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Oculomotor integration in patients with a pulvinar lesion

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ABSTRACT

The pulvinar nucleus of the thalamus, with its connections to visual areas and to frontal and parietal oculomotor cortex, might serve as a nexus for integrating cortical control of voluntary eye movements with reflexive eye movements generated by the superior colliculus. To investigate this hypothesis, we tested five patients with a unilateral lesion of the pulvinar on the oculomotor capture paradigm. In this task, participants have to ignore a distractor item and make a saccade to a target in a visual search display. Results showed that the interference of the distractor was stronger when it was presented contralateral to their lesion compared to when it was presented in the ipsilesional visual field. These findings were confirmed by an additional single case experiment in which we measured saccade trajectory deviations as evoked by a single distractor. These results show that the pulvinar is involved in the successful influence of higher order signals (like our goals and intentions) on the guidance of our eye movements.

1. Introduction

The pulvinar, the largest nucleus in the thalamus, has reciprocal connections throughout the brain. Because it receives input from various cortical areas like frontal and parietal cortex, the pulvinar has been proposed to facilitate cortico-cortical communication, providing a nexus where the activity of one cortical area can modulate another (Guillery & Sherman, 2002; Kaas & Lyon, 2007; Shipp, 2003). Besides cortical input, subcortical areas are also connected to the pulvinar (Romanski, Giguere, Bates, & Goldman-Rakic, 1997; Shipp, 2003). For instance, tectothalamic fibers arising from superficial layers of the SC project ipsilaterally to the pulvinar (Cowey & Stoerig, 1991) and the superior colliculus (SC) projects to cortical areas via synapses in the pulvinar.

The pulvinar has been implicated in various visual functions in which different parts of the cortex are involved. It has been suggested, for instance, that the pulvinar is part of a distributed network that mediates attentional processing (Posner & Petersen, 1990). Indeed, lesion studies have shown deficits in engaging attention to the contralesional visual field (Arend et al., 2008; Danziger, Ward, Owen, & Rafal, 2001/2002; Rafal & Posner, 1987; Sapir, Rafal, & Henik, 2002). Besides deficits in engaging attention, patient studies have also implicated the human pulvinar in visual filtering (LaBerge & Buchsbaum, 1990), feature binding (Ward, Danziger, Owen, & Rafal, 2002) and in automatic response channel activation by associated stimuli (Danziger, Ward, Owen, & Rafal, 2004).

One of the putative functions of the human pulvinar that remains relatively unexplored is its role in oculomotor control. Animal studies have shown that saccades can be elicited by electrical stimulation of thalamic nuclei (Crommelinck, Roucoux, & Meulders, 1977; Maldonado & Schlag, 1984; Schlag & Schlag-Rey, 1971), and that single units in thalamus are active in relation to saccades (Crommelinck et al., 1977; Schlag-Rey & Schlag, 1977; Schlag & Schlag-Rey, 1984a, 1984b). Single-cell recordings in the pulvinar have observed modulation in response to a visual stimulus as a function of the position of the eye in the orbit (Petersen, Robinson, & Keys, 1985; Robinson, McClurkin, & Kertzman, 1990). So, although it is known that the pulvinar is involved in oculomotor responses, its specific function in oculomotor control remains unclear. One study on patients with thalamic lesions found an absence of the fixation offset effect for visually triggered eye movements (Rafal, McGrath, Machado, & Hindle, 2004). Furthermore, patients with pulvinar lesions showed an ipsilesional bias in decision making as revealed by the antisaccade task (longer latencies to initiate saccades away from contralesional targets) and a temporal order judgment task (Arend et al., 2008).

On the basis of the connectivity of the human pulvinar, it might serve as a nexus for integrating cortical control of voluntary (top-down) eye movements with reflexive (bottom-up) eye movements generated by the superior colliculus. As mentioned, the pulvinar receives input both from cortical areas and the superior colliculus (Guillery & Sherman, 2002; Shipp, 2003). Cortical control of voluntary eye movements originates from cortical areas, like the frontal eye fields and the lateral intraparietal area (Munoz, 2002). The role of the superior colliculus in generating reflexive eye movements is also well established (e.g. Schiller, Sandell, & Maunsell, 1987). If the

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proposed functional role of the pulvinar is correct, it is important for the successful influence of higher order signals (like our goals and intentions) on the guidance of our eye movements.

To test this hypothesis, we used the oculomotor capture task developed by Theeuwes, Kramer, Hahn, and Irwin (1998) and Theeuwes, Kramer, Hahn, Irwin, and Zelinsky (1999). In this paradigm, the task of the participant is to make an eye movement to a target circle with a unique color. In half of the trials, an addition circle is presented with abrupt onset ('distractor'). In a large portion of trials, participants are unable to inhibit an eye movement to the location of the distractor before executing a saccade to the target ('capture trials') (Theeuwes et al., 1998, 1999). Erroneous saccades to the distractor are purely reflexive, because, in contrast to the antisaccade task, the distractor does not need to be attended in order to successfully perform the task (see also Godijn & Kramer, 2006; Van der Stigchel, in press; Van der Stigchel et al., 2007b). In this task, there is a competition between a voluntary eye movement to the target and a reflexive eye movement to the onset distractor. In order to successfully perform the task, the reflexive eye movement to the distractor needs to be inhibited. A failure of inhibition is therefore reflected in an erroneous eye movement to the distractor.

In the current study, we tested five patients with a unilateral lesion of the pulvinar on the oculomotor capture task, and compared performance when the distractor was presented in the contralesional versus the ipsilesional visual field. If there is indeed less cortical control of reflexive eye movements to the contralesional visual field, an increased amount of capture trials should be observed when the distractor was presented in the contralesional visual field. Because any behavioral deficits are predicted to be lateralized, the crucial analysis is a within-subject comparison of performance in the contra- and ipsilesional visual field. This way, the patients act as their own control group. Data from an age-matched control group will be reported in order to verify that any behavioral imbalance between both visual fields is not present in healthy participants.

2. Experiment 1

2.1. Methods

2.1.1. Subjects

All five patients were active and independent without any mental impairment. All had intact visual fields and none had visual extinction or hemispatial neglect on neurological examination or pencil and paper tests including drawing, copying and cancellation. All participants gave informed consent according to the standards of the Declaration of Helsinki for a protocol that was approved by the institutional review boards of the hospital and the university.

All patients had 3D MRI scanning with overlapping cuts to permit lesion reconstruction. One patient (TN) was scanned with a 1.5 T scanner and a voxel size of 1 mm on T1-weighted images, and the other four were scanned at 3 T with voxel size of .7 mm. The 4dfp suite, a non-commercial software package, was used to register the anatomical images to a Talairach atlas representative target image, 711-2B, and resample them to a 2 mm isotropic image resolution. Lesion boundaries were traced on each slice using Mricron after automatically correcting for image intensity inhomogeneity using a variant of Styner, Brechbuhler, Szekely, and Gerig (2000) and the assumption that the objects imaged in the Philips scanner exhibit a parabolic three-dimensional gain field (10 free parameters).

DG is a 78-year-old, right-handed man who suffered a hemorrhage in the left thalamus 4 years before the present testing. His right arm and leg are weak, but he can walk with a cane. The hemorrhage destroyed most of the pulvinar, sparing only the most posterior ventro-lateral part (see Fig. 1). DG has corrected-to-normal vision.

TN is a 63-year-old hypertensive right-handed woman, who suffered a right thalamic hemorrhage 8 years previously. She has residual left arm and leg weakness and sensory loss but can walk with a cane. The lesion is restricted to the anterior pulvinar affecting the most rostral and dorsal part of the topographic maps of the ventral pulvinar, and causes deficits restricted to the inferior left quadrant (Ward et al., 2002). The region damaged in the lateral, ventral and anterior 'corner' of the pulvinar corresponds to the locus of activation for contralateral pulvinar maps observed in a previous fMRI investigation (Morel, Magnin, & Jeanmonod, 1997).

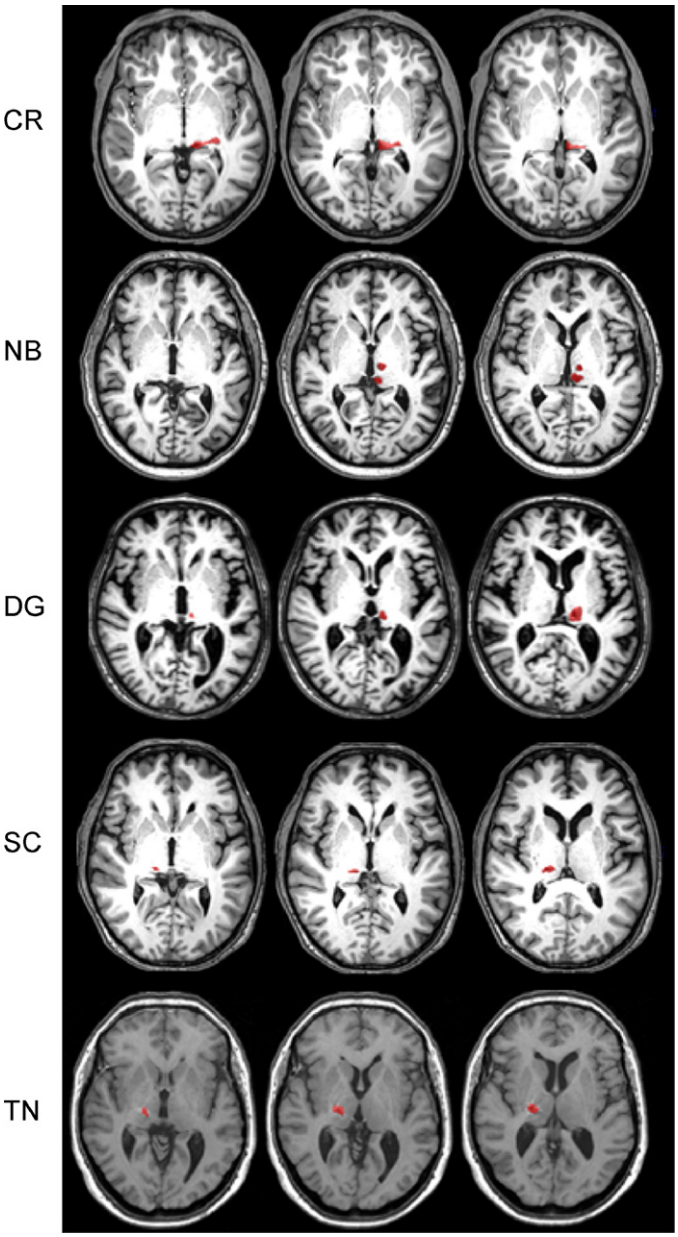

Fig. 1. Normalized T1-weighted MRI scans for each patient. Axial slices aligned from ventral to dorsal (from left to right) are 0, 3 and 6 mm above the AC-PC line. Lesion locations are highlighted in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

TN has corrected-to-normal vision. For TN, only the bottom-left visual field was considered contralesional.

CR is a 22-year-old right-handed man who suffered a closed head injury in a fall 2 years before testing, resulting in a hemorrhagic contusion and avulsion restricted to the posterior pole of the left pulvinar. High-resolution multispectral MRI revealed no other brain pathology. He has made a full clinical recovery, showing no mental symptoms or motor impairment, and was studying at University.

SC is a 46-year-old hypertensive man, previously employed as an auto mechanic, who suffered an intracerebral hemorrhage in the right thalamus on 19 months prior to testing. He has residual left sided clumsiness and aggravating sensory symptoms. He had an episode in 2005 when he had similar symptoms, pins and needles down the left side of his body, which largely recovered. Examination reveals dystonic posturing of the left arm, and pseudoathetotic in the fingers. The visual fields are intact and the cranial nerves are including eye movements. Strength is intact but both leg and finger movements are very clumsy and his finger dexterity is poor. There is some subjective decrease in sensation on the left side of his face and throughout the left side of his body. He is able to distinguish pin-prick from dull and has only a slightly elevated threshold to detect light touch. He experiences dysthesiae and perceives ordinary sensory stimuli as being painful. He is able to recognize objects in his left hand and has intact position sensation. The deep tendon reflexes are a

bit brisker on the left side and the plantar response is extensor. He is able to walk without a stick but circumducts the leg while he walks.

NB is a 63-year-old man who suffered an ischemic stroke in the left thalamus in 5 months prior to testing. He had slurred speech and right neglect, but these quickly recovered leaving no residual neurological deficit.

Additionally, we ran seven control subjects matched for age with the tested patients (21, 44, 62, 62, 65, 76, 81 years old).

2.1.2. Apparatus

Participants performed the experiment in a sound-attenuated setting, viewing a display monitor from a distance of 59 cm. Eye movements were recorded by an Eyelink1000 system (SR Research Ltd., Canada), an infra-red video-based eye tracker that has a 1000 Hz temporal resolution and a spatial resolution of 0.01°. The participant's head was stabilized with a chin rest, and an infra-red remote tracking system compensated for any residual head motion. The left eye was monitored. An eye movement was considered a saccade when either eye velocity exceeded 35°/s or eye acceleration exceeded 9500°/s^2.

2.1.3. Stimuli

See Fig. 2 for the display sequence of the experiment. Participants viewed a display containing a gray plus sign (1.0° × 1.0°) on a black background in the center of the display, which was used as fixation point. Six green circles (1.7° in diameter) were positioned on an imaginary circle around central fixation point with a radius of 8.6° at 1, 3, 5, 7, 9, or 11 o' clock. After 800 ms, all circles, except one, changed color to red. The remaining green circle was the target circle. This target circle was either located at 1, 5, 7 or 11 o'clock. Halve of the trials an additional red circle was presented simultaneously with abrupt onset on the same imaginary circle as the other circles ('distractor'). The distractor was always positioned in the opposite field to the target at a fixed position. When the target was presented at one o'clock, the distractor was presented at eight o'clock, and similarly: target at 5, distractor at 10; target at 7, distractor at 2; target at 11, distractor at 4 o'clock. The target display was presented for 2000 ms. Afterwards all objects were removed from the display. The experiment consisted of 344 experimental trials and 24 practice trials. DG performed 312 experimental trials.

2.1.4. Procedure and design

Participants were instructed to fixate the center fixation point until the target appeared, when they were to move their eyes to the target. It was stressed that they should try to make a single accurate saccade. Each session started with a nine-point grid calibration procedure. In addition, simultaneously fixating the center fixation point and pressing the space bar recalibrated the system by zeroing the offset of the measuring device at the start of each trial. The sequence of trials was randomized.

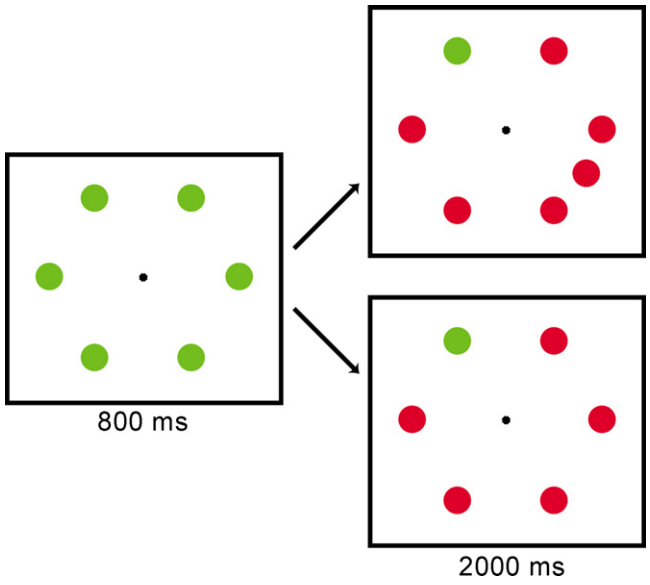

Fig. 2. The procedure of Experiment 1. In half of the trials, an onset distractor appeared simultaneously with the target. Participants were instructed to initiate an eye movement to the target as soon as they detected it presence.

3. Data analysis

Saccade latency was defined as the interval between target onset and the time on which the eye landed on the target. When the endpoint of a saccade was within 3.4° of the target (i.e. twice the size of the target), it was classified as being landed on the target. Trials were excluded when the latency of the saccade was lower then 80 ms or higher then 1200 ms. Moreover, trials were excluded from analysis when a saccade larger than 5° was made before the onset of the target. The exclusion criteria led to a loss of 5.4% of trials.

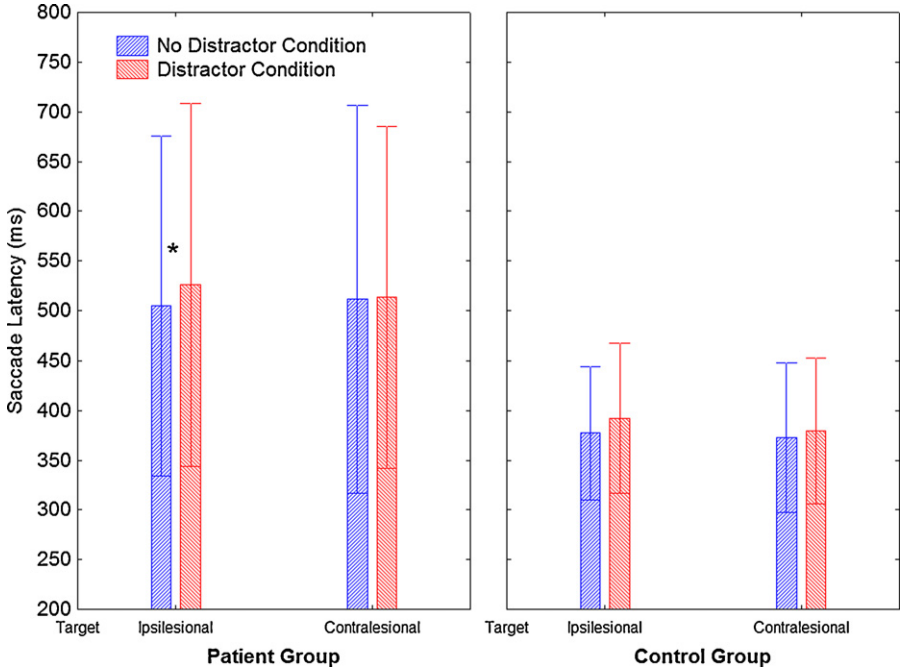

Fig. 3. Saccade latencies for the oculomotor capture paradigm for both the patients and the control group. Note that the distractor was always presented in the opposite visual field; e.g. when the target was presented in the ipsilesional visual field, the distractor was presented in the contralesional visual field. Error bars indicate 95% confidence intervals.

Table 1
Means of the individual patients for the different conditions.

Patient	Latency (ms)				Capture (%)	
	No distractor		Distractor present		Contralesional distractor	Ipsilesional distractor
	Ipsilesional target	Contralesional target	Ipsilesional target	Contralesional target		
CR	362	350	366	386	1.2	0
DG	729	759	762	731	11.3	9.3
NB	493	493	503	485	9.4	3.6
SC	433	412	459	410	16.9	12.2
TN	507	543	542	555	5.6	4.9

For saccade latencies, *t*-tests were used to compare whether saccade latencies in the no-distractor condition were different for the contralesional and the ipsilesional visual field. To investigate the interference of the distractor, we compared saccade latencies in the no-distractor condition to the distractor condition for both contralesional and ipsilesional visual field.

A capture trial was defined as a trial in the distractor condition in which a saccade landed on the distractor before landing on the target. Saccades were classified as landed on the distractor when the endpoint of a saccade was within 3.4° of the distractor (i.e. twice the size of the distractor). *t*-Tests were used to compare the percentage capture for contralesional and ipsilesional distractors.

4. Results

4.1. Saccade latency

No-distractor condition: There was no difference between saccade latencies to the contralesional (mean = 511 ms; st. dev. = 157 ms) and the ipsilesional visual field (mean = 505 ms; st. dev. = 138 ms; $t(4) = 0.59$; $p = 0.59$; see Fig. 3). Table 1 shows the individual means for the different conditions.

Distractor condition: There was a significant increase in saccade latency to an ipsilesional target when a contralesional distractor was presented (mean = 526 ms; st. dev. = 147 ms) compared to when no distractor was presented ($t(4) = 3.50$; $p < 0.03$). This effect was absent for ipsilesional distractors (mean = 514 ms; st. dev. = 139 ms; $t(4) = 0.21$; $p = 0.84$). There was no significant difference between trials with a contralesional and an ipsilesional distractor ($t(4) = 0.97$; $p = 0.39$).

4.2. Capture trials

There was a significant difference in the percentage capture induced by contralesional (mean = 8.9%; st. dev. = 5.9%) versus ipsilesional distractors (mean = 6.0%; st. dev. = 4.8%; $t(4) = 2.83$; $p < 0.05$; see Fig. 4). Table 1 shows the individual means for the different conditions.

4.3. Control group

To validate whether similar hemispheric differences might emerge in a group of healthy individuals, contralesional and ipsilesional targets for each control participant were matched to the lesion location of the age-matched patient. That is, for example, for a control matched to a patient with a left hemisphere lesion, the right visual field was designated as 'contralesional', and the left visual field as 'ipsilesional'. Also for the control participants, there was no difference between saccade latencies to the contralesional (mean = 372 ms; st. dev. = 81 ms) and the ipsilesional visual field in the no-distractor condition (mean = 377 ms; st. dev. = 73 ms; $t(6) = 0.64$; $p = 0.55$; see Fig. 3). For both the contralesional (mean = 379 ms; st. dev. = 79 ms) and the ipsilesional visual field (mean = 392 ms; st. dev. = 81 ms), there was no significant increase in saccade latency when a distractor was presented (p's > 0.20). With respect to the capture trials, there was no significant difference in the percentage capture induced by a distractor between the two visual fields (contra: mean = 5.5%; st. dev. = 8.5%; ipsi: mean = 4.1%; st. dev. = 3.5%; $t(6) = 0.58$; $p = 0.58$; see Fig. 4).

5. Discussion Experiment 1

The results of Experiment 1 show that a distractor presented contralateral to the pulvinar lesion interfered more with target selection than an ipsilesional distractor. This was revealed by an increased percentage of capture trials for contralesional distractor compared to ipsilesional distractors. Furthermore, saccade latencies to ipsilesional targets were increased when a contralesional distractor was presented. These results confirm the hypothesis that there is less top-down control of reflexive saccades towards contralesional visual stimuli in patients with a pulvinar lesion. It must be noted that the behavioral differences between the influence of contralesional and ipsilesional distractors were small. Although every patient showed the expected effect and the effect is significant in all five patients, the mean difference in percentage capture is only 3%. Also the effect on saccade latency is small, but consistent (see also Table 1). The reported behavioral imbalance between contralesional and ipsilesional visual fields was not present in an age-matched control group.

To provide further evidence for the decreased cortical influence on the contralesional visual field, we ran a second experiment in which saccade trajectory deviations were measured. Saccade deviations are known to reflect the amount of inhibition evoked by a distractor (for a review, see Van der Stigchel, Meeter, & Theeuwes, 2006). In the current case study, DG executed eye move-

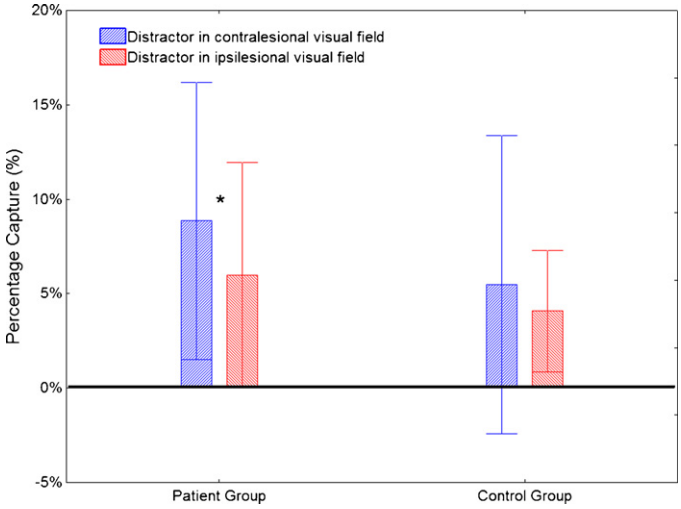

Fig. 4. Percentage capture for both the contralesional and the ipsilesional visual field for both the patients and the control group. Error bars indicate 95% confidence intervals.

ments to a single target presented on the vertical meridian. A distractor was presented on a proportion of trials. This distractor could either appear in the contralesional or the ipsilesional visual field. The direction of the saccade trajectory is informative of the amount of inhibition evoked by the distractor, because the inhibition is reflected by a deviation of the trajectory away from the distractor (Doyle & Walker, 2001; Van der Stigchel, Meeter, & Theeuwes, 2007a; Van der Stigchel & Theeuwes, 2006). Moreover, this deviation away increases with longer latencies, because top-down inhibition takes time to develop (McSorley, Haggard, & Walker, 2006; Mulckhuyse, Van der Stigchel, & Theeuwes, 2009; van Zoest, Donk, & Theeuwes, 2004). If there is indeed an imbalance in the amount of top-down influence between both visual fields, this should be reflected by the deviations of the eye movement trajectories. Furthermore, to investigate the timing of these inhibitory processes, we used the fixation gap and overlap paradigm (McSorley et al., 2006; Mulckhuyse et al., 2009; Saslow, 1967) to induce both short and long saccade latencies.

6. Experiment 2

6.1. Methods

6.1.1. Stimuli

All figures (fixation, target, distractor) were gray on a black background. Each trial started with the presentation of a 'plus' character ($1.0^\circ \times 1.0^\circ$) in the center of the screen that functioned as the fixation stimulus. After a variable period of 800–950 ms, the target appeared (a solid circle with a diameter of 1.4°) located at an eccentricity of 8.9° on the vertical meridian (either above or below fixation). There were five different combinations of the timing between fixation offset and target onset: the fixation point was removed 150 ms before the target appeared, 50 ms before the target appeared, simultaneously when the target appeared, 50 ms after the target appeared, or 150 ms after the target appeared.

In one-third of the trials, the target was the only element presented. In the remaining trials, a diamond-shaped distractor (sides measuring $1.2^\circ \times 1.2^\circ$) appeared at the same time as the target. The distractor was always located in the same vertical hemifield as the target, but half the time it was in the hemifield ipsilateral to the lesion, and half the time in the contralateral hemifield. The distractor was presented 6.9° away from fixation in the horizontal direction and 5.2° away in the vertical direction. Both elements were presented for 1500 ms.

6.1.2. Procedure and design

DG was instructed to fixate the center fixation point until the target appeared, when he was to move his eyes to the target. It was stressed that he should try to make a single accurate saccade. The experiment consisted of a training session of 30 trials and an experimental session of 300 trials. DG heard a short tone when the saccade latency was higher than 600 ms or lower than 80 ms. The sequence of trials was randomized, in terms of both target location (up or down) and distractor condition (none, contralateral or ipsilateral).

6.1.3. Data analysis

In this experiment, saccade latency was defined as the interval between target onset and the initiation of a saccadic eye movement. If saccade latency was shorter than 80 ms or longer than 600 ms, the trial was removed from analysis. Trials were excluded if there was no saccade or the first saccade was too small ($<5^\circ$). If the endpoint of the first saccade had an angular deviation of more than 22.5° from the center of the target, the saccade was classified as an error and also not analyzed. Furthermore, the initial saccade starting position had to be within 1° from the center fixation point for the horizontal direction.

In the remaining trials we measured saccade deviation, defined as the mean angle of the saccade path relative to the angle of a straight line between the saccade starting position and the target location. The mean angle of the saccade path was calculated by averaging the angles of the straight lines between the saccade starting position and the different sample points (for a more detailed overview of saccade trajectory computation, see Van der Stigchel et al., 2006). For each saccade in a trial with a distractor we compared its mean path angle to that of the averaged mean-path-angles of all saccades in trials without a distractor, to determine if the saccade in the presence of a distractor deviated towards or away from the location of the distractor. Deviations were signed so that a positive value indicated deviation towards the distractor, and a negative value deviation away.

Separate calculations were made for each distractor location ('Left Upper', 'Left Lower', 'Right Upper', and 'Right Lower'), but then collapsed in each hemifield. Using the remaining data, we used *t*-tests to determine whether the deviations in saccade trajectory were significantly different from zero. Note that a mean saccade deviation of zero indicates no difference between the no-distractor and the distractor condition. We also investigated whether there was a correlation between saccade latency and saccade deviation for both hemifields. To eliminate the role of outliers, we excluded trials in which the deviation or the latency was further than two and a half standard deviations away from the mean.

All exclusion criteria led to a loss of 17.0% of trials. In the majority of these trials, fixation was inaccurate (i.e. the initial saccade starting position was not within 1° from the center fixation point for the horizontal direction or too early eye movements were made).

7. Results

7.1. Saccade latency

In the no-distractor condition, mean saccade latency was 289 ms (st. dev. = 66 ms). When a distractor was presented in the ipsilesional visual field, the mean saccade latency was not significantly higher (mean = 309 ms; st. dev. = 69 ms; $t(181) = 1.86$; $p = 0.06$).[1] This was also the case for a distractor presented in the contralesional visual field (mean = 296 ms; st. dev. = 69 ms; $t(186) = 0.65$; $p = 0.52$).

As expected, saccade latency was influenced by the different timings between fixation offset and target onset. Saccade latency increased with later fixation offset (*−150 ms difference*: mean = 259 ms, st. dev. = 58 ms; *−50 ms difference*: mean = 274 ms, st. dev. = 71 ms; *0 ms difference*: mean = 292 ms, st. dev. = 55 ms; *+50 ms difference*: mean = 311 ms, st. dev. = 60 ms; *+150 ms difference*: mean = 346 ms, st. dev. = 68 ms). Saccade latency was significantly lower in trials in which the fixation point was removed before target onset compared to trials in which the fixation point was removed after target onset ($t(198) = 6.63$; $p < 0.0001$).

7.2. Saccade deviation

When the distractor was presented in the contralesional visual field, the mean saccade deviation was −0.022 rad (st. dev. = 0.13 rad). This was not significantly different from zero ($t(65) = 1.33$; $p = 0.19$). When the distractor was presented in the ipsilesional visual field, the mean saccade deviation was −0.085 rad (st. dev. = 0.15 rad). This was significantly different from zero ($t(61) = 4.31$; $p < 0.0001$). The saccade deviation away from a distractor in the ipsilesional visual field was significantly stronger than the deviation away from a distractor in the contralesional visual field ($t(125) = 2.49$; $p < 0.03$).

7.3. Saccade latency-saccade deviation correlation

We investigated the relation between saccade latency and saccade deviation for the ipsilesional and the contralesional field. Results showed that there was a significant negative correlation for the ipsilesional visual field ($r = -.27$; $p < 0.05$), but no significant effect for the contralesional visual field ($r = -.15$).

7.4. Control group

To validate that the correlation for the ipsilesional visual field was in the normal range, we ran four control subjects (mean age = 76 years; st. dev. = 4 years). For the saccade deviations obtained in these control subjects, correlations between saccade latency and saccade deviation were significant for distractors in

[1] Effects of a distractor on saccade latency are generally not observed with a limited number of possible target locations (Van der Stigchel & Theeuwes, 2006, 2008). Also for the control group, there was no significant increase in saccade latency when the distractor was presented in the 'ipsilesional' visual field compared to trials without a distractor (all trials included in an independent *t*-test: $t(641) = 1.47$; $p = 0.14$). For the 'contralesional' field, this difference was (marginally) significant ($t(652) = 2.16$; $p = 0.03$). This makes these effects difficult to interpret.

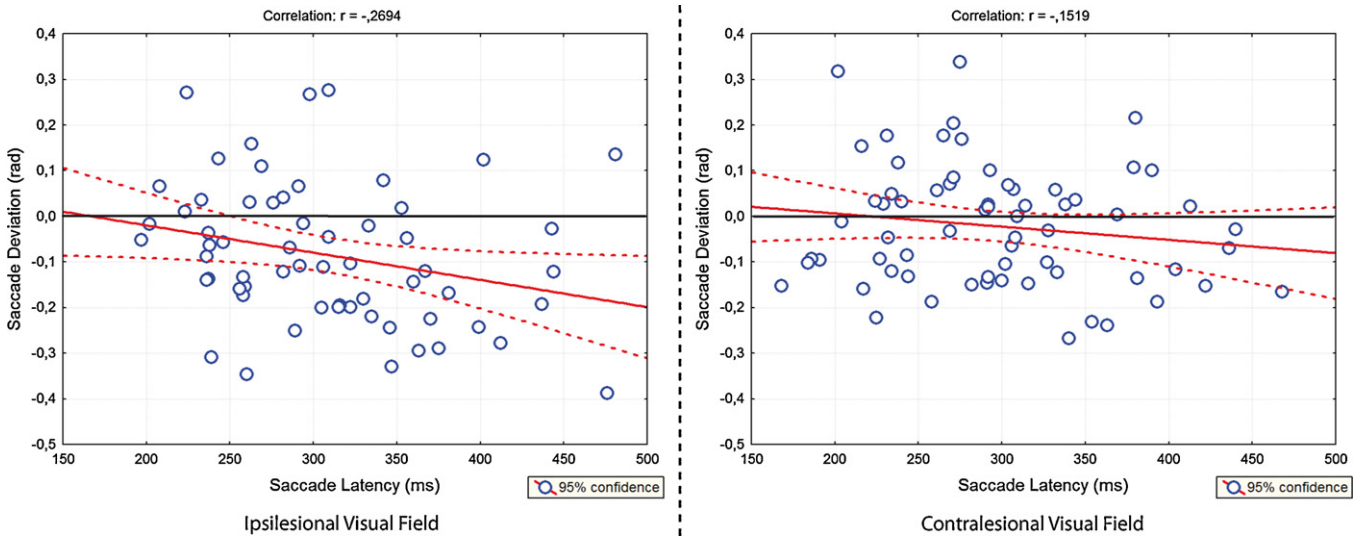

Fig. 5. The relation between saccade latency and saccade deviation for distractors in the ipsilesional and the contralesional field. There was a significant negative correlation for the ipsilesional visual field.

both visual fields (for distractors in the 'contralesional' visual field: $r = -.36$; for distractors in the 'ipsilesional' visual field: $r = -.25$). These correlation values were similar to the negative correlation obtained for the ipsilesional visual field in DG ($r = -.27$).

8. Discussion Experiment 2

Saccade trajectory deviations evoked by a single distractor were measured in DG. Results showed that saccade trajectories deviated away from an ipsilesional distractor, but not from a contralesional distractor (see Fig. 5). Because deviations away have been contributed to oculomotor inhibition of the distractor (Sheliga, Riggio, & Rizzolatti, 1994; Tipper, Howard, & Jackson, 1997), this shows that inhibition was stronger for the ipsilesional visual field compared to the contralesional field. Moreover, we observed a significant negative correlation between saccade latency and saccade deviation only for distractors in his ipsilesional field. Because it is known that top-down inhibition takes time to develop (McSorley et al., 2006; van Zoest et al., 2004), this finding verifies that the effect of inhibition was stronger in his ipsilesional field compared to the contralesional field. The behavioral imbalance between ipsilesional and contralesional visual fields reported in the patient with pulvinar lesion was not present in an age-matched control group. This experiment is in line with an imbalance in the amount of top-down influence on eye movements between both visual fields in patients with a lesion to the pulvinar.

In line with Experiment 1, the present results indicate that top-down influence in the contralesional visual field is not completely absent in patients with a lesion to the pulvinar. Deviations evoked by a contralesional distractor did not deviate towards or away from a contralesional distractor, but were intermediate between these two types of deviations. Because deviations towards a distractor are generally attributed to a relative lack of oculomotor inhibition (Van der Stigchel et al., 2006), these findings indicate that top-down inhibition of a contralesional distractor is still present, but less strong compared to the ipsilesional visual field.

9. General discussion

The current study investigated the role of the human pulvinar in oculomotor control. More explicitly, the hypothesis was tested that the pulvinar serves as a nexus for integrating cortical control of voluntary eye movements with reflexive eye movements. In the first experiment, all five patients performed an oculomotor capture paradigm in which a reflexive eye movement has to be inhibited. Because of the onset of the distractor automatically evokes the programming of an eye movement to its location, oculomotor inhibition is necessary to cancel the eye movement to the distractor (Theeuwes et al., 1998). Insufficient top-down inhibition results in an erroneous eye movement to the distractor. Results showed that all patients made more errors to a contralesional distractor compared to an ipsilesional distractor. This result therefore confirms the proposed hypothesis concerning the role of the human pulvinar in the oculomotor system. Because the influence of higher order signals on the guidance of the eye movements was less strong for the contralesional visual field, eye movements to the contralesional visual field were influenced more dominantly by bottom-up reflexive information than eye movements to the ipsilesional visual field.

In a second experiment, a single patient was tested on an oculomotor distractor experiment in which saccade trajectory deviations were measured. Because deviations away from a distractor are generally attributed to top-down inhibition (Sheliga et al., 1994; Tipper et al., 1997), they can be used as a measure of the strength of inhibition. Results showed that saccade trajectories to a vertical target deviated away from the distractor, but only when it was presented in the ipsilesional visual field. Moreover, the saccade deviation increased in time, which is one of the hallmarks of top-down oculomotor inhibition (McSorley et al., 2006; van Zoest et al., 2004). These effects were absent for the contralesional visual field. The results of this experiment are therefore in line with an imbalance in the amount of top-down control between the two visual fields.

Models of eye movement selection have assumed that oculomotor inhibition of reflexive eye movements in the superior colliculus comes from cortical areas like the frontal eye fields (McSorley, Haggard, & Walker, 2004; Trappenberg, Dorris, Munoz, & Klein, 2001). Whereas the intermediate layers of the SC receive fast projections from cortical area V1 (Schiller, Malpeli, & Schein, 1979), responses in the dorsolateral prefrontal cortex and the frontal eye fields are known to be responsive to task demands (Bichot & Schall, 2002; Pierrot-Deseilligny, Milea, & Muri, 2004). Because the pulvinar receives input from frontal areas (Leh, Chakravarty, & Ptito, 2008), this accounts for the lack of inhibition that was observed in the contralesional visual field.

The proposed account is consistent with earlier studies of lesions of the human pulvinar. Pulvinar patients were shown to initiate

saccades with longer latencies away from contralesional targets compared to ipsilesional targets in the antisaccade task (Arend et al., 2008). This points to a less strong oculomotor inhibition in the contralesional field, as the automatically evoked eye movement program to the target needs to be inhibited to successfully execute an eye movement to its mirrored location (Everling & Fischer, 1998).

Deficits in the contralesional visual field were only observed when a distractor was presented. Selection of the target was not impaired when no distractor was presented; there was no difference in saccade latency to targets in the contralesional and ipsilesional visual field. This seems to implicate that the pulvinar is not involved in target selection in visual search, but plays a role when a reflexive eye movement has to be inhibited by higher order processes. This result is consistent with a recent study by Snow, Allen, Rafal, and Humphreys (2009), who found that patients with pulvinar lesions were only impaired in goal-directed selection when a distractor was present.

As also pointed out in earlier studies of lesions of the human pulvinar (Arend et al., 2008), the observed deficits are generally quite small. In line with this, patients do not complain about their vision or report impairment of visually guided behaviors in their everyday life. Deficits as a result of pulvinar damage can therefore be considered subclinical. The amount of capture and the deviation evoked by a contralesional distractor in the present study also indicate that top-down inhibition in the contralesional visual field is still present, but less strong compared to the ipsilesional visual field. It seems like the contribution of the pulvinar to the integration of bottom-up and top-down signals can – to a large extent – be taken over by other (cortical) areas where such integration might occur. Integration of higher order signals is therefore not crucially dependent on the pulvinar, but the current study has shown that the pulvinar does play a role in integration of higher order and lower order information in the human oculomotor system.

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