

available at www.sciencedirect.comwww.elsevier.com/locate/brainres

**BRAIN
RESEARCH**

Research Report

Directing attention to a location in space results in retinotopic activation in primary visual cortex

Jaap Munneke*, Dirk J. Heslenfeld, Jan Theeuwes

Vrije Universiteit, Amsterdam, Netherlands

ARTICLE INFO
Article history:

Accepted 11 May 2008

Available online 27 May 2008

Keywords:

Preparatory attention

Endogenous cueing

Event-related fMRI

Human V1

ABSTRACT

It is well-known that directing attention to a location in space enhances the processing efficiency of stimuli presented at that location. Previous studies have shown that directing spatial attention manifests itself as an increase in spontaneous firing rate of neurons (the baseline signal) in extrastriate cortex at the retinotopic corresponding location. There has been considerable debate as to whether this preparatory effect of attention also occurs in human striate cortex (area V1). In the present study, participants had to direct attention to a cued location in space, while changes in blood oxygen level dependent (BOLD) signals were measured. We show that in conditions in which there was no change in sensory stimulation, modulations due to flexibly shifting spatial attention were present throughout early visual cortex (areas V1, V2 and V3). In all early visual areas, the increased BOLD signal in response to the cue was retinotopically specific. The present study shows that voluntary top-down attentional control modulates activity not only in extrastriate but also in striate cortex. This modulation occurs quickly and flexibly in a retinotopic fashion, and serves to facilitate target processing in a continuously changing environment.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

It has long been established that attention exerts influence on the visual system in order to cope with the vast amount of information that is passed on from the retina to the brain. Visual attention allows people to select information that is relevant for ongoing behaviour. Directing visual attention towards a location in space is thought to enhance the processing efficiency of objects presented within the attended area (Posner and Petersen, 1990). The effective utilization of spatial information is related to an attention mechanism that operates analogous to a “beam of light”. As a metaphor, Posner described visual selective attention as a “spotlight” that enhances the efficiency of the detection of events within its beam (Posner, 1980, p. 172). Providing information about the

location of an upcoming target usually involves a cueing procedure in which a cue indicates the location of the target. Such a cue may consist of a centrally presented arrow that points to the likely target location (e.g. Posner, 1980), or a word (“right” or “left”) (e.g. Vecera and Rizzo, 2004) indicating the target location. Cueing in this way is typically referred to as “endogenous” or top-down, because participants are instructed to use this information in a top-down way to improve their performance. Typically, this preparatory effect of attention is revealed by performance benefits in responding to a target presented at the cued location relative to conditions in which no advance information about the target location is provided.

Previous studies have shown that the deployment of attention modifies neural activity in several areas in visual cortex (Moran and Desimone, 1985; Spitzer et al., 1988). Preparatory

* Corresponding author. Department of Cognitive Psychology, Vrije Universiteit, Van der Boechorststraat 1, 1081 BT Amsterdam, The Netherlands. Fax: +31 20 598 8971.

E-mail address: JA.Munneke@psy.vu.nl (J. Munneke).

cueing effects modulate brain activity as early as visual area V2 and can be found in numerous other structures of the extrastriate cortex including areas V3, V4 and MT (Corbetta et al., 2005; Hopfinger et al., 2000; Kastner et al., 1999; Luck et al., 1997). From these and from behavioural studies (e.g. Treisman and Gelade, 1980) it has become clear that attention plays an important role in early visual processing.

The preparatory signal evoked by spatial cueing manifests itself as an increase in spontaneous firing rate of neurons in those parts of visual cortex that code the cued location. Increases in activity based on location cueing have been labeled baseline shifts (Hopfinger et al., 2000; Kastner et al., 1999; Ress et al., 2000). These shifts in baseline activity, which occur in a retinotopic fashion in visual cortex, are thought to reflect the top-down signal from areas outside the visual cortex. Brain areas possibly responsible for the top-down signal are the superior eye fields (SEF), the frontal eye fields (FEF) and the superior parietal lobule (SPL), all of which modulate with the attentional effects in the visual cortex (Corbetta et al., 1998; Kastner et al., 1999; Ruff et al., 2006).

Deploying attention thus changes the excitability of sensory neurons in a spatially specific manner. Typically, only extrastriate cortex shows modulated activity as a function of where attention is directed (Giesbrecht et al., 2003; Hopfinger et al., 2000). Whether attention also modulates preparatory activity in the earliest part of the visual cortex, area V1, is still subject for debate. Although many studies showed that attention modulates the processing of sensory information in primary visual cortex (Brefczynski and DeYoe, 1999; Gandhi et al., 1999; Martinez et al., 1999; Silver et al., 2005; Somers et al., 1999; Tootell et al., 1998; Worden and Schneider, 1996), conflicting results have been reported concerning preparatory attention following the presentation of a cue. A number of studies failed to show baseline shifts in V1 (Corbetta et al., 2005; Hopfinger et al., 2000; Luck et al., 1997), whereas others did (Jack et al., 2006; Kastner et al., 1999; Ress et al., 2000; Silver et al., 2007). However, in none of these studies were the V1 modulations found to be evoked by a flexible allocation of preparatory attention to various regions in visual space. For example, Kastner et al. (1999) used a blocked design in which participants had to direct their attention to one location in space throughout a block of trials. Jack et al. (2006), Ress et al. (2000) and Silver et al. (2007) used a design in which participants had to report the presence of a ring-shaped target surrounding the fixation point. However, these tasks never

required the participants to constantly shift attention to different locations in the visual field in order to detect the target. Therefore, even though the reported activations in V1 reflect preparatory attention, it is not clear whether such effects would be observed when participants shift attention to an unpredictable location in an endogenous way from trial to trial (e.g., Posner, 1980).

In the present study we used a variant of the classic Posner cueing task to direct attention to different locations in an endogenous fashion from trial to trial. An example of a trial is given in Fig. 1. Participants were instructed to direct their attention covertly to the ‘2’ or ‘8’ o’clock position on an imaginary circle. Subsequently, a target display was presented which consisted of an annulus of many tilted line segments, plus a target vertical or horizontal line at the indicated location. Participants had to decide by button press whether the target orientation was present at the indicated location. We determined whether under these trial-by-trial cueing conditions we would observe attention-related brain activity in V1 in a retinotopic fashion.

2. Results

2.1. Behavioral data

Participants performed significantly better when a target was validly cued, compared to performance on neutrally cued targets ($t(9)=8.419, p<0.001$). Mean d' was 1.95 for validly cued targets, compared to a d' of 1.16 for uncued targets. All participants showed a larger d' on trials in which the target was preceded by a valid cue.

2.2. fMRI data

We determined the hemodynamic brain responses evoked by the cues in two ways. First, fMRI signals evoked by cues were separated from fMRI signals evoked by targets by means of a deconvolution analysis, separately for each participant and region of interest (ROI). Fig. 2b shows the activity evoked by the cues, separately for each ROI and averaged over participants and hemispheres. For each latency, we tested whether cues indicating contralateral targets (i.e., when the corresponding visual field location is attended) led to larger responses than cues indicating ipsilateral targets (when the corresponding

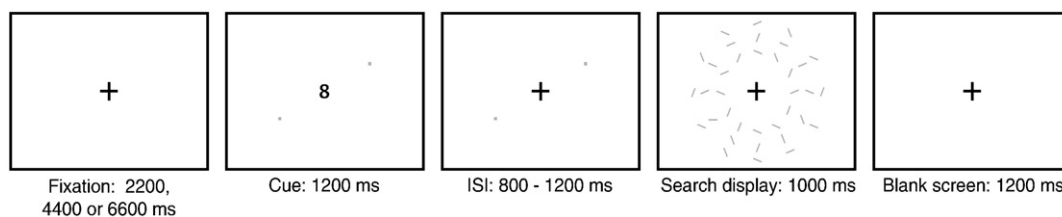


Fig. 1 – Experimental procedure. Participants focused on a centrally presented fixation point. A cue consisting of either a “2” or an “8” indicated the likely target location. Participants were told to covertly orient their attention to either the “2” or “8” o’clock position. A “0” (neutral cue) indicated that the target could appear at either location. The search display consisted of a cluttered field of slightly tilted line segments. One line segment was oriented either vertical or horizontal, the orientation determining the appropriate response. In 25% of the trials, the cue was not followed by a search display; these served to compute fMRI responses to cues and targets independently.

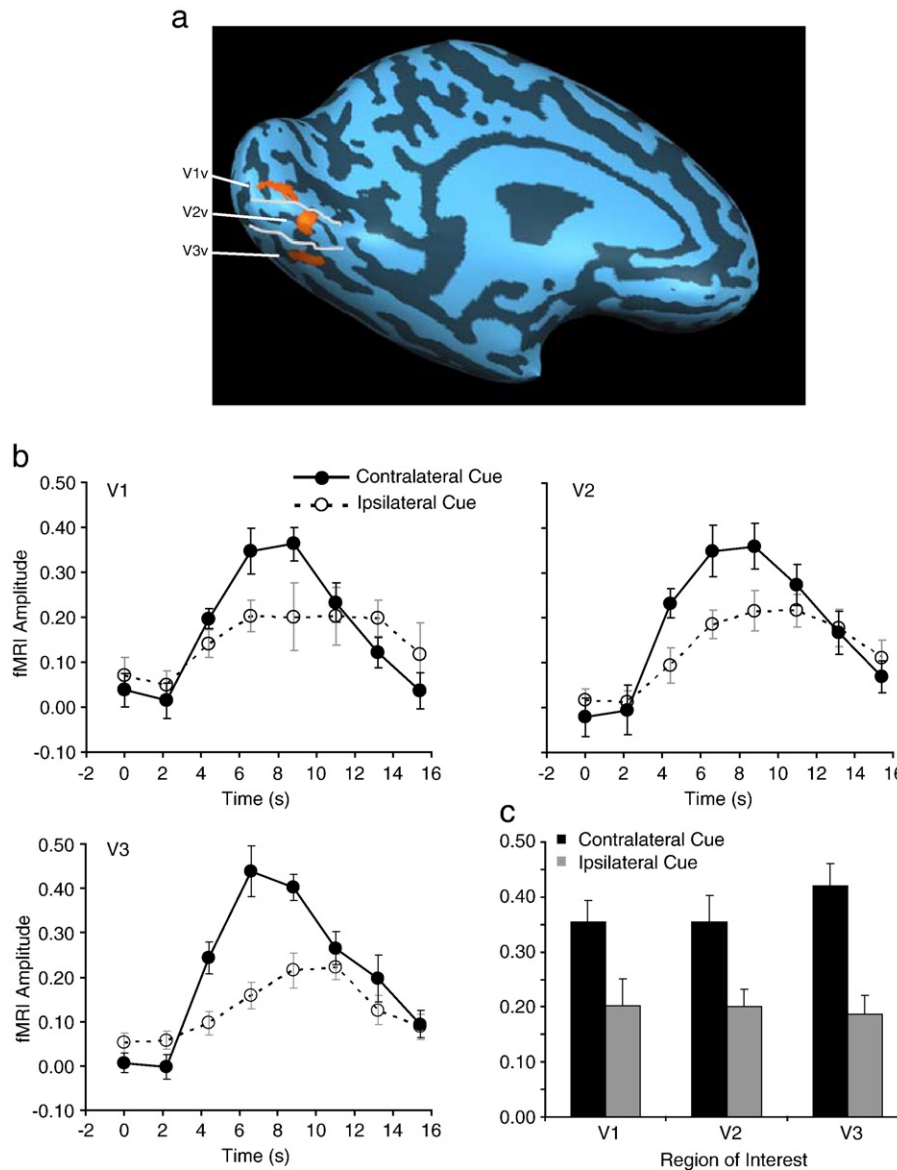


Fig. 2 – a) Inflated hemisphere with ROIs from a typical participant. **b)** Cortical activation in response to all cues. Results of the deconvolution analysis. Activation evoked by cues indicating the contralateral visual field (such that the corresponding location is attended) was compared to activation evoked by cues indicating the ipsilateral visual field (such that the corresponding location is unattended). A significant increase in activation is seen throughout early visual cortex, including areas V1, V2 and V3. **c)** Difference in activity between contralateral and ipsilateral cues for the time period between 6.6 and 11 s for V1, V2 and V3. Error bars represent normalized standard errors (Loftus and Masson, 1994).

visual field location is unattended) in the defined regions of interest. For V1 this effect was present between 6.6 and 11 s after cue-onset (smallest $F(1,9)=5.700$, $p<0.041$), in V2 and V3 the effect was present between 4.4 and 11 s after cue-onset (V2: smallest $F(1,9)=7.675$, $p<0.022$; V3: smallest $F(1,9)=11.103$, $p<0.009$). For the latencies during which all ROIs showed significant effects of cueing (between 6.6 and 11 s post-cue), the effect increased linearly over ROIs ($F(1,9)=11.053$, $p=0.009$; see Fig. 2c, Table 1), indicating that the attentional modulation became larger in hierarchically higher areas in visual cortex.

In a second, independent analysis, we computed event-related averages for the catch trials, i.e. those trials that were not followed by targets, separately for each ROI and participant,

in order to determine effects of cueing without any further contribution from target displays. Fig. 3a gives the event-related BOLD responses evoked by the catch trials, averaged over participants and hemispheres. Again, for each latency and ROI we tested whether cues indicating contralateral targets evoked a larger response than cues indicating ipsilateral targets. Increased activity to contralateral cues was found in V1 between 8.8 and 13.2 s post-cue (smallest $F(1,9)=7.251$, $p<0.025$); in V2 and V3 this effect was observed between 6.6 and 13.2 s post-cue (V2: smallest $F(1,9)=8.365$, $p<0.018$; V3: smallest $F(1,9)=7.169$, $p<0.025$). Again, a linear increase in activity was observed over ROIs from 8.8 to 13.2 s ($F(1,9)=16.437$, $p=0.003$; see Fig. 3b, Table 1). Note that this increase of activity towards

Table 1 – Normalized fMRI responses averaged over 10 participants between 6.6 and 11 seconds post-cue on cue–target trials and between 8.8 and 13.2 post-cue on catch trials, separately for each ROI and attention condition

ROI	Cue-target (6.6 s–11 s)			Catch trials (8.8 s–13.2 s)		
	Ipsilateral	Contralateral	% Change	Ipsilateral	Contralateral	% Change
V1	0.202	0.355	75.75	–0.170	–0.076	55.37
V2	0.201	0.354	76.34	–0.193	–0.054	71.84
V3	0.187	0.420	124.74	–0.220	–0.001	99.57

In addition, the averaged percentage of signal increase is given, separately for each ROI. The left columns are derived from the cue-evoked responses as computed in the deconvolution analysis over all trials. The right columns are derived from the event-related averages of the catch trials only.

higher visual areas was observed merely on the basis of a cue (i.e., in catch trials), without any further change in sensory input. Table 1 gives the normalized activity to contralateral and ipsilateral cues, as well as the percentage change, for each ROI and for both types of analyses.

In order to examine whether the observed attentional effects were retinotopically specific, we also looked at activity in homologue regions corresponding to the remaining two quadrants (i.e., clock positions ‘4’ and ‘10’), which were never cued. In none of those ROIs (V1, V2, V3) was a significantly different activity observed in the hemisphere contralateral to the cued side, indicating that the effects of cueing were highly

specific at the corresponding retinotopic location in all three early visual areas (for V1, largest $F(1,9)=2.737$, ns; for V2, largest $F(1,9)=1.300$, ns; for V3, largest $F(1,9)=3.122$, ns).

3. Discussion

The present study used a classic Posner cueing task in which on each trial participants directed attention to the location indicated by a centrally presented symbolic cue. Consistent with previous studies we found an improved sensitivity for detecting targets at the location indicated by the cue relative to

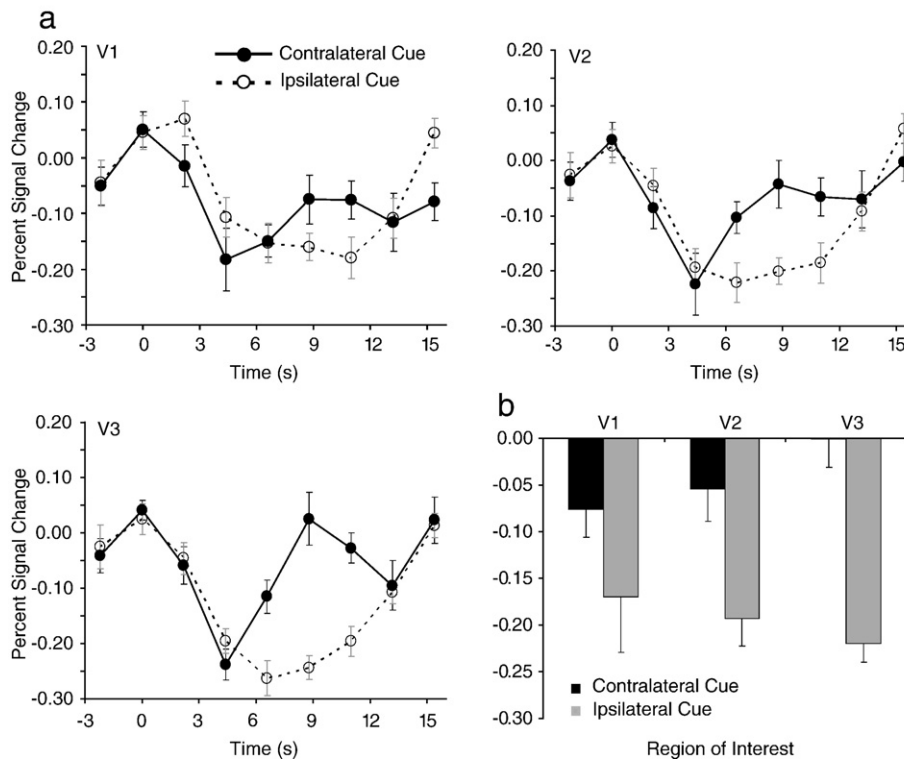


Fig. 3 – a) Cortical activation in response to cues in catch trials, i.e. cues that were not followed by target displays. Activation evoked by cues indicating the contralateral visual field was compared to activation evoked by cues indicating the ipsilateral visual field, without any sensory contribution from target displays. Each curve represents the averaged time course of the fMRI signal, averaged across trials, hemispheres and participants. A significant decrease in activation is seen throughout early visual cortex, including areas V1, V2 and V3. b) Difference in activity between contralateral and ipsilateral cues for the time period between 8.8 and 13.2 s for V1, V2 and V3, for cues in catch trials. Error bars represent normalized standard errors (Loftus and Masson, 1994).

conditions in which no location information was provided. In addition, we show that under these conditions there is increased activation in visual cortex contralateral to the side indicated by the cue. Moreover, this activity is retinotopic and seen in all visual areas including primary visual cortex. In other words, when participants endogenously shift their attention between regions in visual space, a change in activity was observed at the corresponding retinotopic locations in V1. The fMRI data show that after cue presentation, activation in retinotopically corresponding areas in V1 increases when the cue indicated the corresponding contralateral visual field location, even in catch trials in which no target stimulus was presented. We therefore conclude that the striate cortex is not a mere passive relay station for visual information but is actively involved in preparatory attentional processes. The current findings are consistent with the suggested metaphor (Posner, 1980) that compares directing attention to a spotlight that “illuminates” parts of the visual world around us. In line with this notion, our results suggest that directing the spotlight results in an increased activity in areas as early as V1.

The present findings are consistent with previous studies showing preparatory effects in striate cortex to targets or in more sustained paradigms. Previous fMRI investigations showed modulation of target-elicited neural activity as a function of attention (Brefczynski and DeYoe, 1999; Gandhi et al., 1999; Martinez et al., 1999; Silver et al., 2005; Somers et al., 1999; Tootell et al., 1998; Worden and Schneider, 1996). Typically in these types of tasks, two or more stimuli were presented simultaneously, and participants were instructed to direct their attention to each location in turn and to detect or discriminate target stimuli presented at that location. These studies showed that spatial attention changes the sensory activity evoked by a target within both striate and extrastriate cortex. In addition to these studies, effects of attention have also been demonstrated in V1 based on the mere preparation for a target, in the absence of further visual stimulation (Jack et al., 2006; Kastner et al., 1999; Ress et al., 2000; Silver et al., 2007). In these studies the observed modulations were obtained when participants directed their attention to the same location consistently over a whole block of trials. The current study extends these findings and shows that similar effects can be observed when observers shift attention flexibly on a trial-by-trial basis to unpredictable locations.

In contrast to the present finding, it should be noted that electrophysiological studies using event-related potentials (ERPs) suggested that spatial attention does not modify activity in primary visual cortex (Di Russo et al., 2003; Martinez et al., 1999, 2001; Noesselt et al., 2002). These studies found modulations of fMRI responses to attended stimuli in V1 without accompanying effects on the electrophysiological C1 component. It was concluded that attentional effects in V1 are the result of delayed re-entrant feedback from higher visual areas. On the other hand, Kelly et al. (2008) using more sophisticated averaging procedures, showed that spatial attention can modulate the electrophysiological C1 response. Furthermore, several studies report a retinotopic decrease in EEG alpha power over occipital regions in spatial cueing tasks (Kelly et al., 2006; Thut et al., 2006; Worden et al., 2000), suggesting that early visual areas must be involved in attentional preparation. Our data show that spatial attention can

modulate the fMRI V1 response even in catch trials which are not followed by a target display, and therefore not subject to re-entrant activation. This suggests that the fMRI V1 effects observed by Martinez and others may have contained early, genuine modulations as well, which may have been too small to be detected by standard ERP procedures.

In addition to signal increases in response to all cues (most of which were followed by search displays), we also observed fMRI signals in early visual areas in response to catch trials (in which no search display followed the cue). Note that the BOLD responses to catch trials (Fig. 3a) are quite different from the BOLD responses to all cues (Fig. 2b). As it was highly likely that a target display would follow the cue (catch trial probability was only 0.25), the observed difference in activity is most likely due to the absence of the expected search display. Davidson et al. (2004) reported decreased activity following the absence of an expected stimulus. Indeed, when no search display is presented in the current task a decrease in activity is observed as well. However, the effects of attention are still present, showing a relative increase of brain activity at the corresponding retinotopic location.

The attentional modulation increased linearly over ROIs with the largest cueing effects occurring in V3. This trend is thought to be due to the increase in receptive field size of neurons in higher visual areas.

While in our study activity in V1 was clearly modulated by preparatory spatial attention, other studies have failed to find this effect (e.g. Corbetta et al., 2005; Hopfinger et al., 2000; Luck et al., 1997). This difference may be explained in a number of ways. First, it has been argued that the presence of distractors plays an important role in preparatory spatial attention. Serences et al. (2004) showed that cue-evoked preparatory attention is directly linked to a distractor-suppression component of attention. When observers know that there is a high likelihood that distractors accompany the target, cue-evoked activity may not only show an increase due to excitatory processes, but also an inhibitory effect suppressing distractor locations around the expected target. In the present study, the target was always embedded in distractors. The mere expectation that distractors will be present may have resulted in a stronger preparatory effect that is not seen in studies that present targets without distractors (e.g. Luck et al., 1997; Corbetta et al., 2005). Second, task difficulty has been shown to influence activity in V1 as well. Ress et al. (2000) showed that decreased difficulty in target detection led to a loss in preparatory attentional effects in V1. This implies that only when attention is in high demand, V1 shows an effect of selective preparation. It is possible that studies that did not find preparatory effects in V1, did not use a task difficult enough to require such early selective modulation. In this view attention in V1 operates in a different fashion compared to regions in extrastriate cortex, which do show an effect of attention even when the demand for attention is relatively low.

In the current study, eye movements were recorded in order to establish whether subjects maintained fixation during the critical cue-target period. Eye movements during this period would lead to inflated performance and undesirable effects in early visual cortex. Due to technical constraints we could not use infrared eye-tracking, but resorted to the

electro-oculogram (EOG). There was no effect of cue direction on the EOG traces, but the method is not entirely optimal. It is sensitive to relative systematic eye movements, so it requires proper fixation at the beginning of a trial and enough trials with the same type of response. On the other hand, subjects needed to fixate at the center in order to identify the cue, and eye movements towards the target location would have moved that location out of the cortical regions of interest, so would have weakened the attentional effects. Therefore we feel confident that our results are not caused by systematic confounding eye movements.

In sum, the present study shows that primary visual cortex is activated by preparatory spatial attention. By endogenously changing the focus of attention from trial to trial, a change in activity in primary visual cortex was observed at the corresponding retinotopic location. In combination with recent ERP work (Kelly et al., 2008) our findings suggest that primary visual cortex may operate as a locus of initial sensory gain control, prioritizing visual input from an attended location.

4. Experimental procedures

4.1. Participants

Based on the results of an eye movement screening study, 10 healthy participants (3 male, mean age=23.7) were selected to take part in the fMRI experiment. All participants were right-handed and had normal or corrected-to-normal vision. Informed consent was obtained before taking part in the experiment. Participants received a financial compensation. The protocol was approved by the ethical committee of the VU University Medical Center, Amsterdam, The Netherlands.

4.2. Stimuli and task

An example of an experimental trial is given in Fig. 1. Participants were instructed to focus on a centrally presented fixation point, which was presented for either 2200, 4400 or 6600 ms. Following fixation, a cue appeared at the center of the screen for 1200 ms. The cue could be one of the digits '2', '8', or '0', and subtended 0.65 by 0.38°. This digit instructed participants to covertly shift their attention to the corresponding location on an imaginary clock. Digits '2' or '8' indicated that the target could appear at the corresponding clock location; when '0' was presented, the target could appear at either of these locations. The neutral condition served to estimate the uncued baseline performance. After cue presentation the screen went blank for a random duration of 800–1200 ms, during which participants were instructed to maintain attentional focus on the cued location. To help participants focus on the exact location in an otherwise blank display, two faint, one-pixel dots were presented throughout the trial indicating the two possible target locations. The search display, presented for 1000 ms, contained either a horizontal or a vertical line functioning as target stimulus. Participants responded manually if they detected one of the target orientations. The target was embedded in distractor stimuli, consisting of tilted lines, subtending 22° from the horizontal or vertical position. Distractors were presented on

three imaginary circles surrounding the point of fixation at a distance of respectively 4.14, 5.49 and 6.84 visual degrees. Targets were always presented on the middle circle so that they were fully surrounded by distractors. The difficulty of the task was adjusted on-line in order to maintain a steady performance level. Changes in task difficulty were achieved by increasing or decreasing the length of the line by 2 pixel after every ten trials. All lines were extended when performance dropped below 75% and shortened when performance was higher than 75%. After the target disappeared from the screen, a blank screen appeared for 1200 ms, during which the participant was still allowed to respond. After this period a new trial was initiated. The onset of each trial was synchronized to the onset of an fMRI volume (see below).

In 25% of the trials, the cue was not followed by a target display. Instead a blank screen lasting 2200 ms was presented after which a new trial was initiated. These catch trials were inserted to decorrelate fMRI responses evoked by cues and targets within a trial (e.g., Ollinger et al., 2001). In total, 320 trials were presented to each participant, divided over 5 blocks. Participants were instructed to respond as accurately as possible. Stimulus presentation and response collection were controlled using E-Prime 1.1 (Psychology Software Tools).

4.3. EOG screening task

Before taking part in the fMRI experiment participants were carefully screened for their ability to shift attention but not their eyes, as eye movements would confound the results in the scanner. Participants were seated in a dimly lit room at a distance of 100 cm from the presentation screen. To measure eye movements, tin electrodes were placed at the outer canthi of each eye and above and below the right eye. Electro-oculogram (EOG) signals were averaged for each condition (cue left, cue right), providing the average deflection from the fixation point between cue and target presentation. Participants started with a practice block, and five experimental blocks were presented

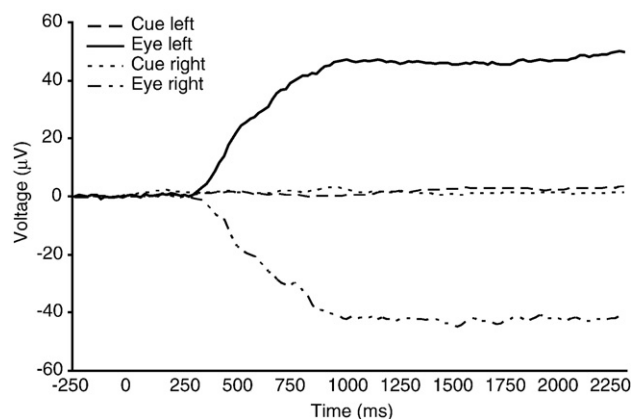


Fig. 4 – Horizontal EOG time-locked to the onset of the cue, averaged over all participants participating in the fMRI study. No eye movements were observed following the cue during the critical trial period (dotted and dashed line). For comparison, induced eye movements to the left and right-target location are added (solid and dash-dotted line). Target eccentricity was 5.5° of visual angle.

subsequently, identical to the task in the MRI scanner. Finally, one additional block of trials was presented during which participants were instructed to make an eye movement towards the cued location. Fig. 4 displays the averaged cue-locked EOG for all 10 participants participating in the MRI study, showing trials of the main task and trials in which eye movements were required. As can be seen no eye movements were initiated after cue presentation in the main task.

4.4. Scan acquisition

Imaging sessions took place in a 1.5 T Siemens Sonata scanner (Siemens Medical Systems, Erlangen, Germany), using an 8-channel phased-array head coil. Participants viewed the stimuli through a mirror attached to the head coil. Functional data were collected using an EPI sequence scanning the whole brain in 24 near-axial slices. Scanning parameters for the main task were: TR=2200 ms, TE=55 ms, flip angle=90°, slice thickness=4 mm, gap=0.8 mm, acquisition matrix=64×64, and in-plane resolution=3.1×3.1 mm. All volumes were on-line motion corrected.

A 3-D anatomical scan was made at the end of the session, using a T1-weighted MP-Rage sequence. Scanning parameters were: TR=2730 ms, TE=3.43, TI=1000 ms, flip angle=7°, sagittal slice thickness=1 mm, acquisition matrix=256×224 pixels, in-plane resolution=1×1 mm.

EOG was also recorded in the scanner between 2 carbon electrodes placed at the outer canthi of each eye, to ensure that participants did not make eye movements during the MRI sessions. Analysis of these data showed that participants were able to maintain fixation also during scanning. We tested the difference between EOG traces following leftward and rightward pointing cues and found no effect ($t(9)=1.744$, ns).

4.5. Retinotopic mapping of visual areas

In two additional blocks, the vertical and horizontal meridian as well as the two target locations at clock positions '2' and '8' where stimulated with local flickering checkerboard patterns. The checks were counterphased at 10 Hz; each stimulus lasted 4 s and was followed by the next after 8 s. These localizer blocks served to identify the borders between visual areas V1, V2, V3, and the exact projection of the relevant visual field locations within these areas.

4.6. MRI data analysis

MRI data were analyzed using BrainVoyager QX 1.8 (Brain Innovation, Maastricht, The Netherlands). The first two volumes of each block were omitted in order to avoid differences in T1 saturation. The preprocessing of the remaining functional volumes consisted of slice scan-time correction, highpass filtering (0.01 Hz), slight spatial smoothing (3 mm FWHM Gaussian kernel), but no temporal smoothing.

The functional scans were automatically and if necessary manually coregistered to each individual anatomical scan and converted to Talairach space (Talairach and Tournoux, 1988) resulting in 4D functional data sets in Talairach space (e.g., Goebel et al., 2001). Anatomical scans were also converted to Talairach space and segmented in order to separate the va-

rious tissues in each hemisphere. Based on the boundary between gray and white matter a model of the cortical surface was created. The segmented brains were then inflated, resulting in a smooth model of the cortical surface on which the functional data was projected. Based on the retinotopic data, regions of interest (ROIs) were defined in each of the 20 hemispheres corresponding to the projections of clock positions '2' and '8' in dorsal visual areas V1d, V2d, V3d in the right hemisphere, and ventral areas V1v, V2v, V3v/VP in the left hemisphere. Fig. 2a shows a typical inflated left hemisphere and the three ROIs. In addition, based on the meridian activation, we also defined the homologue regions corresponding to clock positions '4' and '10', in order to determine the retinotopic nature of the attentional modulation.

Preparatory effects due to the cue were analyzed in these ROIs using two strategies: (a) We estimated the BOLD responses to all cues (both in catch trials and trials in which target displays followed the cue) by means of a deconvolution GLM. A regressor was assigned to each of 8 volumes following the onset of all leftward, rightward and neutral cues, as well as following the onset of all left- and right-target displays. Note that the presence of catch trials (i.e., cue only) allowed us to decorrelate cue-related signals from target-related signals (e.g., Ollinger et al., 2001). (b) We estimated the BOLD responses to the catch trials (i.e., only those trials in which cues were not followed by target displays) by computing event-related averages separately for each participant, ROI, and cue (i.e., the digit '2' or '8'). This allowed us to analyze BOLD responses to cues without any possible sensory contribution from target displays.

In both analyses, the resulting time series were averaged across hemispheres for each ROI (i.e., V1, V2, V3). Cueing effects were identified by comparing responses to cues indicating targets in the contralateral visual field (i.e., when the corresponding location was attended) with responses to cues indicating targets in the ipsilateral visual field (when the corresponding location was unattended), separately for each ROI and latency (i.e. fMRI volume).

Acknowledgments

This research was funded by a grant from Human Frontier Science Program (HSFP-RGP39/2005) to Jan Theeuwes. Correspondence concerning this article should be addressed to Jaap Munneke, Department of Cognitive Psychology, Vrije Universiteit, Amsterdam, The Netherlands. E-mail: JA.Munneke@psy.vu.nl.

REFERENCES

- Brefczynski, J.A., DeYoe, E.A., 1999. A physiological correlate of the 'spotlight' of visual attention. *Nat. Neurosci.* 2 (4), 370–374.
- Corbetta, M., Akbudak, E., Conturo, T.E., Snyder, A.Z., Ollinger, J.M., Drury, H.A., et al., 1998. A common network of functional areas for attention and eye movements. *Neuron* 21 (4), 761–773.
- Corbetta, M., Tansy, A.P., Stanley, C.M., Astafiev, S.V., Snyder, A.Z., Shulman, G.L., 2005. A functional MRI study of preparatory

- signals for spatial location and objects. *Neuropsychologia* 43 (14), 2041–2056.
- Davidson, M.C., Horvitz, J.C., Tottenham, N., Fossella, J.A., Watts, R., Ulug, A.M., et al., 2004. Differential cingulate and caudate activation following unexpected nonrewarding stimuli. *Neuroimage* 23 (3), 1039–1045.
- Di Russo, F., Martinez, A., Hillyard, S.A., 2003. Source analysis of event-related cortical activity during visuo-spatial attention. *Cereb. Cortex* 13, 486–499.
- Gandhi, S.P., Heeger, D.J., Boynton, G.M., 1999. Spatial attention affects brain activity in human primary visual cortex. *Proc. Natl. Acad. Sci. U. S. A.* 96 (13), 3314–3319.
- Giesbrecht, B., Woldorff, M.G., Song, A.W., Mangun, G.R., 2003. Neural mechanisms of top-down control during spatial and feature attention. *NeuroImage* 19 (3), 496–512.
- Goebel, R., Muckli, L., Zanella, F.E., Singer, W., Stoerig, P., 2001. Sustained extrastriate cortical activation without visual awareness revealed by fMRI studies of hemianopic patients. *Vis. Res.* 41 (10–11), 1459–1474.
- Hopfinger, J.B., Buonocore, M.H., Mangun, G.R., 2000. The neural mechanisms of top-down attentional control. *Nat. Neurosci.* 3 (3), 284–291.
- Jack, A.I., Shulman, G.L., Snyder, A.Z., McAvoy, M., Corbetta, M., 2006. Separate modulations of human V1 associated with spatial attention and task structure. *Neuron* 51 (1), 135–147.
- Kastner, S., Pinsk, M.A., De Weerd, P., Desimone, R., Ungerleider, L.G., 1999. Increased activity in human visual cortex during directed attention in the absence of visual stimulation. *Neuron* 22 (4), 751–761.
- Kelly, S.P., Lalor, E.C., Reilly, R.B., Foxe, J.J., 2006. Increases in alpha oscillatory power reflect an active retinotopic mechanism for distractor suppression during sustained visuospatial attention. *J. Neurophysiol.* 95, 3844–3851.
- Kelly, S.P., Gomez-Ramirez, M., Foxe, J.J., 2008. Spatial attention modulates initial afferent activity in human primary visual cortex. *Cereb. Cortex*. doi:10.1093/cercor/bhn022.
- Loftus, G.R., Masson, M.E.J., 1994. Using confidence intervals in within-subject designs. *Psychon. Bull. Rev.* 1, 476–490.
- Luck, S.J., Chelazzi, L., Hillyard, S.A., Desimone, R., 1997. Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *J. Neurophysiol.* 77 (1), 24–42.
- Martinez, A., Anllo-Vento, L., Sereno, M.I., Frank, L.R., Buxton, R.B., Dubowitz, D.J., et al., 1999. Involvement of striate and extrastriate visual cortical areas in spatial attention. *Nat. Neurosci.* 2 (4), 364–369.
- Martinez, A., Di Russo, F., Anllo-Vento, L., Sereno, M.I., Buxton, R.B., Hillyard, S.A., 2001. Putting spatial attention on the map: timing and localization of stimulus selection processes in striate and extrastriate visual areas. *Vis. Res.* 41, 1437–1457.
- Moran, J., Desimone, R., 1985. Selective attention gates visual processing in the extrastriate cortex. *Science* 229 (4715), 782–784.
- Noesselt, T., Hillyard, S.A., Woldorff, M.G., Schoenfeld, A., Hagner, T., Jancke, L., et al., 2002. Delayed striate cortical activation during spatial attention. *Neuron* 35, 575–587.
- Ollinger, J.M., Shulman, G.L., Corbetta, M., 2001. Separating processes within a trial in event-related functional MRI — I. The method. *NeuroImage* 13 (1), 210–217.
- Posner, M.I., 1980. Orienting of attention. *Q. J. Exp. Psychol.* 32, 3–25.
- Posner, M.I., Petersen, S.E., 1990. The attention system of the human brain. *Annu. Rev. Neurosci.* 13, 25–42.
- Ress, D., Backus, B.T., Heeger, D.J., 2000. Activity in primary visual cortex predicts performance in a visual detection task. *Nat. Neurosci.* 3 (9), 940–945.
- Ruff, C.C., Blankenburg, F., Bjoertomt, O., Bestmann, S., Freeman, E., Haynes, J.D., et al., 2006. Concurrent TMS-fMRI and psychophysics reveal frontal influences on human retinotopic visual cortex. *Curr. Biol.* 16 (15), 1479–1488.
- Serences, J.T., Yantis, S., Culbertson, A., Awh, E., 2004. Preparatory activity in visual cortex indexes distractor suppression during covert spatial orienting. *J. Neurophysiol.* 92 (6), 3538–3545.
- Silver, M.A., Ress, D., Heeger, D.J., 2005. Topographic maps of visual spatial attention in human parietal cortex. *J. Neurophysiol.* 94, 1358–1371.
- Silver, M.A., Ress, D., Heeger, D.J., 2007. Neural correlates of sustained spatial attention in human early visual cortex. *J. Neurophysiol.* 97, 229–237.
- Somers, D.C., Dale, A.M., Seiffert, A.E., Tootell, R.B.H., 1999. Functional MRI reveals spatially specific attentional modulation in human primary visual cortex. *Proc. Natl. Acad. Sci. U. S. A.* 96 (4), 1663–1668.
- Spitzer, H., Desimone, R., Moran, J., 1988. Increased attention enhances both behavioral and neuronal performance. *Science* 240 (4850), 338–340.
- Talairach, J., Tournoux, P., 1988. Co-planar Stereotaxic Atlas of the Human Brain. Thieme, New York.
- Thut, G., Nietzel, A., Brandt, S.A., Pascual-Leone, A., 2006. α -band electroencephalographic activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection. *J. Neurosci.* 26 (37), 9494–9502.
- Tootell, R.B.H., Hadjikhani, N.K., Vanduffel, W., Liu, A.K., Mendola, J.D., Sereno, M.I., et al., 1998. Functional analysis of primary visual cortex (V1) in humans. *Proc. Natl. Acad. Sci. U. S. A.* 95 (3), 811–817.
- Treisman, M.A., Gelade, A., 1980. Feature-integration theory of attention. *Cogn. Psychol.* 12 (1), 97–136.
- Vecera, S.P., Rizzo, M., 2004. What are you looking at? Impaired ‘social attention’ following frontal lobe damage. *Neuropsychologia* 42, 1657–1665.
- Worden, M., Schneider, W., 1996. Visuospatial attentional selection examined with functional magnetic resonance imaging. *Soc. Neurosci.* 22, 1856 (Abs).
- Worden, M.S., Foxe, J.J., Wang, N., Simpson, G.V., 2000. Anticipatory biasing of visuospatial attention indexed by retinotopically specific α -band electroencephalography increases over occipital cortex. *J. Neurosci.* 20, RC63.