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The role of the frontal eye fields in the oculomotor inhibition of reflexive saccades: Evidence from lesion patients

S. Van der Stigchel[a,*], M. van Koningsbruggen[b], T.C.W. Nijboer[a], A. List[b], R.D. Rafal[b]

[a] Experimental Psychology, Helmholtz Institute, Utrecht University, Utrecht, The Netherlands
[b] School of Psychology, Bangor University, Bangor, United Kingdom

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ABSTRACT

The current study investigated the role of the frontal eye fields (FEF) in the suppression of an unwanted eye movement ('oculomotor inhibition'). Oculomotor inhibition has generally been investigated using the antisaccade task, in which an eye movement to a task-relevant onset must be inhibited. Various lines of research have suggested that successful inhibition in the antisaccade task relies heavily on the FEF. Here, we tested whether the FEF are also involved in the oculomotor inhibition of reflexive saccades. To this end, we used the oculomotor capture task in which the to-be-inhibited element is task-irrelevant. Performance of four patients with lesions to the FEF was measured on both the antisaccade and oculomotor capture task. In both tasks, the majority of the patients made more erroneous eye movements to contralesional elements than to ipsilesional elements. One patient showed no deficits in the antisaccade task, which could be explained by the developmental origin of his lesion. While we confirm the role of the FEF in the inhibition of task-relevant elements, the current study also reveals that the FEF play a crucial role in the oculomotor inhibition of task-irrelevant elements.

1. Introduction

While exploring our environment, we make eye movements to inspect possible relevant locations. The decision on where to make the next eye movement is influenced by both top-down (or endogenous) factors, like task demands, and bottom-up (or exogenous) factors, like the abrupt onset of an element (Godijn & Theeuwes, 2002; Trappenberg, Dorris, Munoz, & Klein, 2001). There is, therefore, continuous competition between these two factors. For example, while driving, our eyes may be captured by a flashing billboard when our goal is to keep our eyes on the road. The suppression of an unwanted eye movement is called 'oculomotor inhibition' and refers to the rejection of a distractor to enable a saccade to the target location. Previous research has indicated that oculomotor inhibition often fails, resulting in erroneous eye movements that conflict with task requirements (Theeuwes, Kramer, Hahn, & Irwin, 1998).

Oculomotor inhibition has generally been investigated using the antisaccade task (for reviews, see Everling & Fischer, 1998; Munoz & Everling, 2004). In this task, participants are presented with an abrupt appearance of a visual stimulus in the periphery ('onset') after which they have to execute an eye movement away from the onset location to its mirror opposite position. The eye movement that is automatically evoked by the presence of the onset has to be inhibited, while a top-down generated eye movement has to be executed to the mirror location of the onset. A failure of oculomotor inhibition will result in the execution of an erroneous eye movement toward the onset. Results on the antisaccade task have shown that participants frequently make an erroneous saccade to the onset location.

Various lines of research have suggested that successful inhibition in the antisaccade task relies heavily on the Frontal Eye Fields (FEF). Neuro-imaging studies have shown that FEF activity is greater for anti- than for prosaccades (Clementz, Brahmbhatt, McDowell, Brown, & Sweeney, 2007; Curtis & D'Esposito, 2003), an effect that is especially noticeable just before saccade generation (McDowell et al., 2005). Chronic FEF lesions lead to an increased number of contralesional errors in the antisaccade task, pointing to a failure in oculomotor inhibition in the visual field contralateral to the lesion (Guitton, Buchtel, & Douglas, 1985; Hodgson et al., 2007; Machado & Rafal, 2004a). Furthermore, TMS application over the FEF results in an increased number of erroneous prosaccades to an onset contralateral to the site of stimulation (Terao et al., 1998).

The current study investigates whether the FEF are also involved in the oculomotor inhibition of reflexive saccades. Errors in the antisaccade are not fully reflexive because the onset is task-relevant: participants must direct their attention to the onset and use this object's location to direct their attention and eyes to the mirror location. Furthermore, there is an explicit instruction not to look at

* Corresponding author.
E-mail address: s.vanderstigchel@uu.nl (S. Van der Stigchel).

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the onset, but to saccade to the opposite direction. To test whether the FEF are also involved in the inhibition of purely reflexive eye movements, one needs a task in which the to-be-inhibited object is not task-relevant. For this, we used the oculomotor capture task developed by Theeuwes et al. (1998) and Theeuwes, Kramer, Hahn, Irwin, and Zelinsky (1999). In this paradigm, the task requires the participant to make an eye movement to a target defined by its unique color. In half of the trials, an additional 'distractor' circle is presented with an abrupt onset. 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 (i.e., 'capture trials') (Theeuwes et al., 1998; Theeuwes et al., 1999). In contrast to the antisaccade task, erroneous saccades in the oculomotor capture paradigm are purely reflexive, because the distractor does not need to be attended in order to successfully perform the task. Moreover, there is no explicit task instruction to ignore the distractor. The distractor is therefore task-irrelevant (see also Godijn & Kramer, 2006).

The difference between the antisaccade and the oculomotor capture tasks is not trivial, as previous research has revealed that different groups perform differently in these tasks. For instance, whereas antisaccade performance improves with increasing age (i.e., older children make fewer antisaccade errors than younger children), younger and older children are not differently captured by the onset in the oculomotor capture task (Kramer, Gonzalez de Sather, & Cassavaugh, 2005). Similarly, older adults do not make more errors in the standard oculomotor capture task, whereas they make more errors than younger adults in the antisaccade task (Kramer, Hahn, Irwin, & Theeuwes, 2000; Nieuwenhuis, Ridderinkhof, de Jong, Kok, & van der Molen, 2000). Furthermore, children with ADHD perform worse than controls on the antisaccade task (Klein, Raschke, & Brandenbusch, 2003; Mostofsky, Lasker, Cutting, Denckla, & Zee, 2001; Munoz, Armstrong, Hampton, & Moore, 2003), whereas they do not make more errors than controls in the oculomotor capture task (Van der Stigchel et al., 2007). Therefore, the mechanisms and neural substrates underlying oculomotor inhibition in both tasks may differ.

In the current study, we tested four patients, with unilateral lesions involving the FEF, on both the oculomotor capture task and the antisaccade task. Thus, we were able to compare performance on both tasks to investigate whether both types of oculomotor inhibition can be disentangled in patients with lesions to the FEF. From studies in non-human primates, it is known that the FEF code for saccades in contralateral oculomotor space, and thus control contralateral saccades (Bruce, Goldberg, Bushnell, & Stanton, 1985; Sommer & Tehovnik, 1997). Because any behavioral deficits are predicted to be lateralized, the critical analysis for each task is a within-subject comparison of performance in the contra- vs ipsilesional visual fields. This way, the patients act as their own controls. Previous studies have already revealed that there is no imbalance in the oculomotor capture task between both visual fields in healthy controls (Van der Stigchel, Arend, van Koningsbruggen, & Rafal, 2010; Van der Stigchel & Nijboer, 2010). If the FEF are involved in the inhibition in the oculomotor capture task, more saccades to the onset distractor are expected when the distractor is presented in the contralesional visual field compared to the ipsilesional visual field. Similarly, more erroneous prosaccades are expected in the antisaccade task when the onset is presented in the contralesional compared to the ipsilesional visual field.

2. Methods

2.1. Patients

Case 1 is a 72-year old woman who suffered a right middle cerebral artery territory stroke 4 years prior to testing. She initially had left hemiparesis and hemispatial neglect. Symptoms of her neglect recovered, as did her left leg strength. She is living independently and is left with residual spastic weakness and loss of dexterity in the left hand. There is no sensory deficit and clinical examination did not reveal any obvious impairment in eye movements. Her lesion involves part of the dorsolateral prefrontal cortex, the precentral gyrus motor and premotor cortices, undercutting the posterior frontal eye field in the depth of the intersecting precentral and superior frontal sulci.

Case 2 is a 52-year old man with congenital spastic, left hemiplegia and a seizure disorder due to right hemisphere open-lip schizencephally, affecting the frontal operculum, motor and premotor cortices and dorsolateral prefrontal cortex.

Case 3 is an 82-year old man who suffered a small left hemisphere stroke 4 years prior to testing. The only resulting neurological impairment was tactile agnosia in the right hand. The lesion is in the distribution of the middle cerebral artery including the hand area of the precentral gyrus and premotor cortex. It undercuts the precentral sulcus at the intersection with the superior frontal sulcus and extends laterally into the opercular post-central gyrus.

Case 4 is a 52-year old woman who suffered a left hemisphere stroke 8 years prior to testing. The lesion involves Broca's area and extends into the FEF. She initially presented with aphasia and problems with writing and calculation, but these have recovered and she has no motor or visual deficits and no visual neglect or extinction.

Fig. 1 shows the individual scans and a composite group lesion reconstruction on a normalized template brain. The FEF was identified on axial images as the intersection of the superior frontal gyrus and the precentral sulcus, the posterior part of the middle frontal gyrus adjacent to these sulcal landmarks, or the white matter undercutting these landmarks.

None of the patients had additional neurological or psychiatric illness. 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.

2.2. Apparatus

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 .01°. The participant's head was stabilized with a chin rest, and an infrared 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. Participants performed both experiments in a sound-attenuated setting, viewing a display monitor from a distance of 57 cm.

2.3. Stimuli and procedure

Each experiment 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. In both experiments, the sequence of trials was randomized.

Antisaccade task. See Fig. 2 for an example of the display sequence. Participants were presented with a central fixation point (circle: 2°) and two white placeholders (square: 1°) on a grey background. The placeholders were presented 8° to the left and right of the fixation point and were present throughout the trial. After 400–600 ms, the onset (square: 2°) was presented for 1000 ms. The onset was presented either on the left or right side of fixation. Trials were arranged pseudo-randomly to prevent presentation of more than four successive onsets at the same location. The experiment consisted of 72 experimental trials and 10 practice trials.

Participants were instructed to fixate the center fixation point until the onset appeared. When the onset appeared, participants were to move their eyes to the mirror location of the onset in the opposite visual field. It was stressed that they should try to make a single accurate saccade.

Oculomotor capture task. Participants viewed a display containing a centrally presented fixation cross (1.38°) on a black background. Six green circles (2.30° in diameter) were positioned at one, three, five, seven, nine, and eleven o'clock on an imaginary circle around a central fixation point (radius: 11.50°). After 800 ms, all circles, except one, changed its color to red. The remaining green circle was the target circle. Note that in this task, the target is a singleton, but there is no luminance change at the target location. Thus, search for the target is entirely endogenous, with no reflexive component that might activate a collicularly mediated visual grasp reflex which drives the eyes to foveate a suddenly appearing peripheral stimulus (Machado & Rafal, 2004b).

The target circle was either located at one, five, seven or eleven o'clock (i.e., not on the horizontal meridian). In half of the trials, a red circle was presented simultaneously with an abrupt onset on the same imaginary circle as the other circles. The distractor was always positioned in the opposite field to the target at a fixed position, diametrically opposite to the location of the target. The target display was presented for 2000 ms. The experiment consisted of 344 experimental trials and 24 practice trials. Case 3 was only able to perform 160 experimental trials.

Participants were instructed to fixate the center fixation point until the target was presented, when they were to move their eyes to the target. It was stressed that they should try to make a single accurate saccade.

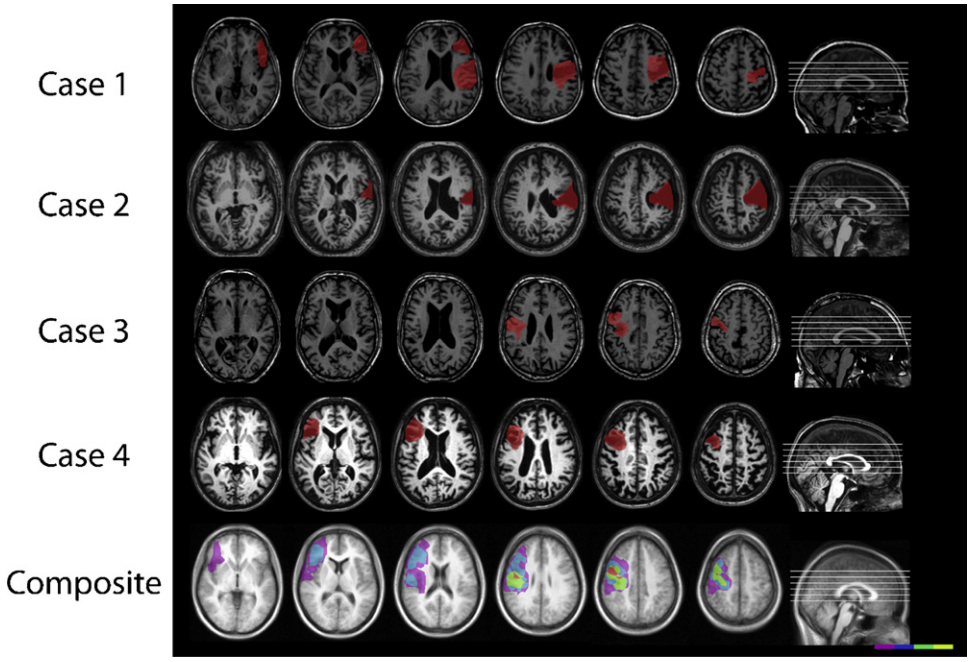

Fig. 1. Images of lesions in the patients. The lower slices represent a composite group lesion reconstruction on a normalized template brain (on the basis of T1-weighted axial MRI). All the lesions are reflected onto the right hemisphere (shown on the left side). The color bar depicts the number of patients (1–4) with a lesion in the area indicated by the color.

2.4. Data analysis

Antisaccade task. Saccade latency was defined as the interval between target onset and the initiation of a saccadic eye movement. Trials were excluded when the latency of the saccade was lower than 80 ms or higher than 750 ms. The latency criteria resulted in 11% excluded trials. Saccades with an amplitude above 20° (well outside the 8° fixation-to-onset distance) were also excluded from the analyses (which resulted in 4% excluded trials). For the first saccade, we analyzed whether it was executed in the direction of the onset or in the direction of the mirrored location. A saccade that was initiated toward the onset was considered an erroneous prosaccade.

To investigate whether the proportion of correct antisaccades was higher for the ipsilesional compared to the contralesional visual field, we ran Pearson's Chi-square tests for each participant on the number of trials in which a correct antisaccade was executed for both the left and the right visual fields. Because the outcome measure is categorical (error vs correct) and non-parametric, this test can be used to test whether the frequency distribution of erroneous and correct saccades differs between both visual fields.

Due to the low number of experimental trials (72 trials) and the strong imbalance in performance across visual fields, saccade latencies were not analyzed.

Oculomotor capture task. When the endpoint of a saccade was within 4.60° of the target's center, it was classified as reaching the target. Trials were excluded when the latency of the saccade was lower than 80 ms or higher then 1000 ms. Trials with a latency of more or less than 2 times the standard deviation of each participant's mean were also excluded (see e.g., Van der Stigchel & Nijboer, 2010). The latency criteria resulted in 6% excluded trials. Moreover, trials were excluded from analysis in which no saccade, too early or too small a first saccade (<2°) was made (which resulted in 12% excluded trials).

Saccades were classified as reaching the distractor when the endpoint of a saccade was within 5.75° of the distractor. Because saccades to the distractor are automatic and not under top-down control, they tend to be less accurate than saccades that are initiated toward the target (see e.g., Van der Stigchel, de Vries, Bethlehem, & Theeuwes, 2011). Therefore, this criterion was chosen to be somewhat more liberal than for the saccades to the target. To investigate whether the proportion of eye movements to the distractor was higher for distractors presented in the contralesional visual field compared to the ipsilesional visual field, we ran a Pearson's Chi-square test for each participant on the number of trials in which an eye movement was executed toward the distractor for both the ipsilesional and the contralesional visual fields.

Saccade latencies were analyzed using two-tail *t*-tests for independent samples. For each patient, we compared saccade latencies in the no-distractor condition when an eye movement was made to the contralesional vs the ipsilesional visual field. Furthermore, for each patient, we analyzed whether saccade latencies in the distractor condition were different compared to the no-distractor condition. These latter analyses were performed separately for the conditions with a target in the contralesional and ipsilesional visual fields. Note that the distractor was always presented in the opposite visual field to the target. There was no patient with enough capture errors in both visual fields (i.e., more than 40% in both visual fields) to enable an analysis of the latency of erroneous capture saccades (i.e., saccades toward the distractor).

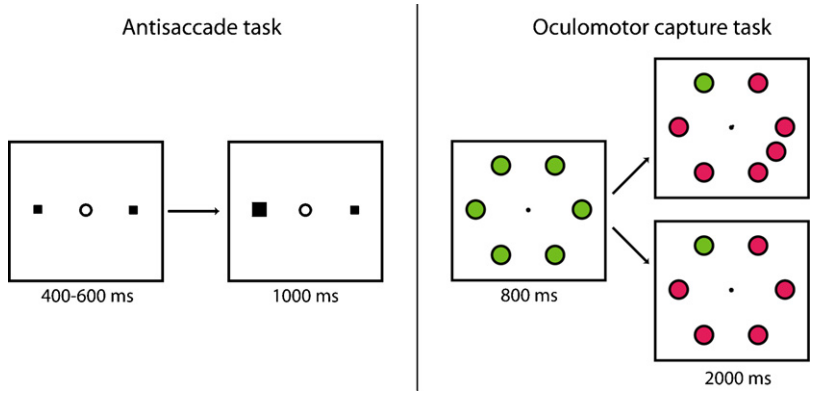

Fig. 2. Lay-out and timing of the antisaccade task and the oculomotor capture task.

3. Results

3.1. Antisaccade task: errors

As can be seen in Table 1, three of the four patients (1–4) had a significant imbalance between errors made to contralesional and ipsilesional onsets. In these three cases, there were more erroneous saccades executed to contralesional onsets compared to ipsilesional onsets. No imbalance was observed for Case 2, who had the exact same number of errors in response to contralesional and ipsilesional onsets.

To ensure that the imbalance was not due a speed-accuracy trade-off, we analyzed saccade latencies for the only patient with an imbalance who performed more than 2 correct antisaccades in response to a contralesional onset (Case 4). No imbalance was observed for Case 2, while Case 1 and 3 had 0 and 2 correct antisaccades in response to a contralesional onset, respectively. For Case 4, an independent *t*-test revealed that there was no difference in saccade latencies between correctly performed antisaccades for the contralesional (mean = 467 ms; st. dev. = 115) and the ipsilesional visual field (mean = 449 ms; st. dev. = 144; $t(17) = .30$; $p = .76$).

3.2. Oculomotor capture task: errors

Table 2 shows the individual results for the four cases with respect to the proportion errors in the oculomotor capture task. In all four cases, a significant imbalance was observed between errors made in response to contralesional and ipsilesional distractors (albeit at .05 level for one case, but note that this patient performed only half of the trials that the other patients performed). In these four cases, more capture saccades were initiated toward contralesional distractors compared to ipsilesional distractors.

3.3. Oculomotor capture task: latencies

The results for the saccade latencies were inconclusive. See Table 3 for the individuals' mean latencies for the different conditions (i.e., no distractor, contralesional distractor, ipsilesional distractor). When comparing whether saccade latencies in the no-distractor condition were different when an eye movement was made to a target in the contralesional vs the ipsilesional visual field, independent *t*-tests revealed significant differences in two cases. For Case 1, saccade latencies were shorter to a target in the ipsilesional field compared to the contralesional field [$t(52) = 2.55$; $p < .02$]. The opposite effect was observed for Case 3 [$t(27) = 2.59$; $p < .02$]: saccade latencies to a target in the contralesional field were shorter than to targets in the ipsilesional visual field. For the other cases, no significant differences were observed. We did not observe a clear or consistent trend in these results, also in relation to the lesion location. Different factors like fatigue or limited number of trials might have resulted in the variability in results. Because saccade latencies were not the primary measure in the present study, these results will not be interpreted further.

Furthermore, we analyzed whether saccade latencies in the distractor conditions were different compared to the no-distractor condition. This analysis was performed for saccades to target in each visual field separately. It should be noted that previous studies have generally found no increase in saccade latencies when a saccade is made to a target in the presence of a distractor (e.g., Theeuwes, de Vries, & Godijn, 2003; Van der Stigchel et al., 2010). Indeed, only for Case 4, saccade latencies to a target in the ipsilesional visual field were higher when a contralesional distractor was presented, compared to the no-distractor condition [$t(37) = 2.89$; $p < .01$]. In the other cases, no significant increase in the distractor condition was observed.

4. Discussion

The current study focused on the involvement of the frontal eye fields (FEF) in the inhibition of unwanted saccades. Performance of four patients with lesions to the FEF were measured in two tasks in which an eye movement has to be inhibited. In the antisaccade task, an eye movement has to be inhibited to a task-relevant onset, whereas in the oculomotor capture task, the to-be-inhibited onset is task-irrelevant. Section 3 indicated that in both tasks, the majority of the patients made more erroneous eye movements when the to-be-inhibited element was presented in the contralesional visual field compared to when it was presented in ipsilesional visual field.

Table 1
Individual results of the proportion errors in the antisaccade task.

	Proportion excluded trials	Proportion errors to ipsilesional onset	Proportion errors to contralesional onset	$X^2(1)$	*p*-Value
Case 1	.04	.58	1.00	19.160	<.0001
Case 2	.03	.63	.63	0	1.00
Case 3	.32	.54	.92	8.992	<.01
Case 4	.07	.59	.82	4.229	<.05

Table 2
Individual results of the proportion errors in the oculomotor capture task.

	Proportion excluded trials	Proportion errors to ipsilesional distractor	Proportion errors to contralesional distractor	$X^2(1)$	*p*-Value
Case 1	.05	.10	.51	33.096	<.0001
Case 2	.08	.0	.14	11.661	<.001
Case 3	.44	.36	.65	3.746	.05
Case 4	.21	.01	.09	4.333	<.05

Table 3
Individual results of the saccade latencies to the target in the oculomotor capture task. Means and standard deviation are given in ms. Significant effects are given in bold.

	Contralesional target			Ipsilesional target			
	No distractor	Distractor present		No distractor	Distractor present		No. dis.: contra vs ipsi.
Case 1	499 (91)	548 (109)	$t(32) = 1.35$; $p = .19$	434 (96)	462 (110)	$t(52) = 1.00$; $p = .32$	$t(52) = 2.55$; ***p < .02***
Case 2	420 (110)	391 (88)	$t(97) = 1.46$; $p = .15$	397 (121)	411 (106)	$t(108) = .65$; $p = .52$	$t(103) = 1.02$; $p = .31$
Case 3	460 (94)	516 (149)	$t(14) = .85$; $p = .41$	596 (169)	482 (60)	$t(22) = 1.85$; $p = .08$	$t(27) = 2.59$; ***p < .02***
Case 4	366 (117)	311 (60)	$t(31) = 1.78$; $p = .09$	341 (99)	429 (180)	$t(42) = .2.12$; ***p < .05***	$t(36) = .67$; $p = .51$

In these trials, oculomotor inhibition of the eye movement to the contralesional field fails, resulting in an erroneous saccade to the contralesional field.

Although the role of the FEF in the inhibition of task-relevant contralesional onsets is already established (Guitton et al., 1985; Hodgson et al., 2007; Machado & Rafal, 2004a), the current study shows that oculomotor inhibition of task-irrelevant eye movements also relies on the FEF. Kramer et al. (2005, 2000) have already distinguished two qualitatively different types of inhibition with an automatic/implicit form of inhibition playing a central role in oculomotor distractor tasks and an intentional/effortful inhibition mostly subserving performance in the antisaccade task. The present study shows that both types of inhibition might be subserved by the FEF.

Interestingly, however, not all patients showed impaired behavior on the antisaccade task. Case 2 was impaired in the inhibition of task-irrelevant distractors, whereas the inhibition of task-relevant distractors was unaffected. Performance in his contralesional field was similar to performance in his ipsilesional field, and his bilateral performance was comparable to the results in the ipsilesional field of the other patients. There are two possible explanations for the absence of an effect in this patient. First, the finding that not all patients with a lesion to the FEF are impaired in the antisaccade task seems consistent with previous literature. For instance, Gaymard, Ploner, Rivaud, and Pierrot-Deseilligny (1994) found no increase in erroneous eye movements in the antisaccade task in a patient with a small acute ischemic lesion of the FEF, though the patient's spatial short-term memory was impaired. Other studies have pointed to the dorsolateral prefrontal cortex as a critical lesion site for producing deficits in the antisaccade task (i.e., more antisaccade errors, Pierrot-Deseilligny et al., 2003; Pierrot-Deseilligny, Rivaud, Gaymard, & Agid, 1991; Ploner, Gaymard, Rivaud-Pechoux, & Pierrot-Deseilligny, 2005). Second, the lesion of Case 2 was developmental (congenital agensis of the FEF). The observation of preserved inhibition in the antisaccade task in Case 2, in whom parts of the cortex where the FEF are generally located never developed, indicates that other areas have partly taken over the role of this segment of the cortex. However, the finding that he made more contralesional erroneous saccades in the oculomotor capture task indicates that inhibition of reflexive saccades is still affected. Thus, this patient has developed the ability to apply strategic, but not automatic, oculomotor inhibition. Although speculative, this result might implicate that different aspects of oculomotor inhibition might be subserved by different areas within the FEF, or by different FEF connectivity.

There are a number of models which have implicated the FEF in oculomotor inhibition. These models of eye movement behavior state that oculomotor competition is resolved in the midbrain superior colliculus (SC) (Godijn & Theeuwes, 2002; Meeter, Van der Stigchel, & Theeuwes, 2010; Trappenberg et al., 2001). The SC integrates input from many cortical areas (Lock, Baizer, & Bender, 2003; Lui, Gregory, Blanks, & Giolli, 1995; Munoz, 2002) and sends the result of this integration process to the brainstem premotor circuitry where the eye movement is programmed (Moschovakis, 1996). Various frontal areas project to the intermediate and deep layers of the SC, like the FEF (i.e., Huerta, Krubitzer, & Kaas, 1986). It has been proposed that the FEF arbitrates in resolving the demands of competing oculomotor activations via connections to the SC via the substantia nigra pars reticulata of the basal ganglia (Basso & Wurtz, 1997, 2002; Munoz & Schall, 2003). In models of eye movement control, the FEF have therefore been claimed to be responsible for the inhibition of distractor activity in the SC (i.e., Godijn & Theeuwes, 2002; Trappenberg et al., 2001). When both target and distractor activity are present in the motor map of the SC, the competition between these two peaks of activity is resolved by lowering the activity of the peak associated with the distractor. In line with this, the FEF has been known to select one location as the target by activating corresponding neural populations and by inhibiting neurons corresponding to distractor locations (Schlag-Rey, Schlag, & Dassonville, 1992). The results of the current study suggest that connections between the FEF and the SC are underlying the inhibition of both task-relevant and task-irrelevant distractors.

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References

Basso, M. A., & Wurtz, R. H. (1997). Modulation of neuronal activity by target uncertainty. *Nature*, *389*, 66–69.
Basso, M. A., & Wurtz, R. H. (2002). Neuronal activity in substantia nigra pars reticulata during target selection. *The Journal of Neuroscience*, *22*(5), 1883–1894.
Bruce, C. J., Goldberg, M. E., Bushnell, M. C., & Stanton, G. B. (1985). Primate frontal eye fields. II. Physiological and anatomical correlates of electrically evoked eye movements. *Journal of Neurophysiology*, *54*(71), 4–734.
Clementz, B. A., Brahmbhatt, S. B., McDowell, J. E., Brown, R., & Sweeney, J. A. (2007). When does the brain inform the eyes whether and when to move? An EEG study in humans. *Cerebral Cortex*, *17*(11), 2634–2643.
Curtis, C. E., & D'Esposito, M. (2003). Success and failure suppressing reflexive behavior. *Journal of Cognitive Neuroscience*, *15*(3), 409–418.
Everling, S., & Fischer, B. (1998). The antisaccade: A review of basic research and clinical studies. *Neuropsychologia*, *36*(9), 885–899.
Gaymard, B. M., Ploner, C. J., Rivaud, S., & Pierrot-Deseilligny, C. (1994). The frontal eye field is involved in spatial short-term memory but not in reflexive saccade inhibition. *Experimental Brain Research*, *129*, 288–301.
Godijn, R., & Kramer, A. F. (2006). Prosaccades and antisaccades to onsets and color singletons: Evidence that erroneous prosaccades are not reflexive. *Experimental Brain Research*, *172*, 439–448.
Godijn, R., & Theeuwes, J. (2002). Programming of endogenous and exogenous saccades: Evidence for a competitive integration model. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(5), 1039–1054.
Guitton, D., Buchtel, H. A., & Douglas, R. M. (1985). Frontal lobe lesions in man cause difficulties in suppressing reflexive glances and in generating goal-directed saccades. *Experimental Brain Research*, *58*, 455–472.
Hodgson, T., Chamberlain, M., Parris, B., James, M., Gutowski, N., Husain, M., et al. (2007). The role of the ventrolateral frontal cortex in inhibitory oculomotor control. *Brain*, *130*, 1525–1537.
Huerta, M. F., Krubitzer, L. A., & Kaas, J. H. (1986). Frontal eye field as defined by intracortical microstimulation in squirrel monkeys, owl monkeys, and macaque monkeys: I. Subcortical connections. *Journal of Comparative Neurology*, *253*, 415–439.
Klein, C., Raschke, A., & Brandenbusch, A. (2003). Development of pro- and antisaccades in children with attention-deficit hyperactivity disorder (ADHD) and healthy controls. *Psychophysiology*, *40*, 17–28.
Kramer, A. F., Gonzalez de Sather, J. C. M., & Cassavaugh, N. D. (2005). Development of attentional and oculomotor control. *Developmental Psychology*, *41*(5), 760–772.
Kramer, A. F., Hahn, S., Irwin, D. E., & Theeuwes, J. (2000). Age differences in the control of looking behavior: Do you know where your eyes have been? *Psychological Science*, *11*(3), 210–217.
Lock, T. M., Baizer, J. S., & Bender, D. B. (2003). Distribution of corticotectal cells in macaque. *Experimental Brain Research*, *151*, 455–470.
Lui, F., Gregory, K. M., Blanks, R. H., & Giolli, R. A. (1995). Projections from visual areas of the cerebral cortex to pretectal nuclear complex, terminal accessory optic nuclei, and superior colliculus in macaque monkey. *Journal of Comparative Neurology*, *363*, 439–460.
Machado, L., & Rafal, R. (2004a). Control of fixation and saccades during an antisaccade task: an investigation in humans with chronic lesions of oculomotor cortex. *Experimental Brain Research*, *156*, 55–63.
Machado, L., & Rafal, R. (2004b). Control of fixation and saccades in humans with chronic lesions of oculomotor cortex. *Neuropsychology*, *18*(1), 115–123.
McDowell, J. E., Kissler, J. M., Berg, P., Dyckman, K. A., Gao, Y., Rockstroh, B., et al. (2005). Electroencephalography/magnetoencephalography study of cortical activities preceding prosaccades and antisaccades. *Neuroreport*, *16*(7), 663–668.
Meeter, M., Van der Stigchel, S., & Theeuwes, J. (2010). A competitive integration model of exogenous and endogenous eye movements. *Biological Cybernetics*, *102*, 271–291.
Moschovakis, A. K. (1996). The superior colliculus and eye movement control. *Current Opinions in Neurobiology*, *6*, 811–816.
Mostofsky, S. H., Lasker, A. G., Cutting, L. E., Denckla, M. B., & Zee, D. S. (2001). Oculomotor abnormalities in attention deficit hyperactivity disorder. A preliminary study. *Neurology*, *57*, 423–430.
Munoz, D. P. (2002). Commentary: Saccadic eye movements: Overview of neural circuitry. *Progress in Brain Research*, *140*, 89–96.

Munoz, D. P., Armstrong, I. T., Hampton, K. A., & Moore, K. D. (2003). Altered control of visual fixation and saccadic eye movements in attention-deficit hyperactivity disorder. *Journal of Neurophysiology*, *90*, 503–514.

Munoz, D. P., & Everling, S. (2004). Look away: The anti-saccade task and the voluntary control of eye movement. *Nature Reviews Neuroscience*, *5*, 218–228.

Munoz, D. P., & Schall, J. D. (2003). Concurrent, distributed control of saccade initiation in the frontal eye field and superior colliculus. In W. C. Hall, & A. K. Moschovakis (Eds.), *The superior colliculus: New approaches for studying sensorimotor integration*. Boca Raton: CRC Press.

Nieuwenhuis, S., Ridderinkhof, K. R., de Jong, R., Kok, A., & van der Molen, M. W. (2000). Inhibitory inefficiency and failures of intention activation: Age-related decline in the control of saccadic eye movements. *Psychology and Aging*, *15*(4), 635–647.

Pierrot-Deseilligny, C., Muri, R. M., Ploner, C. J., Gaymard, B. M., Demeret, S., & Rivaud-Pechoux, S. (2003). Decisional role of the dorsolateral prefrontal cortex in ocular motor behaviour. *Brain*, *126*(6), 1460–1473.

Pierrot-Deseilligny, C., Rivaud, S., Gaymard, B., & Agid, Y. (1991). Cortical control of memory-guided saccades in man. *Experimental Brain Research*, *83*, 607–617.

Ploner, C. J., Gaymard, B. M., Rivaud-Pechoux, S., & Pierrot-Deseilligny, C. (2005). The prefrontal substrate of reflexive saccade inhibition in humans. *Biological Psychiatry*, *57*, 1159–1165.

Schlag-Rey, M., Schlag, J., & Dassonville, P. (1992). How the frontal eye field can impose a saccade goal on superior colliculus neurons. *Journal of Neurophysiology*, *67*, 1003–1005.

Sommer, M. A., & Tehovnik, E. J. (1997). Reversible inactivation of macaque frontal eye field. *Experimental Brain Research*, *116*(2), 229–249.

Terao, Y., Fukuda, H., Ugawa, Y., Hikosaka, O., Hanajima, R., Furubayashi, T., et al. (1998). Visualization of the information flow through human oculomotor cortical regions by transcranial magnetic stimulation. *Journal of Neurophysiology*, *80*(2), 936–946.

Theeuwes, J., de Vries, G.-J., & Godijn, R. (2003). Attentional and oculomotor capture with static singletons. *Perception & Psychophysics*, *65*(5), 735–746.

Theeuwes, J., Kramer, A. F., Hahn, S., & Irwin, D. E. (1998). Our eyes do not always go where we want them to go: Capture of eyes by new objects. *Psychological Science*, *9*, 379–385.

Theeuwes, J., Kramer, A. F., Hahn, S., Irwin, D. E., & Zelinsky, G. J. (1999). Influence of attentional capture on oculomotor control. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1595–1608.

Trappenberg, T. P., Dorris, M. C., Munoz, D. P., & Klein, R. M. (2001). A model of saccade initiation based on the competitive integration of exogenous and endogenous signals in the superior colliculus. *Journal of Cognitive Neuroscience*, *13*(2), 256–271.

Van der Stigchel, S., Arend, I., van Koningsbruggen, M. G., & Rafal, R. D. (2010). Oculomotor integration in patients with a pulvinar lesion. *Neuropsychologia*, *48*(12), 3497–3504.

Van der Stigchel, S., de Vries, J., Bethlehem, R., & Theeuwes, J. (2011). A global effect of capture saccades. *Experimental Brain Research*, *210*(57–65).

Van der Stigchel, S., & Nijboer, T. C. W. (2010). The imbalance of oculomotor capture in unilateral visual neglect. *Consciousness and Cognition*, *19*(1), 186–197.

Van der Stigchel, S., Rommelse, N. N. J., Deijen, J. B., Geldof, C. J. A., Witlox, J., Oosterlaan, J., et al. (2007). Oculomotor capture in ADHD. *Cognitive Neuropsychology*, *24*(5), 535–549.