Visual motion, eye motion, and relative motion:
A parametric fMRI study of functional specializations of smooth pursuit eye movement network areas

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The ability to pursue moving objects with the eyes is vital to humans. However, it remains unclear how the brain differentiates visual object motion, smooth pursuit eye movements (SPEM), and eye movement-induced relative motion on the retina and where visual-to-oculomotor transformation takes place. To characterize functional differences of SPEM-processing cortical areas, we simultaneously measured functional magnetic resonance imaging (fMRI) and smooth pursuit to visual, oculomotor, and visuo-oculomotor stimuli varying the quantity of background dots of the stimuli. Resulting activations involved the whole visuo-oculomotor network. They varied among regions depending on the functional tasks and parametric changes of the background. Activation in many SPEM regions increased from 1 to 16 background dots but decreased at 36 dots. This could be an effect of coherent-texture perception. Putative MST area was not influenced by the amount of moving or stationary background dots. It probably participates in visuo-oculomotor transformation. Parts of the posterior parietal cortex seem specifically activated with relative motion between eye and background, but not with motion per se. This could be important for the perception of spatial references.

Keywords: fMRI, smooth pursuit eye movements, visual motion, multimodal, visuo-oculomotor transformation


Introduction

During pursuit of a visual object like a bird in a flock landing on a tree, our brain can correctly interpret the birds as moving. The observer, the tree, and the sky are correctly interpreted as being fixed in space. This is possible even though the tree moves relative to the retina. The cortical processing of different coordinate systems (retinal information, information of object movement in space, information of eye movement relative to the head) and visual-to-motor transformations necessary to generate

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these precise eye movements in the presence of all these different stimuli remain largely unclear.

A specific network of cortical areas is activated during SPEM: the frontal and supplementary eye fields (FEF, SEF), the posterior parietal cortex (PPC), the precuneus (PCU), the motion-sensitive complex MT+, and the cingulate gyrus (CG; e.g., Berman et al., 1999; Kimmig, Greenlee, Huethe, & Mergner, 1999; Petit & Haxby, 1999). In Kimmig et al. (2008), we reported that visual components of activation during SPEM are located in MT+, the PPC, and PCU. Motor processing is specifically taking place in FEF, SEF, and the cingulate gyrus.

Different areas within the cortical smooth pursuit eye movement (SPEM) network of monkeys and humans have been functionally described to participate in the integration of different modalities. The posterior parietal cortex (PPC; within and near to the intraparietal sulcus—IPS), with the ventral intraparietal cortex (VIP; for a review, see Bremmer, 2005; Bremmer et al., 2001) and the lateral intraparietal cortex (LIP; Andersen, 1997) have been described as multimodal. That is, they integrate visual, somatosensory, auditory, and vestibular signals. Furthermore, the IPS has been shown to code visual motion and eye movements in retinal or head/space coordinates (Andersen, Essick, & Siegel, 1985; Bremmer, 2005), to subserve visuomotor (visual to head centered coordinates) transformations (Andersen, Snyder, Batista, Buneo, & Cohen, 1998; Grefkes & Fink, 2005; Grefkes, Ritzl, Zilles, & Fink, 2004). In contrast to the human occipital cortex where maps of visual space are retinotopic, not spatiotopic (Gardner, Merriam, Movshon, & Heeger, 2008), the motion-sensitive area MT+ has been shown to process visual (retinal) input and head centric eye movement signals (Bremmer, Distler, & Hoffmann, 1997; Dukelow et al., 2001; Goossens, Dukelow, Menon, Vilis, & van den Berg, 2006; Ilg, Schumann, & Thier, 2004).

Since in human fMRI experiments the described brain areas are supposed to process sensory (visual) input and code an oculomotor output (eye movement), they are expected to be multimodally activated in visual, oculomotor, and visuo-oculomotor conditions.

We formerly suggested that MT+ and a part of the PPC perform a visuomotor transformation (retinal to head/space coordinate transformation) during SPEM since they showed to be activated by all three stimulation types (Kimmig et al., 2008). A description of the functional specialization, task sharing, and interaction between these two regions and other regions of the SPEM network during eye movements is still lacking.

In this study, we investigated the significance of the visual background during SPEM and fixation using a parametric approach; we varied the number of moving or stationary background dots and investigated the BOLD responses in the SPEM network. We tested (1) visual stimulation: subjects fixated a central stationary dot while background dots moved, (2) oculomotor stimulation: subjects pursued a central dot while background dots moved in parallel, and (3) visuo-oculomotor stimulation: subjects pursued a central dot while background dots were stationary. We tested whether cortical activations of the SPEM network are dependent on the number of coherently moving background dots in these three stimulus conditions. In the visual motion condition, we hypothesized for instance an increase in activation with an increasing number of dots in MT+. Concerning the oculomotor conditions, we previously suggested that the eye movement signal is continuously dispersed across the visual map of MT+. Accordingly, during SPEM we hypothesize the MT+ activation to be independent of the number of moving dots.

**Methods**

**Visual stimulation**

Visual stimulation was controlled by a PC using Matlab (R.14, The Mathworks). The PC controlled a tricolor LED board (60 × 30 cm = 24° × 12° of visual angle; 8192 LEDs) with a sampling rate of 1 kHz. The stimulation paradigm of this experiment was an extension of the one we used in Kimmig et al. (2008). In the present study, we used a retinotopically more widespread visual stimulus (ca. 20 × 10° of visual angle vs. 10 × 4° of visual angle in the former experiment). Great care was taken to avoid disturbing effects of eye movement-induced motion of the frame of reference (e.g., the bore of the magnet) on the retina: the room was completely darkened and all light sources inducing stray light were covered. Furthermore, the LED board was dimmed such that subjects in the scanner saw only the visual stimulation dots. The LED board was placed behind the gantry at a distance of 140 cm from the subjects’ eyes.

In the central screen position, subjects saw one green fixation dot and—depending on the task—four different numbers of red background dots (dot size = 0.2° of visual angle). The fixation dot and at least one background dot were continuously visible. During all conditions, the subjects had to fixate or pursue the central dot (Figure 1). During the rest periods (duration 15 s; Figure 1a), all dots remained stationary. Three different stimulation types occurred in alternation with the rest periods (duration 15 s each): visual stimulation—the background dots moved sinusoidally in the horizontal plane and subjects had to fixate the stationary fixation dot (retinal stimulation; Figure 1b); oculomotor stimulation—both the fixation dot and the background dots moved in parallel sinusoidally in the horizontal plane; subjects had to track the fixation dot with their eyes (Figure 1c); visuo-oculomotor stimulation—the fixation dot moved sinusoidally in the horizontal plane and subjects had to track this dot with
their eyes while the background dots remained stationary (Figure 1d). Each dot moved horizontally ±5° to the right and left sides of the visual hemifield at a velocity of 0.33 Hz (peak velocity 10°/s, duration of one complete sinus cycle, including ±5° to the right and to the left: 3 s). The number of background dots of every stimulation type varied parametrically in four steps (1, 4, 16, and 36 background dots) resulting in 16 different conditions (4 visual, 4 motor, 4 visuo-oculomotor, 4 rest). The twelve stimulation conditions occurred in a pseudorandom fashion in alternation with the 4 rest conditions (fixation dot plus background dots, all remaining stationary). Every stimulation condition (visual condition: 1 background dot, 4 background dots, 16 background dots, 36 background dots; oculomotor condition: 1 background dot, 4 background dots, 16 background dots, 36 background dots; visuo-oculomotor condition: 1 background dot, 4 background dots, 16 background dots, 36 background dots) was presented in two trials (containing 5 sine cycles of the moving pursuit target and/or background dots per trial); every rest condition (1 background dot, 4 background dots, 16 background dots, 36 background dots) was presented in six trials (see Figure 1). Each subject performed three series resulting in six repetitions per stimulation condition and eighteen repetitions per rest condition per subject.

**MR eye tracking**

To record eye movements, we used the Freiburg MR-Eyetracker system, a fiber-optic limbus tracking device (Kimmig et al., 1999). A multichannel computer program (LabVIEW, National Instruments, Austin, TX, USA) was used to acquire and display the signals derived from the MR-Eyetracker. The sampling frequency was 500 Hz; the best spatial resolution was 0.2° of visual angle. Deviation from linearity for ±20° was less than 5%. The stimulus position was displayed and recorded in parallel to the eye movement data. For calibration, subjects shifted their eyes repeatedly from the central fixation point toward targets at lateral locations of ±5°. Calibration of eye position was performed prior and after each run. Accuracy of calibration was about 0.25°. The eye calibration served as a control and could be used for offline recalibrations.

**MR imaging**

Magnetic resonance imaging was performed with a 3-T Magnetom TRIO research scanner (Siemens). The scanner was equipped with an eight-channel receive head coil. Functional imaging was performed with a T2*-weighted
echo-planar imaging (EPI) sequence, which included fully automated motion and distortion correction during image reconstruction (Zaitsev, Hennig, & Speck, 2004). High-resolution, sagittal T1-weighted images were acquired with the MP-RAGE (magnetization prepared rapid acquisition gradient echo) sequence to obtain a 3D anatomical scan of the brain. The technical parameters of the fMRI sequence were TE 30 ms, TR 2.5 s, flip angle 90°, matrix 64 × 70, and a voxel size of 3 × 3 × 3 mm³. Data acquisition was performed in 36 slices per volume, which contained the whole brain except for ventral parts of the cerebellum. To minimize head motion, the subject’s head was fixed in the MR head coil using fixation cushions in the neck and right and left of the subjects’ cheeks. The effects of gradient noise were reduced by sound-dampening headphones.

The stimulation protocol for each sequence of the experiment consisted of forty-eight 15-s intervals including 24 periods of rest (OFF) and 24 periods of stimulation (ON), in alternating order. This protocol produced 288 EPI volumes per series (duration 12 min). Each subject performed three series.

Subjects

Twenty healthy subjects took part in this study; 17 right-handed subjects and one left-handed subject were included into the statistical analysis. Two subjects were excluded from the analysis due to fatigue that was detected online by the investigator during the measurements by visual inspection of the measured eye movement trace. These subjects closed their eyes for longer periods than the expected duration of expected blinks, which lead to an untimely stop of the measurements and exclusion from data analysis. Age ranged between 18 and 35 years and vision was normal or corrected to normal. Written informed consent was obtained from all subjects. The study was approved by the Ethics Committee of the University of Freiburg in accordance with the Declaration of Helsinki.

Data analysis

Eye movement data

Previously, we showed that mostly saccadic frequency but not the amplitude of small correction saccades significantly influence the cortical BOLD activation (Haller, Fasler, Ohlendorf, Radue, & Greenlee, 2007; Kimmig et al., 2001). Therefore, completed measurements of eye movement data were analyzed separately for smooth pursuit eye movements and contaminating saccades. Since saccades in the pursuit signal are to some degree inevitable, the measures of saccadic frequency and mean saccade amplitude indicate whether saccades are balanced between rest and stimulation periods. Saccades were detected by an interactive computer program written in Matlab (R2009a, The MathWorks, Natick, MA) using velocity and amplitude criteria threshold algorithm (velocity threshold 35°/s, 0.5° of amplitude) and subsequently included saccade frequency as a parameter into the brain data analysis. Artifacts like drifts or blinks were identified by visual inspection. In the following, saccades, blinks, and artifacts were extracted from the pursuit velocity trace and were interpolated linearly. As a measure for the goodness of SPEM performance, we used the velocity gain. The gain was defined by the ratio of eye velocity to target velocity (a gain of 1 represents optimal pursuit).

fMRI data

We used the software package SPM5 (Wellcome Department of Cognitive Neurology, London, UK). To account for residual head motion, the first preprocessing step of the functional MRI data consisted in motion correction via SPM5 realignment. Then, T1 images were segmented into gray and white matters using the unified segmentation method by Ashburner and Friston (2005). The resulting normalization parameters were used to write the normalized EPI volumes in MNI space. The last preprocessing step consisted of spatial smoothing with a Gaussian kernel of 8 mm (full width at half maximum).

For statistical analysis, the data were fitted to a general linear model to establish parameter estimates for each subject. Contrasts were defined to yield the sizes of the condition effects of (1) the four rest conditions (rest condition including 1, 4, 16, 36 background dots), (2) the four visual stimulations (visual stimulation including 1, 4, 16, 36 background dots), (3) the four oculomotor stimulations (oculomotor stimulation including 1, 4, 16, 36 background dots), and (4) the four visuo-oculomotor stimulations (visuo-oculomotor stimulation including 1, 4, 16, 36 background dots) in every subject.

Kimmig et al. (2001) showed that saccadic frequency but not saccadic amplitude is changing the BOLD signal. For this reason, we corrected on the single subject level for effects that correlated with saccadic frequency. To our knowledge, this is currently the most appropriate method to correct for unwanted/polluting activations in smooth pursuit brain data. Thus, to avoid contaminating BOLD activation due to correction saccades during the different conditions, we modulated parametrically for saccadic frequency on the single subject level including additional regressors for the mean saccadic frequency of each stimulation or rest period into the general linear model.

Group level statistics were performed by including the individual contrast images for the sixteen condition effects of 18 subjects into a second level random effects Flexible Factorial Design analysis. The specific effects were tested with appropriate T-contrasts and corrected for multiple comparisons (family-wise error correction (FWE)). Clusters of voxel surpassing an individual threshold of p = 0.05 (corrected) were considered to be significant activations.
We calculated differential contrasts for the twelve stimulation tasks vs. the equivalent rest condition (e.g., the visual condition with 4 background dots minus the rest condition with 4 background dots). Furthermore, we calculated contrasts of the three different main stimulation types performing linearly increasing parametric modulation of the number of background dots in order to see which areas increase in relation to the different stimulation types.

In addition, we performed a region of interest (ROI) analysis of four well-definable cortical areas of the SPEM network calculating the mean % BOLD signal change values of ROIs defined by activated voxels of the group statistics over both hemispheres. For calculation of the % BOLD signal change values, we used the group result ROIs as a kind of mask and calculated mean % BOLD signal change from the voxels of these defined ROI masks over the BOLD signal change values of every single subject. In order to be able to not only look at the height of the modulated activation (which can similarly be shown by effect sizes) but also its expansion, in addition we counted the amount of significantly activated voxels in the ROIs of the different conditions. We chose this method since we wanted to include the effect size and the amount of significantly activated voxels in the analysis. A visualization of the effects could have also been shown in a figure including the cumulated effect sizes of the activated voxels per ROI, which would have been more compact; however, since cumulation of % BOLD signal change would lead to confusing results, we chose to show the effect size (% BOLD signal change) and amount of activated voxels separately.

For visualization purposes, we projected the functional group results onto the left and right hemispheres of the Human Colin Surface-Based Atlas mapped to “Population-Average, Landmark- and Surface-based” Atlas (PALS; van Essen, 2002, 2004, 2005). This atlas is derived from segmented structural MRI volumes of 12 normal young adults and includes the frontal or flattened gray matter surface of the template. Using this method, we are not able to map partial volume effects since these surface-based atlas flat maps per se only include gray matter. When we map SPM t-maps to this cortical atlas surface, only activations defined as gray matter are shown. Data were mapped on the flat-map template and the three-dimensional cortical template of the atlas. This was done using the overlaying algorithm of the Computerized Anatomical Reconstruction and Editing Toolkit (CARET) version 5.3 (http://brainvis.wustl.edu; van Essen et al., 2001).

Statistical representations of the gray matter activations of the three stimulation types were mapped to different colors in functional overlays. Co-activated regions are displayed by weighted additive color, while pure colors indicate regions activated by only one of the tasks (visual—red; oculomotor—blue; visuo-oculomotor—green; intensity scale 0–255 referring to the maximum activation of each contrast). Note that in this view we show only gray matter activation locations. Activations located in the white matter, which are visible in the SPM glass brains, cannot be seen here.

Furthermore, the flat maps show exclusively activation locations and their overlaps surpassing a given T-threshold. In the flat maps, we used a lower T-threshold of $T = 3.5$ (cluster level corrected BOLD activations). With this uncorrected threshold, we wanted to show that non-activation of certain areas of the SPEM network during some of the tasks is not only due to the very rigid FWE correction threshold used in the SPM glass brains. Note that in the flat maps we see activation maxima without considering differences of effect sizes in the given conditions.

We report all findings in the Montreal Neurological Institute (MNI) coordinate system. Anatomical activation localization was performed via the SPM5 tool “wfu picatlas” (Maldjian, Laurienti, & Burdette, 2004; Maldjian, Laurienti, Kraft, & Burdette, 2003). Functional names of visual areas such as V1–V7 and LOP (part of the LOC/LOP complex) are derived from the PALS Atlas and are exclusively used as an orientation help. For example, the definition of basal visual cortex is not very specific but can include parts of V1, V2, and V3. We consider only forebrain activations; cerebellar and brainstem activations were not included in the statistical analysis.

### Results

#### Eye movement data

All subjects followed the moving dot accurately in both pursuit condition types. SPEM gain was close to unity in both tasks (mean gain oculomotor task = 0.94, mean gain visuo-oculomotor task = 0.87; Figure 2a). The gain was lower in the visuo-oculomotor condition than in the oculomotor condition (paired t-test; $p < 0.004$). Saccades occurred at significantly lower frequencies (Figure 2b; effect “task” $F(3, 15) = 23.9; p < 0.001$) and amplitudes (Figure 2c; effect “task” $F(3, 15) = 32.391; df = 3; p < 0.001$) during rest and visual stimulation periods than during pursuit periods. In all conditions, amplitudes of corrective saccades were small (mean = 1.1° of visual angle ±SEM).

#### fMRI data

The overall visual stimulation design (stimulation type vs. rest) led to BOLD activations in the well-known SPEM network, frontal eye fields (FEF), supplementary eye fields (SEF), visual motion area MT+, posterior parietal cortex (PPC), an area stretching from visual area V7 to the lateral occipital cortex (LOP, in the following
named V7/LOP), and posterior cingulate gyrus (pCG; Table 1) similar to Kimmig et al. (2008; visual, oculomotor, and visuo-oculomotor simulations with one background dot). In the current experiment, during the presence of higher amounts of background dots, we detected more extended activations in basal visual areas V1, V2, and V3 in the visual and visuo-oculomotor tasks.

Visual stimulation vs. rest led to bilateral activations in MT+, basal visual areas (V1–V3), V7/LOP, and the PPC (Figure 3a). Activations increased with higher amounts of moving dots starting at 4 or 16 background dots (Figure 3a, columns 1–4). For 36 background dots, the number of activated voxels decreased slightly in most areas. Visual activation in MT+ for 4 and 16 background dots was higher compared to the oculomotor and visuo-oculomotor activations.

Oculomotor stimulation vs. rest led to activations in MT+, V7/LOP, FEF, pCG, and basal visual areas (Figure 3b, columns 1–4). Most activations were found in conditions with one and with 36 background dots (e.g., parts of the FEF were only activated with 1 and 36 background dots; Figure 3b, columns 1 and 4). The most stable activation (in nearly all moving dot conditions) could be seen in MT+. Notably, PPC activation was not detected during oculomotor stimulation.

Visuo-oculomotor stimulation vs. rest led to activations in SEF, FEF, MT+, basal visual areas (V1–V3), V7/LOP, PPC, pCG, and the putamen as a part of the basal ganglia (Figure 3c). These activations were mostly stronger than the oculomotor activations. Visuo-oculomotor activations increased from 1 to 16 or 4 to 16 background dots. For 36 background dots, the number of activated voxels decreased again slightly in nearly all activated areas except in basal visual areas including V1 and in small parts of PPC where activations continued to increase (Table 2). Activations of the putamen were only significant for 16 background dots (not visible in the transverse view of Figure 3).

Basal visual areas were not significantly activated in the case of 1 and 4 background dots in all stimulation types even at the uncorrected threshold of \( T = 3.5 \) (Figure 3; see also Figure 5).

**Parametric modulations of the number of moving dots**

A parametric modulation of the number of moving dots (Table 2, see also % BOLD signal change of SPEM network areas in Figure 4) statistically confirmed the effects seen in the SPM glass brains (Figure 3). Activation size and expansion mostly increased up to a number of 16 background dots and then decreased again in the case of 36 background dots.

During visual and visuo-oculomotor stimulations, the activation of basal visual areas, precuneus, cuneus, and PPC increased significantly (Table 2; first and third columns). Excluding the 36 background dots condition from the visual parametric contrast, the number of parametrically increasing voxels rose and included also area V7/LOP and MT+ (Table 2; second column). Excluding the 36 background dots condition from the visuo-oculomotor parametric contrast, we saw an increase of activated clusters in the PPC and in frontal areas (Table 2, fourth column).

The parametric modulation of the oculomotor stimulation did not show any significant increase or decrease of activation effect size across the number of background dots.

**Multimodally activated regions**

To visualize multimodal regions (putative visuo-oculomotor transformation sites), activation results from all three stimulation types (visual (depicted in red), motor (blue), visuo-oculomotor (green)) were overlaid on cortical flat maps (\( T = 3.5 \); Figures 5a–5d). Activation overlays for all three stimulation types (whitish areas) were located mainly in MT+ and in V7/LOP. MT+ complex: In the sections showing area MT+ (Figure 5,
<table>
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<th>Visual stimulation vs. Rest</th>
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arrowheads), a region of activation of all three stimulation types (white blobs at the anterior pole of the MT+ complex) stayed constant during the parametric modulation of background dots. This can be seen in all four insets. Stimulation with only one background dot started at this anterior location. Activation resulting from 4 and 16 background dots propagated in posterior and dorsal directions, then activation refocused anteriorly for 36 background dots.

This anterior part of MT+ appears to be activated by retinal and extraretinal signals and therefore presumably represents MST. To support this notion, we compared the MT+ activations obtained from the three stimulation types (visual, oculomotor, visuo-oculomotor, number of background dots pooled; Figure 5f) with the results of an MT+ subregion analysis based on the visual properties of MT+ (Figure 5e; Ohlendorf, Sprenger, Speck, Haller, & Kimmig, 2008). In this former study, we used a visual stimulation similar to the one used by Dukelow et al. (2001) and Huk, Dougherty, and Heeger (2002). We localized the MT+ region with a central localizer stimulus (blue) and differentiated between activations induced by motion of the ipsilateral visual hemifield (red; supposedly MST activation) and the contralateral visual hemifield (green). Figure 5f shows that the region activated by all three stimulation types in MT+ (white) is at the same location as the results from ipsilateral stimulation of our previous experiment (yellow overlay). Note that this previous study was performed with exactly the same subject group and a very similar laboratory setup.

Discussion

To our knowledge, this is the first fMRI study that investigated functionally specific modulations of fMRI brain activations in the whole SPEM network during SPEM and fixation in the presence of quantitatively different backgrounds. We found an increase of activation with parametrically increasing numbers of background dots (BDs) during visual and visuo-oculomotor stimulations, which saturated before the highest parametric level. At 36 BDs, most activations declined in spite of stronger retinal stimulation. In the path of visuo-oculomotor processing, we observed the following effects: basal visual areas were only activated by higher amounts of motion stimuli. Furthermore, basal visual area activation was stronger during eye movements than during fixation, in spite of correction for small catch-up saccades. We show areas that were activated by all three stimulation types (visual, oculomotor, and visuo-oculomotor), namely MST, V7/LOP. These areas are the potential visuo-oculomotor transformation sites because they receive all the necessary information. Furthermore, we show an area that responded
specifically to differential motion between the visual background and the eye, PPC.

**Cortical activation in dependence on the amount of motion stimuli**

A parametric modulation of the number of moving dots led to increasing activations in many SPEM regions. Obviously, the more motion stimuli we apply, the more motion-sensitive neurons react and add to the overall activity in the region of interest. A similar positive correlation was described for saccade frequency and cortical activation (Kimmig et al., 2001, 1999). However, we were surprised that the correlation became negative with just 36 dots. This is far away from being a structured, real-world background, and yet, a physiological change must have occurred between 16 and 36 dots. This effect is probably related to the visual motion component because it was evident in the visual and visuo-oculomotor, but not in the oculomotor task (Figures 3 and 5). Currently, we can only speculate on the physiological meaning of this activation decrease. It is conceivable that using very few BDs induces a high ambiguity between target point and background points; at a certain number of BDs (here 36), these dots are perceived as a coherent texture or “the background.” The ambiguity is resolved, the task becomes easier, and the activation effort is reduced.

**Functions of basal visual areas**

Surprisingly, motion of one and four visual dots (compared to stationary dots) did not activate basal visual areas (similar to Kimmig et al., 2008), although the basic elements of the cortical motion-processing stream in primates are V1 direction-selective neurons (Dow, 1974; Gur, Kagan, & Snodderly, 2005; Gur & Snodderly, 2007; Hubel & Wiesel, 1968). Only stronger visual stimulations (16–36 BDs) led to significant activations. In the studies of Culham et al. (1998) and Orban et al. (2003), for the comparison of low contrast moving visual objects with stationary visual objects, similar results were shown but were not discussed. This result indicates that basal visual areas seem to be less sensitive to visual motion than, e.g., area MT+. In addition, our results suggest that basal visual
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<td>9</td>
<td>18</td>
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</tr>
<tr>
<td>R middle frontal gyrus</td>
<td>BA6</td>
<td>9</td>
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</tr>
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<td>16</td>
</tr>
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Table 2. Coordinates show the local maxima of activated voxel cluster in MNI space; cluster level corrected at $p = 0.001$; R = right hemisphere, L = left hemisphere, BA = Brodmann area; fR = functional region; $T$ = T-value at voxel level, $n = 18$. 
areas also receive motor output information (see also Kimmig et al., 2008). Recently, V1 activation in a saccade task has been found to be related to spatial updating (Merriam, Genovese, & Colby, 2007). Hence, during SPEM this information could be a feedback signal of spatial updating, i.e., integration of eye movement motor output into the visual map. Higher activations in basal visual areas might be influenced by attention. However, in a previous study (Ohlendorf, Kimmig, Glauche, & Haller, 2007), varying attentional load during pursuit and fixation did not lead to an increase of activation in basal visual areas during the pursuit task.

**Visuo-oculomotor transformation sites**

In Kimmig et al. (2008), we found two areas, MT+ and the PPC, that seemed to be involved in the transformation of visual input to motor output since they were active in all three stimulation types and thus receive all the information to do the transformation. In the present study, we used different amounts of background dots and found MT+ to be activated again by all three stimulation types. In addition, we found multimodal activation in a more posterior located area (V7/LOP), which thus seems to be a region processing visual and eye movement information.
Concerning the PPC using parametric modulation of the background, we obtained a more specific insight in the functional role of the area (see below).

**Motion-sensitive area MT+**

Previously, we hypothesized that most of the MT+ complex is involved in oculomotor processing when the eyes follow a single moving dot. In contrast, visual processing of the same dot’s motion during fixation hardly activated MT+ (Kimmig et al., 2008). It is known that monkey MT+ receives retinal input and extraretinal input about eye position and is able to process motion in world coordinates (Bremmer, Ilg, Thiele, Distler, & Hoffmann, 1997; Ilg et al., 2004). Furthermore, MT+ has been described to participate in processing of eye movement information (Dukelow et al., 2001; Goossens et al., 2006; Huk et al., 2002). For this reason, we expected an increase in activation with increasing numbers of dots in the visual motion condition due to stronger retinal input. During eye movement conditions instead, the cortical activation should involve constantly large parts of the MT+ complex, independent of the number of moving dots. Indeed, MT+ activations induced by visual stimulation increased in correlation with the number of BDs. In contrast, a small region of MT+ was constantly activated during eye movements independent of the number of BDs. This means that there exist two subareas in MT+ that react differently. One subarea is strongly modulated by the quantity of the visual input, while the other is independent of this input.

![Figure 5](http://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933538/)

Figure 5. SPM group activation results overlaid on flat maps of the right cortical hemisphere (PALS Atlas). (a) One background dot (BD). (b) Four BDs. (c) Sixteen BDs. (d) Thirty-six BDs. Red = visual; blue = oculomotor; green = visuo-oculomotor activation; color mixtures = activation overlays; e.g., white = overlay of all three stimulation activations; MT+, cuneus (V7), PPC, and FEF are already activated during tasks with 1 background dot, further areas of SPEM network get only activated during motion of more than one background dot; basal visual areas (V1, V2) are not activated during stimulation with 1 and 4 background dots. Small inserts showing the MT+ area (yellow arrowheads): general activation of MT+ starts at the frontal pole, propagating in posterior and dorsal direction for 4 and 16 background dots, refocusing anteriorly for 36 background dots. Region of activation of all three stimulation types (white blobs) stays constant. Lower row: (e) left side; results of our previous study (Ohlendorf et al., 2008) showing MT+ activation resulting from localizer stimulation (blue), ipsilateral visual hemifield (red), and contralateral visual hemifield activation (green); (f) right side: overlay of ipsilateral activation results (red in (e)) of our previous study in yellow color on the cortical activation results in MT+ of overall stimulation types (all background dot numbers pooled; FWE corrected). Region of activation of all three stimulation types in MT+ (white) is at the same location as the results from ipsilateral stimulation of our previous experiment (yellow).
retinal stimulation (more BDs induce more activation); another subarea is activated more independently of the amount of BDs. This subregion is multimodally during SPEM and visual motion in all three stimulation types. This MT+ subregion can thus process visual motion information (visual input) and continuously process the eye movement signal (eye position signal/oculomotor output signal), which is independent of the amount of BDs.

As others (Dukelow et al., 2001; Huk et al., 2002), previously we defined area MST as the subdivision of MT+, which responds to ipsilateral optic flow (Ohlendorf et al., 2008). Using the same subject group, we now located the visuo-oculomotor transformation site as MST in the same location within MT+. For this reason, we suppose the MST subregion of the human MT+ complex as a location for visuo-oculomotor transformations.

**Lateral occipital cortex (V7/LOP)**

In this study, we reveal an area we call V7/LOP, which is not yet multimodally activated with little retinal stimulation (1 and 4 BDs) but is activated multimodally in the presence of a higher amount of BD. In our case, the background dots move coherently or remain all stationary, and they appear in a rectangular shape. At higher numbers of dots, the shape/structure becomes apparent and might be detected by the area V7/LOP. Area LO (including LOP) has been shown to be activated preferentially by shape in comparison to scrambled objects (Grill-Spector et al., 1998) and involved in extracting or representing information about object structure from different image cues (Kourtzi & Kanwisher, 2000). LOC in the LOC/LOP complex has been shown to participate in visual recognition (Grill-Spector, Kushnir, Hendler, & Malach, 2000; Ungerleider & Mishkin, 1982). In our case, this area could be responsible for the visuo-oculomotor transformation during eye movements in the presence of a structured background. This would explain why it gets activated at higher amounts of moving dots.

**Motion processing in the posterior parietal cortex (PPC)**

In Kimmig et al. (2008), using only one background dot, part of the PPC was activated by visual, oculomotor, and visuo-oculomotor stimulations. In the present study using parametric variation of BD, this part of the PPC was not significantly activated during oculomotor stimulation. Instead, the PPC seemed mainly activated when visual target and background moved in opposite directions.

Different parts of the PPC in monkeys have been described to be multimodal and to code the spatial location of visual objects (Andersen, 1997; Bremmer, Duhamel, Ben Hamed, & Graf, 2002). The ventral intraparietal area (VIP; Bremmer, 2005; Schlack, Hoffmann, & Bremmer, 2003) codes visual stimuli in an eye-centered (retinal) reference frame and responds to eye movement signals (head-centered reference frame) and other sensory modalities. Furthermore, PPC has been shown to process motion in space (Andersen, 1997; Andersen et al., 1998; Grefkes & Fink, 2005).

Interestingly, in our study PPC activation in the visuo-oculomotor stimulation type increased with the increase of BDs although motion in space was constant. Therefore, the PPC activation cannot represent eye movement processing in head coordinates nor motion in space. Instead, this functional behavior indicates that this part of the PPC participates in integrating the movement of the frame of reference (background) in relation to the visual target. This would well explain the lack of activation during oculomotor stimulation.

**Conclusions**

In this study, we show functionally specific modulations of fMRI brain activations in the whole SPEM network by SPEM and fixation in the presence of quantitatively different backgrounds. The visual component activity in the SPEM cortical network increases with the number of background motion stimuli (summation effect) but breaks down at a certain amount of background motion revealing another physiological process, perhaps related to texture perception. Basal visual areas like V1 receive eye movement motor information, which could be used for spatial remapping. MST and V7/LOP are likely candidates for visual-to-oculomotor transformation during SPEM. Hereby, MST could be more involved into spatial remapping of the eye position in space whereas V7/LOP could perform visuo-oculomotor transformations in the presence of a structured background. The processing of differential motion between eye and background (qualitative reference frame information) seems to take place in the PPC.

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References


