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Research report

Pre-saccadic perceptual facilitation can occur without covert orienting of attention

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ABSTRACT

The pre-motor theory of attention suggests that the mechanisms involved in target selection for eye movements are the same as those for spatial attention shifts. The pre-saccadic facilitation of perceptual discrimination at the location of a saccadic goal (paradigm of Deubel and Schneider, 1996) has been considered as an argument for this theory. We compared letter discrimination performance in a saccade (overt attention – pre-saccadic facilitation) and a fixation (covert attention) task in a patient with right posterior parietal damage and 4 controls.

In the overt attention condition, the patient was instructed by a central cue to make a saccade to a target located at a peripheral location. During the saccade latency (in a period of time of 250 msec following the presentation of the cue), a letter was presented at the target location. Accuracy of leftward saccades was impaired compared to rightward saccades. To evaluate letter discrimination performance in this saccade task (i.e., the presence of pre-saccadic facilitation), we selected only those leftward saccades that were equivalent in accuracy (and latency) to the rightward ones. Within these selected trials, the patient was able to discriminate letters equally well in both visual fields. In contrast, he performed at chance level during the fixation task (covert attention condition) for letters presented at the same peripheral location with the same timing with respect to the cue presentation. The patient could thus discriminate the letter presented at 8° of visual eccentricity while he was preparing a saccade, whereas he was unable to perceive the letter in the fixation task.

Remarkably, in the left visual field, letter discrimination was impossible even when a letter was presented as close as 2.5° of visual eccentricity in the fixation task. Altogether, these results suggest that pre-saccadic perceptual facilitation does not rely on the same processes as those of covert attention, as tested by fixation task. Instead, we propose that pre-saccadic perceptual facilitation results from a form of attention specific to action, which could correspond to a pre-saccadic remapping process.

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1. Introduction

Vision provides the brain with one of the most fundamental forms of information for perception and motor behaviour. Despite the subjective sensation of an instantaneous, global and detailed perception of the visual scene, the structural organisation of the retina allows good visual acuity only in a restricted area, the fovea. Eye movements (known as saccades or overt attention) can bring a new part of the visual scene to the fovea, allowing it to be analysed more precisely by the retina and the visual cortex. Shifts of attention without eye displacements (known as covert attention) have also been shown to improve spatial resolution and contrast sensitivity in peripheral vision (Yeshurun and Carrasco, 1998; Carrasco et al., 2000).

Brain imaging (e.g., Corbetta et al., 1998, Corbetta, 1998; Perry and Zeki, 2000; Nobre et al., 2000) show largely, but not completely, overlapping networks for covert shifts of visual attention towards peripheral objects and saccadic eye movements. Specifically, saccade target selection has been considered to rely on the same processing mechanisms as covert attention (Shepherd et al., 1986; Rizzolatti et al., 1987; Sheliga et al., 1994, 1995; Hoffman and Subramaniam, 1995; Kowler et al., 1995; Deubel and Schneider, 1996; Awh et al., 2006). For example, Deubel and Schneider (1996) designed an elegant dual-task paradigm, which combined a target-directed saccade task with a letter discrimination task. Their results showed that visual discrimination in periphery was best when the discrimination stimulus and saccade target were at the same location in space. This phenomenon called pre-saccadic perceptual facilitation occurs before the eye movement takes place, while the eyes are still at the fixation location.

The usual interpretation of pre-saccadic perceptual facilitation is that saccade preparation automatically induces a covert attentional shift to the location of the saccadic goal, which has been shown to improve spatial resolution in the visual periphery (Yeshurun and Carrasco, 1998). In other words, a single mechanism of spatial attention would select objects both for perceptual processing and for motor action; a saccade cannot occur without without a preceding attentional shift (Deubel and Schneider, 1996; Schneider and Deubel, 2002). An alternative interpretation could be that pre-saccadic perceptual facilitation is a separate mechanism from covert attention, even though, in a normally functioning brain, it is impossible to dissociate the two using psychophysical tasks, since both show similar spatial enhancements.

These two abovementioned interpretations are actually very different. The first one involves a common substrate for 'covert' (fixation) and 'overt' (saccade) shifts of attention and thus predicts that if performance of the former is impaired, for example by a brain lesion, it will also be impaired for the latter. In contrast, the second interpretation suggests that pre-saccadic perceptual facilitation and covert attention processing mechanisms rely on distinct neural substrates and thus implies a possible dissociation between fixation and saccade tasks. Specifically, a brain-damaged patient may be able to do one task but not the other. Here we investigate these two alternatives by comparing the performance of a patient with a unilateral lesion in the posterior parietal cortex (PPC) between left and right visual fields in a covert version and a classical (but simplified) version of the pre-saccadic facilitation paradigm introduced by Deubel and Schneider (1996).

2. Material and methods

2.1. Subjects

Patient O.K. was 35 at the time of testing, 2 years after an ischemic stroke involving the posterior branch of the right sylvian artery. Magnetic resonance imaging revealed a hyperintense signal on T2 sequences located in the right posterior parietal lobe along with a slight damage to the right posterior part of the corpus callosum (Fig. 1 A). During clinical assessment, he demonstrated typical unilateral optic ataxia in his left visual field and/or with his left hand, in absence of any visual field deficits. He did not exhibit any clinical signs of unilateral neglect, tested using line bisection, cancellation and drawing tasks. This finding is in agreement with previous conclusions of a double dissociation between unilateral neglect and optic ataxia (Perenin and Vighetto, 1988; Pisella et al., 2007). He exhibited visual extinction during initial clinical testing, but this disappeared after a month.

The perceptual performance of patient O.K. was compared between visual fields and between the saccade and the fixation tasks. The performance of a group of 4 control subjects (age range: 25–35) was also recorded for comparison with the patient.

2.2. Apparatus

Subjects sat in front of a tailored experimental device composed of a high speed Cathode Ray Tube (CRT) screen (frequency: 160 Hz, 21″), coupled with a high spatial and temporal frequency stimuli presentation device (Visual Stimulus Generator™ ViSaGe®, Cambridge Research System, Rochester, UK). A High Speed Video Eyetracker™ (Cambridge Research System, Rochester, UK) fixed on a head and chin rest registered eye movements of the right eye (frequency: 250 Hz, resolution: .05°) by means of an infra-red camera. The subjects' eyes were at a distance of 64 cm from the screen. The eyetracker, the ViSaGe® and a button press (for the letter discrimination response) were synchronised by a custom software interface developed in our laboratory. This software also controlled the experimental procedure, stimulus presentation and response acquisition.

2.3. Procedure

2.3.1. Letter discrimination task in the saccade and fixation tasks

Initially, five target locations were presented as "8" symbols on both sides of a central visual fixation for a randomised period between 1 and 2 sec (Fig. 1B). A central cue (in the form of a green arrow) was then presented for 150 msec, which indicated the direction towards which the subjects had to covertly shift attention (fixation task) or to make an eye movement (saccade task). In contrast to the task by Deubel

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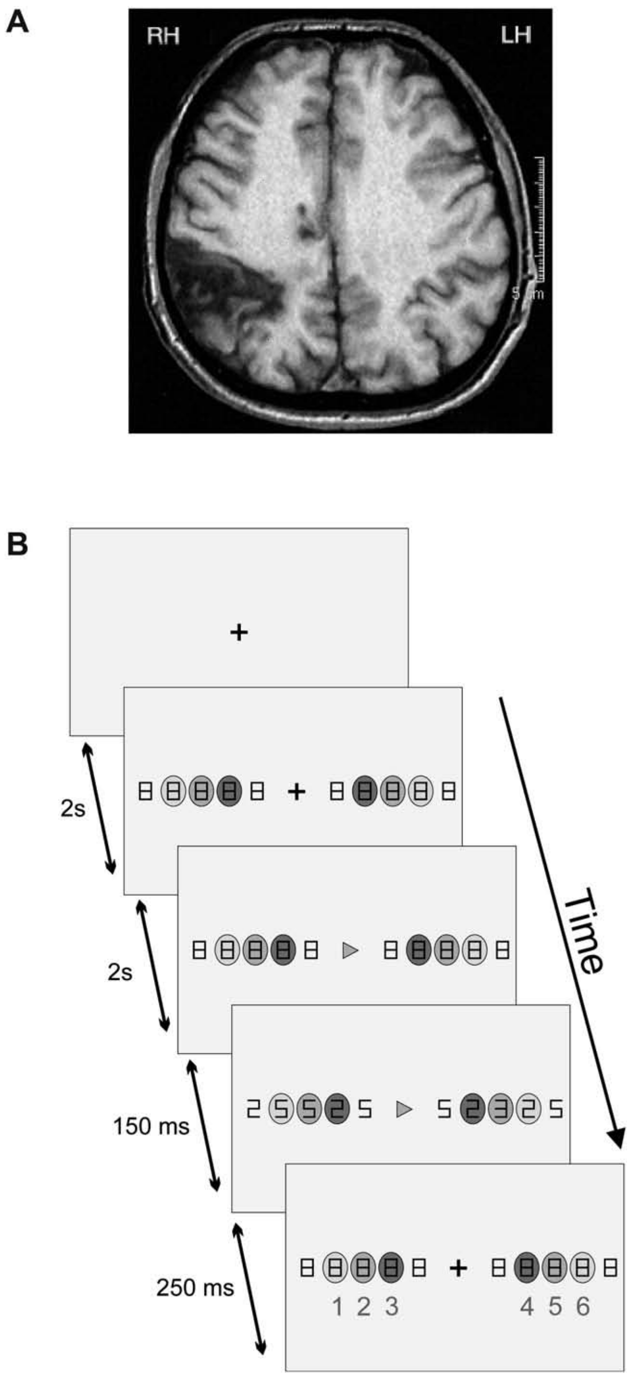

Fig. 1 – Patient's Magnetic Resonance Imaging (MRI) (A) scan and task setup (B). A: MRI depicting patient O.K.'s lesion. The T2 weighted horizontal magnetic resonance imaging section demonstrates an ischemic lesion of the right posterior parietal region. LH: left hemisphere; RH: right hemisphere. B: Task setup. Initial image presented on the screen in the overt and covert versions of the procedure. Subjects fixated on the centre fixation cross. After a delay, the fixation cross was replaced by a green arrow directing the subjects to make an eye movement (Saccade task) or to attend (Fixation task) to the left or the right green position.

and Schneider (1996), where the target letter (E or inverted E) could be presented at three different locations in each visual field, we simplified the task by always presenting the target letter at the green position (8° eccentricity) in the left or the right visual field. The target letter was presented at this location for 250 msec and then masked by the reappearance of the "8" symbols. At the end of the trial, the subjects were asked to press one of two buttons to indicate whether the letter presented was an E or an inverted E (2-alternative forced choice paradigm).

The same letter discrimination task in peripheral vision was performed in the saccade task (adapted from Deubel and Schneider, 1996) and in the fixation task. In the saccade task, the patient was asked to always saccade to the green position. In addition, we also ensured that he did not view the target letter in central vision (e.g., by making an eye movement too quickly and landing on the target while the discrimination letter was still present). We did this by monitoring eye position online. If the eyes moved within a 5° range of the saccade target location before the end of the target presentation time, the program automatically switched to the next stimulus image, i.e., the reappearance of the "8" symbols. In the fixation task, central fixation was required during the entire trial and was monitored online through the eye-tracker recordings.

2.3.2. *Letter discrimination at 2.5° in the fixation (covert orienting) condition*

In order to evaluate the distribution of covert attention in patient O.K. and to demonstrate his ability to shift attention at different locations, we also designed a fixation task in which the discrimination letter was always presented at the location of the very first "8" symbol (2.5°) in the right or in the left visual field. The temporal parameters were identical to the main task.

3. Results

3.1. *Dissociation between saccade and fixation tasks*

In the fixation task, letter discrimination performance was at chance level in both the left and the right visual fields (Fig. 2 – dashed line; 40% correct in the left and 50% in the right; both $\chi^2 < .5$; both $p > .05$) for patient OK. In contrast, performance in the saccade task (Fig. 2 left panel – solid line) was above chance level in the right visual field (83% correct, $\chi^2 = 9.45$; $p < .01$), but not in the left visual field (60% correct, $\chi^2 = .81$; $p > .05$). In quantifying the saccades made to the left and right visual field, we found that leftward saccades showed significantly longer latencies and shorter amplitudes compared to rightward ones [F (1,78)>8, $p < .05$]. In order to directly evaluate the presence of pre-saccadic facilitation in the left visual field, we selected only trials where the leftward saccades were equivalent to the rightward ones in terms of saccadic reaction times and amplitudes (RT between 350 and 550 msec and amplitudes between 6° and 9°). The middle panel of Fig. 2 shows the performance in the letter discrimination task comparing the fixation and the saccade tasks when only these selected saccades were included (74% of the total number of saccades were kept for this analysis, consisting of 23 leftward

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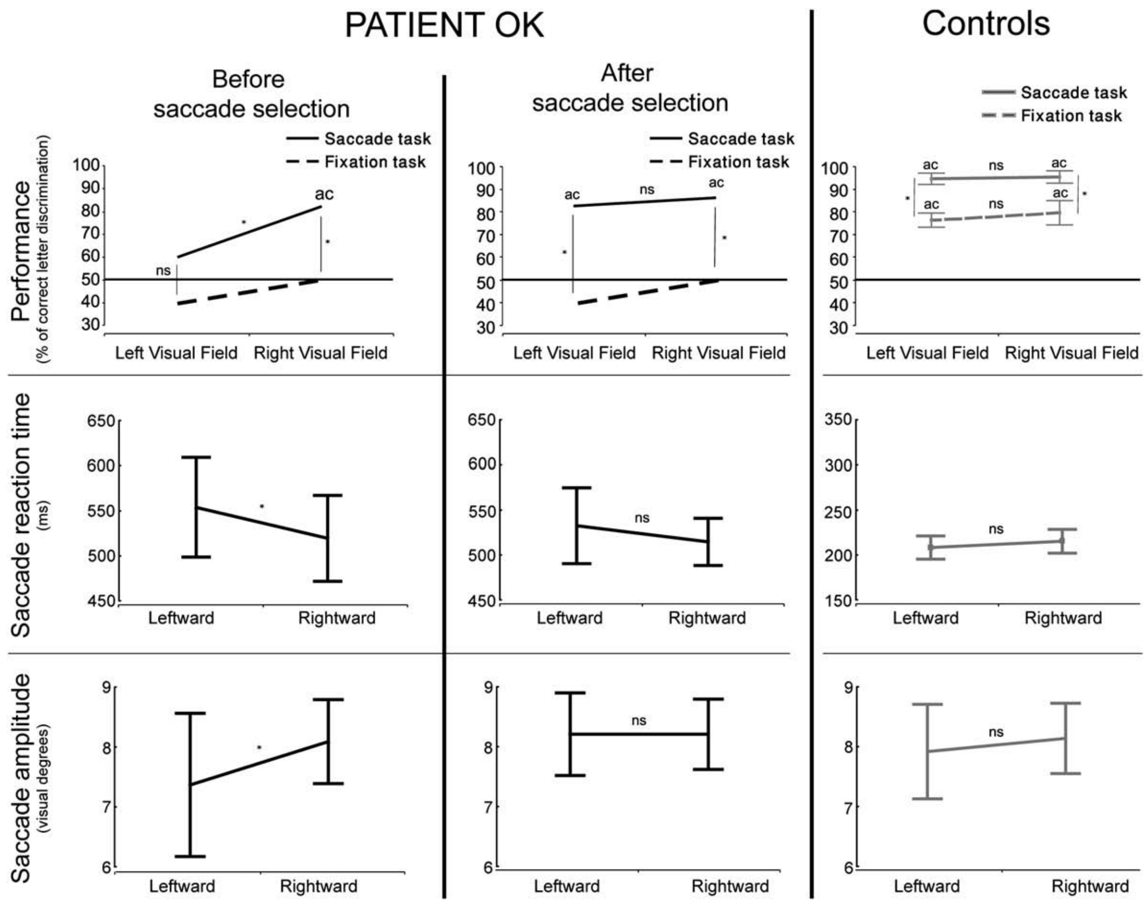

Fig. 2 – Performance of patient OK in the covert and the overt versions of the letter discrimination task (Fixation and Saccade tasks, respectively), before saccade selection (left column), after saccade selection (middle column) and with respect to control performance (right column). Performance is plotted as a percentage of correct responses in the letter discrimination task for the overt (solid line) and covert (dashed line) versions. The performance in the overt version is completed by graphs illustrating the saccade reaction times and amplitudes (mean and SD for leftward and rightward saccades). 'ac' corresponds to performance above chance level (χ^2 comparison with the value of 50%). Performance is compared between conditions (Left *vs* Right visual fields; Saccade *vs* Fixation tasks) using χ^2 statistical analyses. **p* < 05, ns: non-significant differences. Saccade parameters are compared using one-way factorial ANOVAs (leftward *vs* rightward directions).

saccades and 37 rightward saccades). Note that 18 trials were removed due to hypometry whereas only 2 trials were removed due to latency above range. In both visual fields, we found letter discrimination performance above chance level in the saccade task (83% in the left and 86.5% in the right; both $\chi^2 > 5$; both $p < .05$) but at chance level in the fixation task (both $\chi^2 < .5$; both $p > .05$).

In the group of control subjects, the perceptual performance also significantly differed between the saccade and fixation tasks ($\chi^2 > 18$; $p < .001$ in both visual fields). In contrast to the patient however, performance was always above chance level (all $\chi^2 > 29$; $p < .001$), close to 95% in the saccade task [Fig. 2 – solid line: 95% (Standard deviation – SD = 5.0) in the left and 96% (SD = 5.4) in the right] and close to 80% in the fixation task [Fig. 2 – dashed line: 77% (SD = 6.3) in the left and 80% (SD = 10.8) in the right]. Perceptual performance did not differ between left and right visual fields ($\chi^2 < .08$; $p > .05$ in both saccade and fixation tasks) and, in the saccade task, leftward and rightward saccades did not differ [mean amplitudes: 7.9° (95%, Confidence interval – CI = ±.8°) for leftward and 8.1° (95%, CI = ±1.0°) for rightward saccades; mean RT: 208 msec (95% CI = ±22 msec)] for leftward and 215 msec (95% CI = ±23 msec) for rightward saccades [repeated measures analysis of variance tests – ANOVAs: Fs(1, 3)>.5; $p > .05$].

3.2. Asymmetrical distribution of covert attention

Patient O.K.'s performance in the fixation task was at chance level both in the right (ipsilesional) and in the left (contralesional) visual fields. We wanted to test whether the patient was completely unable to perform covert shifts of attention, or whether this ability was preserved at a location closer to fixation and asymmetrical due to the unilateral lesion. We therefore measured the patient's performance in the fixation task at 2.5° of visual eccentricity (first location to the left or right). His performance of letter discrimination in the fixation task at 8 and 2.5° of visual eccentricity is presented in Fig. 3

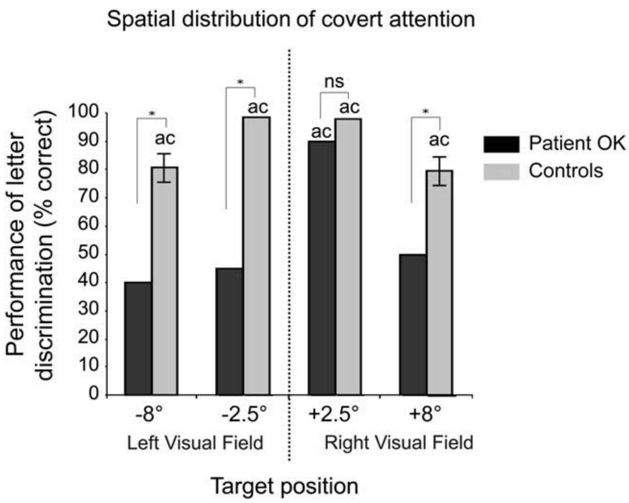

Fig. 3 – Spatial distribution of covert attention. The histogram shows the percentage of correct letter discrimination in the covert versions for patient O.K. (black bars) and the control subjects (grey bars with SD), when the letter was presented at 2.5° or 8° of visual eccentricity in the left or in the right visual fields. At 2.5°, the performance of the four control subjects was at ceiling (100%, SD = 0). 'ac' corresponds to performance above chance level (χ^2 comparison with the value of 50%).Performance is compared between patient and controls using χ^2 statistical analyses. *$p < 05$; ns: non-significant differences.

along with the control subjects' performance. Control performance was a symmetrical function of visual eccentricity. The performance of patient O.K. remained at chance level in his contralesional visual field (left) even at 2.5° of eccentricity (perifoveal vision). In contrast, patient O.K.'s performance at 2.5° in the right ipsilesional visual field was significantly above chance level.

4. Discussion

We found dissociated performance in the patient between saccade and fixation tasks – revealing an impairment of covert attention shifts, especially towards the contralesional visual field, but not of pre-saccadic perceptual facilitation.

Impairment of covert attention after lesions of the superior parietal lobule has been previously described as a shrinking of the attentional field in a patient with bilateral damage (Michel and Hénaff, 2004) and as a deficit in orienting covert attention towards the contralesional visual field with asymmetrical or unilateral damage (Striemer et al., 2007). Patient OK's spatial distribution of covert attention (Fig. 3) shows that a unilateral lesion of the superior parietal lobule can actually lead to both a shrinking and a lateralised deficit of covert attention.

The unilateral lesion of patient OK also affected his saccadic eye movements; in particular, several contralesional saccades were hypometric. A systematic combination of longer reaction times and shorter amplitudes has also been reported in patients with lesion of the parietal eye field without optic ataxia (Pierrot-Deseilligny and Müri, 1997). These two aspects can be observed combined or isolated in hemineglect (Walker and Findlay, 1996) and in optic ataxia (Gaveau et al., 2008). The asymmetrical saccadic deficit of patient OK could be due to an impaired target selection process, which is probably magnified by a crowding effect (Strasburger, 2005).

When patient OK's saccades were accurate, the pre-saccadic perceptual facilitation occurred in both visual fields. Even though letter discrimination in the fixation task was impossible as close as at 2.5° in the left visual field, it was above 80% correct at 8° before saccade execution (saccade task). The good letter discrimination performance of patient O.K. in the saccade task stands in strong contrast with his performance at chance level in the fixation task at the same eccentricity, even in the ipsilesional visual field (Fig. 2). In summary, performance in fixation and saccade tasks were dissociated both in the left and in the right visual fields in the patient.

The two tasks may involve different amounts of covert attention or of attentional disengagement: in the fixation task, the covert shift towards the peripheral target might be restricted or immediately cancelled by a covert shift back to the fixation location. Consequently, the process of making a saccade may enhance or lengthen covert attentional orienting towards the peripheral target. Such quantitative differences between the two tasks might cause that the lateralised deficits of the patient are revealed only in one task, i.e., only in the contralesional visual field at 2.5° of eccentricity in the fixation task.

Alternatively, this dissociation resulting from a lesion to the parietal cortex can be interpreted to reflect a neural dissociation between mechanisms for pre-saccadic perceptual facilitation and covert attention. It could be that there is no single common substrate devoted to perceptual enhancement during saccade preparation and shifts of covert attention, because if that were the case, similar performance should be obtained for letter discrimination in both the fixation and saccade tasks. We therefore suggest that overt and covert attentional processes are functionally and anatomically different and that pre-saccadic perceptual facilitation results from a form of attention specific to action. One could argue that an actual ''shift'' of attention is driven before saccade execution in the saccade task, whereas in the fixation task only a ''distribution of attention'' between peripheral and central loci can be elicited. The present results would thus be reminiscent of a dissociation between distributed and focused attention (Demeyere and Humphreys, 2007). The phenomenon of pre-saccadic perceptual facilitation may also rely on pre-saccadic remapping mechanisms (Duhamel et al., 1992). Trans-saccadic remapping mechanisms have been demonstrated by monkey electrophysiology and more recently in humans, with a possible role in visual perception (review in Pisella and Mattingley, 2004; see also Melcher, 2007). Such a mechanism provides a stable representation of space, by redistributing visual activity at each snapshot. It has been proposed that these remapping processes use efference copy information about the upcoming saccade to remap neural activity to correspond to the future spatial receptive field (Bays and Husain, 2007). This is supported by our results in that the patient was able to discriminate letters only when the saccade was accurate in terms of amplitude. However, while only accurate saccades generate pre-saccadic facilitation in our patient, our data do not allow us to rule out that covert attention also contributes to pre-saccadic facilitation in healthy subjects.

Remapping activity as well as activity related to attention and saccade planning has been recorded in monkeys within the lateral part of the intraparietal sulcus (LIP) (Andersen and Buneo, 2002; Colby and Goldberg, 1999; Colby et al., 1995) but not necessarily from the same neurons. Unfortunately, the limited spatial resolution of brain imaging techniques does not allow us to distinguish separate modules for these three functions in the human. In addition, psychophysical tasks are only able to determine behavioural consequences, which may be similar in healthy controls, such as a spatial resolution enhancement due to covert attention and pre-saccadic perceptual enhancement, but cannot determine the underlying neuronal processes. However, the diversity of the visual semiology after parietal injury (Balint's syndrome, see Pisella et al., 2007, 2008 for reviews) strongly supports the existence of a complex functional network involving separate modules for attention, eye movement and trans-saccadic integration.

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