The cortical eye proprioceptive signal modulates neural activity in higher-order visual cortex as predicted by the variation in visual sensitivity

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Whereas the links between eye movements and the shifts in visual attention are well established, less is known about how eye position affects the prioritization of visual space. It was recently observed that visual sensitivity varies with the direction of gaze and the level of excitability in the eye proprioceptive representation in human left somatosensory cortex (S1EYE), so that after 1 Hz repetitive transcranial magnetic stimulation (rTMS) over S1EYE, targets presented nearer the center of the orbit are detected more accurately. Here we used whole-brain functional magnetic resonance imaging to map areas where S1EYE-rTMS affects the neural response evoked by retinally identical stimuli depending on the direction of rotation of the right eye. After S1EYE-rTMS, a single area in the left cuneus outside Brodmann Areas 17/18 showed an increased neuronal response to a right hemifield target when the right eye was rotated leftwards as compared with when it was rotated rightwards. This effect was larger after S1EYE-rTMS than after rTMS of a control area in the motor cortex. The neural response to retinally identical stimuli in this area could be predicted from the changes in visual detectability observed previously, but not from the location of the visual targets relative to the body. These results strongly argue for a modulatory connection from the eye proprioceptive area in the somatosensory cortex to the higher-order visual cortex. This connection may contribute to flexibly allocate priorities for visual perception depending on the proprioceptively signaled direction of gaze.

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Introduction

The prioritization of space for perception depends on the goals of the organism as well as the salience of the sensory input. In addition to these well-established factors, evidence is accumulating that the posture and movement of one’s own body can also influence the allocation of neural resources (Baldauf and Deubel, 2010; Durand et al., 2010; Grubb et al., 2008; Jackson et al., 2010; Reed et al., 2006, 2008).

Whereas it is well established that planned eye movements cause changes in visual detectability (Deubel and Schneider, 1996; Kowler et al., 1995) and that procedures that alter neuronal activity in oculomotor structures such as the frontal eye fields (FEFs) cause changes in visual sensitivity and alter the activity of the early visual cortex (Moore and Fallah, 2004; Ruff et al., 2006), little is known whether eye position exerts an analogous effect on visual perception and visual cortex responsiveness. Observations in the auditory domain support the idea that the direction of gaze modulates the allocation of attention as sounds presented nearer to the direction of gaze show a perceptual advantage (Morais et al., 1980; Pavani and Driver, 2005).

In the visual domain, it has been proposed that visual sensitivity decreases further from the proprioceptively signaled direction of gaze (Balslev et al., 2011b). This proposal rests on the observation that 1 Hz rTMS over a somatosensory area in the left anterior parietal cortex caused a reduced processing of the eye proprioceptive input, a shift in perceived gaze position towards the center of the orbit (Balslev and Miall, 2008) and at the same time a decrease in visual detection for targets presented further from the center of the orbit. For instance, when the right eye was rotated leftwards, rTMS over this eye proprioceptive representation in left somatosensory cortex (S1EYE) increased detection accuracy in the right visual hemifield and decreased it in the left. In rightward gaze, the detection accuracy for right hemifield targets decreased after S1EYE-rTMS (Balslev et al., 2011b).

The aim of the current experiment was to identify neuronal correlates of the changes in visual detectability induced by rTMS conditioning of S1EYE excitability. We performed whole-brain fMRI immediately after 1 Hz rTMS over S1EYE, in order to map rTMS-induced gaze-dependent changes in neural activity evoked by lateralized visual stimuli. In order

Abbreviations: S1EYE, eye proprioceptive area in the postcentral gyrus as identified by Balslev and Miall (2008); M1, primary motor cortex; rTMS, repetitive transcranial magnetic stimulation; fMRI, functional magnetic resonance imaging.

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to rule out unspecific effects of rTMS, the results were compared to those after rTMS over a control area in motor cortex (M1).

As an alternative hypothesis, we investigated whether the brain area where the visual response depends on eye position and the excitability of S1EYE encoded the location of the stimulus relative to the body — e.g., a gain field representation of the visual stimulus (Andersen et al., 1985). As eye proprioception seems — together with the efference copy of the oculomotor command — to contribute to visual localization (Allin et al., 1996; Balslev and Miall, 2008; Bridgeman and Stark, 1991; Campos et al., 1986, 1989; Gauthier et al., 1990; Lennerstrand et al., 1996) (but see (Lewis et al., 1998) for a different view), a variation in the neural response to retinotopically identical targets that vary with the level of activity in S1EYE may reflect a head-centered representation of the visual stimulus location. It is unknown whether eye proprioception contribute to the gain field representations. To investigate this possibility, additional contrasts tested two organization principles in the gain field maps: first whether the neural activity depended on the laterality of gaze, left vs. to the right or vice versa (Andersen and Mountcastle, 1983; Bremmer, 2000; Deuchsländer et al., 2005; Guo and Li, 1997; Weyand and Malpeli, 1993; Williams and Smith, 2010) and second, whether the neural activity depended on the location of the visual target relative to the head midline (Durand et al., 2010).

Methods

Participants

Nineteen healthy adults (13 females; age range 22–31, median 25), who reported to be right-handed and to have normal vision, participated in this study after giving written informed consent. All participants were naïve to the purpose of the study. The study was approved by the Ethics Committee of Copenhagen and Frederiksberg, Denmark (H-KF-01-131/03).

Task

During fMRI, the left eye was occluded and the right eye fixated a red cross (0.5° of visual angle) on a black LCD screen backprojected onto a mirror (22 × 17°). There were two possible locations for the fixation cross to dictate a rotation of the right eye by 5° to either left or right of the sagittal plane through the eye. Black-white 2 × 2 checkerboards subtending 1° of visual angle and flickering at 16 Hz were presented for 300 ms to the left or right of the fixation at 5° of eccentricity. Participants performed no other task than maintaining fixation. There were four conditions (Fig. 1): A. gaze rotation leftwards and right hemifield target (LgRt), B. gaze rotation leftwards and right hemifield target (LgLt), C. gaze rotation rightwards and right hemifield target (RgLt), and D. gaze rotation rightwards and left hemifield target (RgLt). Trials of each type were grouped in blocks of 20 s of duration. Each block began with a 1 s visual instruction to fixate on the cross. The time interval between the onsets of two consecutive trials was chosen from a random distribution (mean duration 2.04 s, standard deviation 0.27 s). The median number of trials in each block was 10 (range 9–11). The participants performed each block type 7 or 8 times during the 600 s fMRI run. Block order was counterbalanced across subjects. Within subjects, the order of condition presentation was identical in both experimental sessions (S1EYE- and M1-rTMS).

The task for fMRI was designed to test a prediction derived from a previous behavioral study which showed that rTMS over left S1EYE exerts effects on visual accuracy for left and right targets depending on the direction of the lateral rotation of the right eye, leftwards or rightwards (Balslev et al., 2011b). This previous behavioral paradigm was adapted to comply with the constraints of the smaller display in the scanner environment (i.e., smaller eye rotation and smaller eccentricity of the lateral visual stimuli), to maximize the signal-to-noise ratio in the fMRI data (i.e., visual stimuli in the form of flickering checkerboards) and to avoid confounds in the fMRI data analysis (i.e., no motor response was required to ensure that potential changes in motor behavior induced by rTMS would not contaminate the recorded brain activity).

Eye tracking

To ensure that the participants were able to maintain fixation, we monitored the horizontal eye position at 30 Hz with a monocular MR-compatible eye tracker (Mag Design and Engineering, Sunnyvale, CA running ViewPoint from Arrington Research). The eye tracker was placed over the left, non-viewing eye to avoid a reduction in the visual field in the right eye. The eye tracker was calibrated for the screen space at the start of each fMRI session. Blinks were discarded, eye position time-series were detrended. Thereafter, eye position during target presentation was calculated. Trials with a break of fixation of more than ±1° were excluded from the analysis of eye position and modeled as a separate regressor in the design matrices for the fMRI analysis.

Repetitive transcranial magnetic stimulation (rTMS)

The rTMS protocol and stimulation sites were identical with those used in our previous studies that demonstrated an effect of S1EYE-rTMS on perceived eye position (Balslev & Miall, 2008) and visual detectability (Balslev et al., 2011b). Here, stereotactic neuronavigation (Localite Gmbh, Sankt Augustin, Germany) was additionally used to visualize post hoc the placement of the coil relative to the individual
brain anatomy, which confirmed the location of S1EYE in the postcentral gyrus (Fig. 2).

Two somatosensory areas in non-human primates – areas 3a and 2 – are known to receive input from muscle spindles (Huffman and Krubitzer, 2001). Among them, in area 3a of the macaque, single cell recordings confirm a proprioceptive projection from the eye muscles (Wang et al., 2007). Given inter-species differences in brain anatomy and the much lower spatial resolution of TMS compared with the single cell recordings, we cannot verify whether S1EYE-rTMS targets the human area 3a or 2. We argue, however, that this rTMS procedure interferes with processing in a brain area which receives a proprioceptive projection from the eye muscles and which is organized similarly as the primary proprioceptive projection in area 3a in the monkey. First, passive eye movement, a procedure that stimulates the proprioceptive receptors, perturbs visual localization after S1EYE-rTMS but not after M1-rTMS (Balslev and Miall, 2008). Second, S1EYE-rTMS, a procedure that reduces the excitability of the brain area underneath the coil, causes an underestimation of eye rotation in the orbit (Balslev and Miall, 2008). This accords with the organization of the eye proprioceptive area in the monkey where the neural activity increases with the eccentricity of gaze (Wang et al., 2007). Finally, the 3 cm distance on the scalp between the motor hand area identified with rTMS and S1EYE corresponds roughly with the 2.3 cm distance between the motor hand area identified by finger tapping during fMRI and the proprioceptive eye area identified using fMRI (Balslev et al., 2011a).

The duration of the rTMS session was 30 min. Due to the time required for the scanner setup, a maximum of 4 min elapsed between the end of the rTMS and the onset of fMRI data acquisition. In all participants, fMRI scanning was completed at maximum 10 min post rTMS, which is well within the time window where the effect of 1 Hz rTMS can be demonstrated (Thut and Pascual-Leone, 2010). To prevent an eventual adaptation in the eye proprioceptive system (Duke et al., 2006), the participants kept their eyes closed during the rTMS session until the start of the fMRI session.

In the rTMS session, 1800 biphasic stimuli were given using a Medtronic MagPro stimulator. A figure-of-eight coil (MC-B70 Butterfly, MagVenture, Farum, Denmark) was centered over the respective target area, maintained in this position by a coil holder, and continuously cooled off by an ice pad. The participant’s head was restrained by a chin rest, a forehead rest-pad, and a right-side support. The stimulation site was mapped in each subject in relation to the motor hotspot of the left hemisphere, which is the scalp projection of the primary motor cortex. The motor hotspot was defined as the point of a maximum evoked motor response in the relaxed first dorsal interosseus (FDI) muscle of the right hand and used as the control stimulation site (M1). S1EYE was found at 3 cm posterior to the motor hotspot, measured on the scalp, along a line oriented at 45° from the sagittal plane and perpendicular on the central sulcus (identical to Balslev and Miall, 2008 and Balslev et al., 2011b). The mean±SD MNI coordinates for S1EYE were (−45±7, −32±7, 58±9), whereas for M1 these coordinates were (−35±7, −12±8, 59±9) (Fig. 2). Stimulation intensity was set at 110% of the resting motor threshold of the right FDI muscle. To identify the threshold, the subjects were asked to rest the right hand on the table with the fingers slightly spread. The resting motor threshold was then defined as the lowest intensity that reliably elicited a visible twitch in the FDI muscle when the stimulation was given over the motor hotspot. During rTMS, the coil was positioned tangential to the scalp with the long axis of the figure-of-eight coil oriented at 45° to the parasagittal plane. The current flow of the initial rising phase of the biphasic pulse in the TMS coil induced a current flowing from posterior to anterior in the brain. Participants received rTMS over S1EYE or the control stimulation site in M1 on separate days in counterbalanced order.

fMRI analysis

Whole-brain fMRI data after both rTMS sessions were analyzed with SPM5 (http://www.fil.ion.ucl.ac.uk/spm/software/spm5). The images were corrected for the delay in slice acquisition within a brain volume, realigned, spatially normalized to MNI152-template (ICBM), thereby resampled to a voxel size of 3×3×3 mm³, and smoothed with an 8 mm FWHM filter. For each rTMS session, the design matrix for single subject analyses included four regressors of interest for each condition (eye rotation — hemifield stimulation: LgLt, LgRt, RgLt and RgRt). Each regressor coded the onset and the duration of the visual target for the trials where eye position was within ±1° of fixation. The design matrix also included a regressor for the onset and duration of the instruction screen within each block regardless of condition as well as a regressor for all discarded trials due to loss of fixation. All trials were modeled by convolving the event vectors with the hemodynamic response function. To account for head motion, the six parameters from the realignment transformations (3 translations, 3 rotations) were added to the design matrix. The cutoff frequency for high-pass filtering was 1/128 s.

To identify brain areas where the BOLD response to lateralized targets depended on both the rotation of the eye (leftward or rightward) and the level of excitability in the eye proprioceptive area (low after S1EYE-rTMS and normal after M1-rTMS) we ran two 2×2 ANOVAs separately for right and left hemifield targets. These random effects
analyses were implemented using a flexible factorial model across all subjects. In line with our previous behavioral results, we searched for areas showing not only a larger activation when the target was presented near versus far from the center of the orbit after S1EYE-rTMS but also where this difference was larger than that after M1-rTMS. The conjunctions tested were:

a. \((LgRt - RgRt)_{S1EYE-rTMS}\) and \([((LgRt - RgRt)_{S1EYE-rTMS} - (LgRt - RgRt)_{M1-rTMS}]\)

b. \((RgLt - LgLt)_{S1EYE-rTMS}\) and \([((RgLt - LgLt)_{S1EYE-rTMS} - (RgLt - LgLt)_{M1-rTMS}]\)

The two contrasts above tested the prediction that the change in neural activity mirrors the change in visual sensitivity identified in a previous behavioral experiment.

As an alternative explanation for changes in the visually evoked response with the direction of gaze, we also tested whether a modulation of retinal input by the proprioceptive signal of eye position reflected rather a systematic relationship between the neural activity and the location of the target in the body-centered space, e.g., a larger neural activity when the gaze was directed to the left vs. right (contrasts c. and d.), right vs. left (contrasts e. and f.) or when the target was closer to the head midline vs. the periphery (contrasts d. and e.). For these contrasts, only fMRI data acquired during the control M1-rTMS session were used.

c. \((LgLt - RgLt)_{M1-rTMS}\)
d. \((LgLt - RgRt)_{M1-rTMS}\)
e. \((RgLt - LgLt)_{M1-rTMS}\)
f. \((RgLt - LgLt)_{M1-rTMS}\)

For all analyses we report clusters of contiguous voxels with \(t > 2.37\) where the cluster \(p\)-value < 0.05, corrected for multiple comparisons using the family-wise error (FWE). The results of the conjunctions rely on the “conjunction null hypothesis” as introduced by Nichols et al. (2005). A significant conjunction means that all contrasts were individually significant (conjunction of significances). Because this approach is considered conservative (Friston and Penny, 2005), conjunction results were also inspected for trends at an uncorrected level of cluster \(p < 0.05\).

It is relevant here to note that because of the large spontaneous fluctuations of resting state activity, BOLD-fMRI cannot be used to identify the precise area underneath the TMS coil in an off-line protocol (Siebner et al., 2009). fMRI can only detect rTMS induced changes in the task-related activity, but not the session-long, tonic shifts in regional neural activity in the stimulated area, e.g. after S1EYE-rTMS vs. M1-rTMS. Alternative methods such as arterial spin labeling or positron emission tomography which provide absolute measures of tissue perfusion, are better suited to identify the site where rTMS causes long-lasting changes in neural activity (Moisaa et al., 2010).

**Repetitive transcranial magnetic stimulation**

Apart from the occasional twitches in the hand during M1-rTMS caused by the stimulation of the motor hand area as well as in the scalp and face muscles during both S1EYE- and M1-rTMS as a result of the direct stimulation of muscles/nerves, participants reported no effects of the stimulation.

**Functional magnetic resonance imaging**

Whole brain analysis revealed only one significant cluster in the left cuneus posterior and adjacent to the parieto-occipital sulcus (275 voxels, 7.4 cm³, peak at MNI coordinates \(x, y, z = -12, -87, 21\), cluster \(p\)-value < 0.001, corrected; Fig. 3) where the neural response to visual targets presented in the right hemifield depended on the direction of rotation of the right eye and on the level of excitability of S1EYE. The regional response to visual stimulation was larger during leftward compared to rightward gaze after S1EYE-rTMS, and this difference was larger after S1EYE-rTMS compared with M1-rTMS (Fig. 3C). Most voxels within the cluster fell outside the probability maps for the Brodmann areas (BA) 17 (Fig. 3A) and 18 (Fig. 3B) (Amunts et al., 2000) available in the Anatomy Toolbox implemented in SPM (Eickhoff et al., 2005). The increased neural response during leftward compared to rightward gaze after S1EYE-rTMS mirrored previously found changes in visual accuracy after S1EYE-rTMS (Balslev et al., 2011b). For left hemifield targets, no voxels survived the corrected statistical significance threshold. At an uncorrected level of cluster \(p < 0.05\) a single cluster of voxels located in a homologous area in the right medial occipital cortex, posterior to the parieto-occipital sulcus and outside BA17/18 (36 voxels, 0.97 cm³, peak at \((x, y, z) = (18, -75, 36)\) showed an interaction between rTMS type and the direction of rotation of the right eye.

For the whole brain analysis, contrasts c. and f. yielded statistically significant clusters located in the medial occipital, frontal and parietal cortices and cerebellum (Fig. 4), whereas the contrasts d. and e. did not highlight any areas above the statistical significance threshold. Importantly, none of the contrasts c.–f. yielded any statistical significant voxel or cluster within the region of interest (as identified by conjunction a.).

**Discussion**

Using a condition-and-map approach, we showed that inhibitory 1 Hz rTMS of the left S1EYE altered the sensitivity to visual stimulation in the extrastriate medial occipital cortex posterior to the parieto-occipital sulcus. Critically, the rTMS-induced change in the visually evoked BOLD response to a retinotopically identical stimulus depended on the direction of rotation of the eye in the orbit. This indicates that the proprioceptive eye-position signal from the somatosensory cortex can modulate the responsiveness of a higher-order visual area. Because the conditioning effects of S1EYE-rTMS on visually evoked activity were predicted from the previously identified changes in the accuracy of detecting visual targets (Balslev et al., 2011b), these neuroimaging findings identify a putative neural substrate by which eye proprioception affects visual sensitivity.

The experimental design rules out three alternative explanations for this result. First, the effect was largest when rTMS was applied over the somatosensory cortex area S1EYE, compared to a control area in the motor cortex. Compared to S1EYE, the control area M1 lies anatomically closer to the FEF, a structure whose stimulation can cause shifts in attention and changes in visual cortex activity (Ruff et al., 2006). It is therefore unlikely that the change in visual cortex activity after S1EYE-rTMS was caused by FEF activation due to direct spread of the induced electric field. Second, although stimuli presented at different locations on the screen may have had different contrasts which in turn could have caused differences in the visual evoked activity for retinally identical targets, the comparison with
Fig. 3. Higher-order visual area in the left cuneus showing an increased response to a retinally identical target in the right hemifield when the eye was rotated to the left and S1EYE excitability was decreased. The cluster of activation in the left cuneus is shown in red on 3 orthogonal projections cut through the peak activation at MNI coordinates (x, y, z) = (−12, −87, 21). The threshold for visualization is $t > 2.37$, cluster p-value < 0.05, corrected. The cluster is superposed on a group-specific structural image calculated as an average of the 19 participants’ T1-weighted MRI as well as on an overlay consisting of a probability map for the cytoarchitectonic areas BA 17 (A) and BA 18 (B). The probability of a voxel for belonging to the cytoarchitectonic area is color-coded from blue (minimum) to white (maximum) and thresholded at 25% probability. The BOLD signal at the peak activation (C) shows a larger response to a right hemifield target when the right eye was rotated leftwards compared with rightwards and after rTMS over S1EYE compared with M1. *p < 0.05, paired samples t-test, error bar shows 1 standard error.

Fig. 4. Brain areas showing a change in activity depending on the location of the target relative to the head/body. The clusters of activation show brain areas where the visually evoked response was larger in rightward gaze than in leftward gaze for a left hemifield target (A) and in leftward relative to rightward gaze for a right hemifield target (B) in the control data (M1-rTMS). The threshold for visualization is $t > 2.37$, cluster p-value < 0.05, corrected. The cluster is superposed on a group-specific structural image calculated as an average of the 19 participants’ T1-weighted MRI.
the M1-rTMS control condition rules this confound out. Finally, eye tracking confirmed that rTMS did not affect the ability to maintain fixation. To avoid a reduction in the field of view of the right eye to which visual stimuli were presented, the eye tracker was mounted in front of the non-viewing left eye. Monocular fixation does not elicit a different pattern of eye movement compared with binocular fixation, and when the movement of the two eyes diverges, the distance between gazes is usually very small, within 15° of arc (Ditchburn and Ginsborg, 1953). The absence of a statistically significant difference in the position of the left eye across conditions, the exclusion of the trials.

The absence of a statistically significant difference in the position of the left eye across conditions, the exclusion of the trials (Ginsborg, 1953). The absence of a statistically significant difference in the position of the left eye when the movement of the two eyes diverges, the distance between gazes is usually very small, within 15° of arc (Ditchburn and Ginsborg, 1953). The absence of a statistically significant difference in the position of the left eye across conditions, the exclusion of the trials. (Balslev et al., 2011b) has shown no changes in eye position at fixation, nor in the frequency of saccades or microsaccades directed to the left or right visual hemisphere. This establishes a tight link between oculomotor signals and when the movement of the two eyes diverges, the distance between gazes is usually very small, within 15° of arc (Ditchburn and Ginsborg, 1953). The absence of a statistically significant difference in the position of the left eye across conditions, the exclusion of the trials. (Balslev et al., 2011b) has shown no changes in eye position at fixation, nor in the frequency of saccades or microsaccades directed to the left or right visual hemisphere after S1EYE compared with M1-rTMS. Second, when TMS is applied over well known oculomotor atención-related areas of the left hemisphere such as the parietal eye field or the FEF, the effects on visual cortex activity differ from the results reported here. Namely, TMS over the left parietal eye field does not change the visually evoked activity in the medial occipital cortex (Ruff et al., 2008). Left FEF-TMS can alter neural activity in the occipital poles, however, this modulation is identical in the presence and in the absence of visual stimuli (Ruff et al., 2008). Therefore, the change in the visually evoked response caused by S1EYE-rTMS in the current experiment cannot be accounted for by a remote effect on this fronto-parietal circuit involved in oculomotion and attention. Finally, although rTMS applied to the posterior parietal cortex can bias the intersemispheric competition in the allocation of attention, enhancing the perception of stimuli located in the visual hemifield ipsilateral to the hemisphere where rTMS was applied (Hilgetag and Pascual-Leone, 2001), this effect is again different from the changes in visual sensitivity caused by S1EYE-rTMS. After S1EYE-rTMS the response to a target depended not only on its visual hemifield but also on the direction of rotation of the eye in the orbit, e.g., a right visual target was detected more accurately and elicited a larger neural response when the gaze was rotated to the left vs. right whereas for a left target, the results reversed, showing an increased detectability and a trend for a larger neural response in rightward vs. leftward gaze (Balslev et al., 2011b). This establishes a tight link between eye position and the changes in visual responsiveness observed here, and at the same time rules out interhemispheric competition in the allocation of attention as the explanation of these results.

While the current effects were strong for right hemifield targets, analogous effects were only found in trend for left hemifield targets. We do not have a straightforward explanation why the effect of left S1EYE-rTMS was weaker for left compared to right hemifield targets. The connections of the eye proprioceptive area to the visual cortices are incompletely understood, one possibility may be that the connection within the same hemisphere is stronger than the connection from the somatosensory cortex of one hemisphere to the visual cortex of the other hemisphere. This would be in accord with previous observations of a stronger cross-modal interaction between vision and somatosensation when stimuli in both modalities project to the same rather than to opposite hemispheres: a right tactile stimulus significantly enhanced the perception of a right hemifield visual stimulus whereas the suppression effect for a left hemifield visual stimulus was present only in trend (Macaluso et al., 2000).

In cats, passive stretch of the extraocular muscles activates neurons in V1 in the absence of any visual input. Peripheral anesthesia abolishes this response, demonstrating that a proprioceptive projection from the extraocular muscles reaches the early visual cortex (Buisseret and Maffei, 1977). Our study shows a modulatory connection from the eye proprioceptive area in the postcentral gyrus to the extrastriate visual cortex, suggesting that the proprioceptive input may reach the visual cortex through a cortical–cortical connection, via the somatosensory cortex.

An alternative interpretation of the current fMRI findings is that the observed modulation of neural activity was unrelated to the previous behavioral findings. That is, the results do not reflect a change in visual sensitivity, but rather a modulation of retinal input by the proprioceptive signal of eye position coding of the location of the target in the body-centered space. Against this interpretation speak the null results for the comparisons of left- vs. rightward gaze and of target position near the head midline vs. the periphery (contrasts c.–f.) within the region of interest identified by the rTMS type by direction of rotation of the eye interaction (conjunction a.). Based on these negative results, we suggest that the identified area in the left cuneus is less likely to code the location of the visual stimuli in the body centered space, at least not as a left–right or center–periphery gradient.

Outside this region of interest, large clusters in the medial occipital, frontal and parietal cortices and cerebellum showed a modulation of visually evoked activity that depended on the laterality of gaze or on the alignment of the visual target with the head midline (contrasts c. and f., Fig. 4). The increased activity in the left medial occipital cortex when the gaze was directed to the left vs. right and in the right medial occipital cortex for the opposite comparison resembles the results of the study by Deuschländcr et al. (2005). Such activity could reflect the presence of gain field maps, where the visually evoked activity scales from left to right or right to left of the body midline as previously observed in single-cell recordings in the monkey (Andersen and Mountcastle, 1983; Bremmer, 2000; Guo and Li, 1997; Weyand and Malpeli, 1993). However, in the current study, such gain-field activity related to eye position might be confounded by differences in the oculomotor command that maintain the gaze or by differences in the voluntary allocation of attention in space. Therefore, these positive results do not allow a strong conclusion about the presence of gain field maps.

Conclusions

In summary, Balslev et al. (2011b) have previously proposed that eye proprioception can modulate visual perception. This suggestion was based on the observation that visual accuracy changes depending on both the direction of gaze and on the level of excitability in S1EYE. Here we report a brain area in the left cuneus, outside the retinotopic areas where the change in neural activity depended on the responsiveness of the extrastriate visual cortex after S1EYE-rTMS. The change in neural activity in this area could be predicted from these previously observed changes in visual accuracy, but not from the location of the visual stimuli in the body-centered space. The consensus between behavioral and imaging results suggests that a modulatory connection from S1EYE to the extrastriate visual cortex may be the neural mechanism by which eye proprioception influences visual sensitivity.

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