td></td>
<td>R</td>
<td>x = 51, y = -39, z = 30</td>
<td>6</td>
<td>3.07</td>
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<tr>
<td>Superior temporal gyrus</td>
<td>R</td>
<td>x = 45, y = -45, z = 18</td>
<td>2</td>
<td>3.68</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>x = 57, y = -57, z = 15</td>
<td>18</td>
<td>3.56</td>
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45, y = -45, z = 21; Z = 2.92, 1 voxel; x = 51, y = -39, z = 33; Z = 2.74, 3 voxels; see Fig. 5. However, we did not find any activation within the ROI of the superior temporal gyrus as was observed when contrasting invalid and valid trials in the 90% cue validity condition.

**Discussion**

In the present fMRI study, we manipulated cue validity in a cued target detection paradigm and investigated its effect upon the neural mechanisms underlying reorienting of attention. The results of previous imaging studies using central predictive cues, i.e., investigating reorienting in the context of endogenous allocation of attention, which employed cue validities of 75–80% (Corbetta et al., 2000; Kincade et al., 2005; Thiel et al., 2004, 2005) found bilateral activation of the intraparietal cortex in response to invalidly as opposed to validly cued targets.

Brain areas adjoining to the intraparietal sulcus were activated bilaterally with a more extensive activation cluster on the right hemisphere in the 90% cue validity condition. This finding is in line with previous imaging studies using central predictive cues, i.e., investigating reorienting in the context of endogenous allocation of attention, which employed cue validities of 75–80% (Corbetta et al., 2000; Kincade et al., 2005; Thiel et al., 2004, 2005). Thiel et al. (2004) found bilateral activation of the intraparietal cortex in response to invalidly as opposed to validly cued targets. Corbetta et al. (2000) separated cue- and target-related neural activity by using long cue–target intervals. They observed that the right hemispheric intraparietal cortex showed a significant validity effect.

In contrast to the parietal activations under 90% cue validity, reorienting in the 60% condition did not elicit suprathreshold activation of the right parietal cortex in the present study, though subjects exhibited a significant validity effect as indexed by behavioral data. When comparing activity in the 90% and 60% condition, we found clear evidence that neural activity in right parietal cortex was dependent on the validity of the spatial cue. In particular, this analysis yielded stronger activation of the intraparietal cortex as well as parts of the supramarginal and the angular gyrus in conditions of high top–down expectation. This result confirms the importance of this region for attentional reorienting processes. Consistent with this, the area activated in the present experiment represents one of the core regions for the manifestation of spatial neglect which according to the work of Posner et al. (1984) is characterized by a pronounced disengagement deficit. Particularly, a study of Mort et al. (2003) using high-resolution MRI demonstrated that the area most commonly involved in neglect resulting from middle cerebral artery stroke is located in the anteroventral part of the angular gyrus of the inferior parietal cortex. Other studies consider the adjacent region of the supramarginal gyrus as a key region for the manifestation of the neglect syndrome (Vallar, 2001; for a review, see Halligan et al., 2003). A patient study by Friedrich et al. (1998) demonstrated that inferior regions of the parietal cortex play a more crucial role for performance in location-cueing tasks than superior parietal structures.

The ROI analysis demonstrated that the observed parietal activation in this study is close to the temporoparietal part of the ventral fronto-parietal network which is supposed to be involved in reorienting processes in response to unexpected events (Corbetta et al., 2000; Corbetta and Shulman, 2002). Note that it was assumed that this network should predominantly be engaged in reflexive, stimulus-driven (i.e., exogenous) orienting of attention which is
usually operationalized with peripheral cues that are not predictive with regard to the location of the upcoming target. Using central predictive cues (cue validity >50% in both conditions), however, we investigated reorienting in the context of two endogenous cues, i.e., after the voluntary allocation of attention in the present experiment. Interestingly, recent studies challenge the assumption that the tempo-parietal network is especially involved in stimulus-driven attention. Small et al. (2005) investigated the effects of monetary incentives (i.e., enhanced top–down control) on the performance in a cued target detection task with central cueing. The authors observed a significant relationship between activation of the right inferior parietal cortex and the amount of RT costs in response to invalid cues. This relationship was enhanced by monetary rewards. They concluded that the motivational incentive influenced the effort to disengage attention, and that this effort was reflected in greater recruitment of the inferior parietal cortex. Kincade et al. (2005) compared the neural mechanisms related to reorienting under endogenous and exogenous conditions. Using comparable ROI analyses of areas of the ventral fronto-parietal network reported by Corbetta et al. (2000), the authors observed that the modulation of these areas was stronger in response to an invalid endogenous rather than an invalid exogenous cue. Consistently, subjects in the study of Kincade et al. (2005) showed bigger validity effects in the endogenous than in the exogenous condition. The authors interpreted their results as reflecting the mismatch between expectation and sensory input in the endogenous condition.

Thus, an alternative explanation of our findings is that the observed activity in the tempo-parietal region may have resulted from a violation of expectancies rather than from more demanding attentional disengagement. Evidence for a differential modulation of spatially specific activity in occipital cortex in response to the two cues (like, e.g., observed by Hopfinger et al. (2000) when contrasting left- and right-sided cues) would argue for a differential distribution of attention and thus further strengthen our hypothesis that visuospatial reorienting is more difficult in response to a highly valid cue. However, the short cue–target interval and the unilateral target presentation (i.e., without a no-go stimulus on the opposite side), which were chosen in the present study from a psychological perspective, do not permit a separation of cue- and target-related neural activity. Consequently, we cannot investigate laterality effects any further. As invalid trials in the 90% cue validity condition are by definition less frequent than in the 60% condition and expectancy violation is presumably more prevailing under high cue validity, our study does not allow a clear-cut separation of expectancy mismatch and reorienting. Indeed, it has been observed that parts of the ventral fronto-parietal network elicit activation in response to novel or oddball stimuli that do not require visuospatial attention shifts (Linden et al., 1999; Kiehl et al., 2001; Downar et al., 2002). This suggests that these areas may play a more general role in signaling the unexpected appearance of relevant stimuli (Kincade et al., 2005) or coordinating top–down attentional control settings with incoming sensory information (Serences et al., 2005).

### Superior temporal gyrus

Besides the inferior parietal cortex, parts of the superior temporal gyrus are regarded as belonging to the tempo-parietal junction. Activation of this area was found in the 90% cue validity condition, though the cluster was located near the tempo-parieto-occipital junction. Similar regions were also activated in studies investigating endogenous as compared to exogenous allocation of attention (Kim et al., 1999; Mayer et al., 2004) or activity during attentional shifts compared to a baseline condition (Gitelman et al., 1999). It has been suggested that tempo-occipital areas are part of the top–down attentional system (Gitelman et al., 1999, Hopfinger et al., 2000) and that activation of these regions could reflect the inferred movement of the attentional focus to a specific location (Kim et al., 1999). Thus, the increased activity in response to invalidly cued targets in the present study may also result from augmented “movement” processes of the attentional focus rather than representing the disengagement component of reorienting. In this context, it is noteworthy that we did not find any activation in the ROI of the STG when contrasting the validity effects of the two cue validity conditions. However, further research is needed to clearly separate the disengagement and shift component involved in the process of attentional reorienting.

### Middle frontal gyrus/inferior frontal gyrus

Several frontal regions were activated in the present study. In the 60% cue validity condition, the left inferior frontal gyrus was significantly activated in response to invalidly cued targets. In the 90% cue validity condition, the right inferior frontal gyrus was activated, and the comparison of the two validity effects yielded differential activation of two clusters in the right middle frontal gyrus and the right inferior frontal gyrus in the high cue validity condition. These regions are part of the prefrontal cortex which has previously been related to cognitive control processes (for a review, see Miller, 2000). Activation of the right middle and inferior frontal gyrus in location-cueing paradigms has been interpreted as reflecting evaluation processes of unexpected stimuli (Corbetta et al., 2002) or as inhibition of premature responses until reorientation is accomplished (Arrington et al., 2000). As in the case of the parietal activation, the differential activity in frontal areas was mainly caused by differences in invalid trials. One could thus speculate that invalid trials in the 90% cue validity condition required stronger inhibitory processes because of the high predictiveness of the cue. Moreover, recent research suggests a hierarchical model of prefrontal and parietal cortex function in cognitive control with prefrontal regions modulating the activity in posterior brain regions (Brass et al., 2005; Miller and D’Esposito, 2005). We accordingly suggest that the activations observed in this study may reflect such an interplay between frontal and parietal brain areas.

### Conclusion

The present fMRI study demonstrates that the neural mechanisms underlying reorienting of visuospatial attention are susceptible to cue validity manipulations in location-cueing paradigms and that the activation of a right-hemispheric fronto-parietal attentional network is modulated according to the probabilistic information of the spatial cue.

### Acknowledgments

We are grateful to our colleagues from the MR and Cognitive Neurology groups for valuable support and discussions. C.M.T. and G.R.F. are supported by the Deutsche Forschungsgemeinschaft (KFO-112, TP 8).
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