Neuropsychologia 51 (2013) 2988–2994

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Temporal dynamics of error correction in a double step task in patients with a lesion to the lateral intra-parietal cortex

Stefan Van der Stigchel [a,*], Robert D. Rafal [b], Janet H. Bultitude [c]

[a] Department of Experimental Psychology, Helmholtz Institute, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
[b] School of Psychology, Bangor University, Bangor, United Kingdom
[c] Centre for Functional Magnetic Resonance Imaging of the Brain, University of Oxford, Oxford, United Kingdom

ARTICLE INFO

Article history:
Received 25 July 2013
Received in revised form
28 September 2013
Accepted 21 October 2013
Available online 28 October 2013

Keywords:
Eye movements
Intra-parietal cortex
Saccade updating

ABSTRACT

Five patients with lesions involving intra-parietal cortex (IPCx) were tested in a rapid version of the double step paradigm to investigate the role of the IPCx in the rapid, online, updating of a saccade program. Saccades were executed to a single target in either the contra- or the ipsilesional visual field. In two thirds of the trials, a step change in target position required that the saccade shifted to a new location within the same field but in the contra- or the ipsilesional direction, allowing us to investigate whether patients are able to update their saccade program given new exogenous information about the required endpoint of the saccade. This set-up resulted in three types of initial saccades: saccades to the target on no-step trials, uncorrected saccades to the original target location on step trials and corrected saccades to the new target location on step trials. Furthermore, if the updating of the original eye movement program failed, patients performed a second saccade to the new target location that required a rapid error correction. The analysis of the double-step task on a group level indicated that latencies for all trial types were longer when saccades were directed to the contralesional versus the ipsilesional field. Furthermore, longer latencies were required for patients to initiate a corrective second saccade after making an uncorrected first saccade in their contralesional compared to ipsilesional field. There were no differences in the ultimate landing positions of the eye movements for such corrected saccades. These results reveal that deficits in updating of saccade programs only seem to be present if the updating must occur after the gaze has shifted to a new location, pointing to a role of intra-parietal cortex in the processes involved in updating information when the current reference frame has to be updated. In conclusion, the paradigm deployed in the current study allows for a refinement of the role of the intra-parietal cortex in the updating of saccade programs.

1. Introduction

In order to explore our environment, we make fast eye movements, called saccades. These saccades are made in order to point the fovea to a location of interest for detailed visual analysis. Many objects in the visual world are not static, however, but might change position unexpectedly while we are in the process of making an eye movement towards it. In these situations, the saccade program has to be updated in order to land on the object's correct location. One of the paradigms that has been used to investigate this spatial updating is the double step paradigm (Becker & Jürgens, 1979) in which participants are required to execute an eye movement to a target which might change position before or after the saccade is initiated. If the target changes position, the participant has to update the saccade program and a failure of this updating will result in a saccade to the original target location. In these situations, the eye movement has to be corrected and a subsequent eye movement will be executed to the shifted location of the target.

A modified version of this double step paradigm has been used to investigate the neural correlates of the updating of saccade programs (e.g., Heide & Kompf, 1998). In this version, participants make two successive saccades to the location of two targets that briefly appear one after another and disappear before the first saccade can be initiated. This 'slow' version of the task is particularly interesting because successful execution of the second saccade requires updating of the retinal coordinates to account for the change in gaze direction after the first saccade. Unlike the original 'rapid' version of the double step paradigm in which any saccadic updating must occur online, in the modified task the location of the second target can be held in memory and used as the basis for calculating the vector of the second saccade once

* Corresponding author. Tel.: +31 30 253 3356; fax: +31 30 253 4511.
E-mail address: S.VanderStigchel@uu.nl (S. Van der Stigchel).

0028-3932/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.neuropsychologia.2013.10.010

the first saccade has been made. Studies that have investigated the neural correlate of this type of updating have pointed to the lateral intra-parietal cortex (IPCx) as one of the regions in which spatial updating takes place (e.g. Duhamel, Colby, & Goldberg, 1992). In particular, various lesion studies have shown that patients with posterior parietal lesions have difficulty in the updating of the retinal coordinates after the first eye movement (Heide, Blankenburg, Zimmerman, & Kompf, 1995; Heide & Kompf, 1998; Pisella et al., 2011): patients show a complete failure of, or inaccuracies in, executing a second saccade when it requires updating of spatial locations from a contralesional location. This deficit was the most pronounced in patients with lesions to the right posterior parietal cortex (compared to those with left PPC lesions), in whom remapping problems were observed for both contra- and ipsilesional saccades. Similar results were subsequently replicated in studies applying Transcranial Magnetic Stimulation (TMS) to the right posterior parietal cortex in healthy subjects (Morris, Chambers, & Mattingley, 2007; van Donkelaar & Muri, 2002).

The previous studies on spatial updating have nicely illustrated the involvement of the parietal cortex in executing saccade sequences to locations held in memory. As the visual information is absent by the time the saccades are executed and planning is fully based on information held in memory, this type of spatial update has a strong endogenous component. In the oculomotor system, however, a distinction is made between endogenous and exogenous information (Godijn & Theeuwes, 2002; Meeter, Van der Stigchel, & Theeuwes, 2010): endogenous information reflects the intentions, goals and beliefs of the observer, and exogenous information represents the properties of the stimulus environment. When an observer intentionally selects only those objects required for the task at hand, selection is said to occur in an endogenous, voluntary, goal-directed manner. When specific properties present in the visual field determine selection independent of the observer's goals and beliefs, selection is said to occur in an exogenous, involuntary, stimulus-driven manner. Previous studies have observed a dissociation between exogenous and endogenous processes in the oculomotor system (Kramer, Gonzalez de Sather, & Cassavaugh, 2005; Kramer, Hahn, Irwin, & Theeuwes, 2000). In contrast to the slow version of the double step task, the rapid double step paradigm requires updating based on exogenous information: spatial updating is based on visual information that changes during the planning of the oculomotor program. It is currently unclear whether patients with lesions to the IPCx have problems with the rapid, online updating of an original saccade program due to a shift of the original target location. This was the aim of the present study.

In this study, five patients with a lesion to the IPCx completed a rapid version of the double step paradigm. In this task, no sequence of saccades needs to be programmed, but participants simply have to execute a single eye movement to a target as fast as possible. Saccades had to be executed to a target in either the contra- or the ipsilesional visual field. In two thirds of the trials, the target shifted shortly before the saccade was executed to a new location within the same field but in the contra- or the ipsilesional direction. This allowed us to investigate whether patients with IPCx lesions are able to update their saccade program given new exogenous information about the required endpoint of the saccade. Furthermore, if the updating of the original eye movement program failed, patients performed a second saccade to the new target location that requires a rapid error correction. Given that previous studies have suggested that the role of the parietal cortex is to select sensory information for action and to transform it into a representation of use to motor systems ('selection for action', Rafal, 2006), it could be that the integration of the sensory information about the new location of the target is impaired after a lesion to the IPCx, leading to a higher likelihood of failure to update the saccadic coordinates. Furthermore, for trials in which the first saccade is made to the incorrect (non-updated) coordinates, similar deficits might be observed for the corrective second saccade. To ensure that patients did not have attentional deficits that might mediate performance on this task, patients performed a temporal order judgment task that is indicative of attentional differences between the two visual fields (Rorden, Mattingley, Karnath, & Driver, 1997).

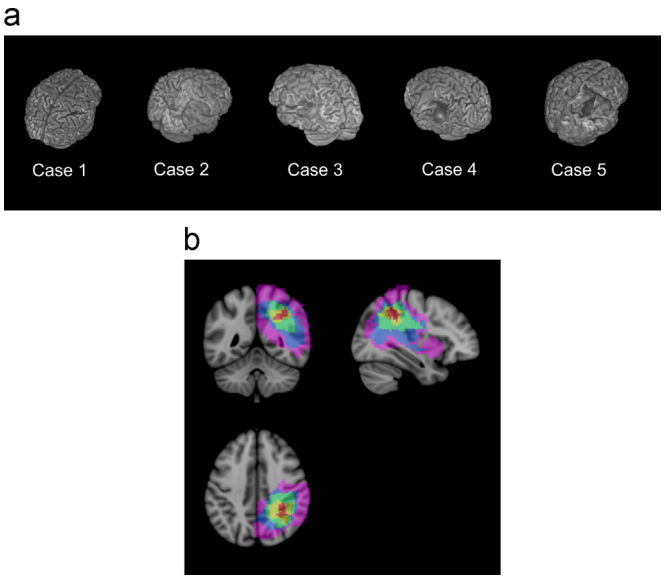

Fig. 1. (**A**): Rendered 3D view of the individual scans. (**B**): An overlap reconstruction of the lesions of all five patients with the left hemisphere lesioned patient's image reflected onto the right. Greater overlap is depicted as brighter red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Methods

2.1. Patients

Two left- and three right-hemisphere-lesioned patients were tested (three men, mean age=56, SD=16). All patients were right-handed. The inclusion criterion for this study was a chronic (>12 months) lesion involving the IPCx. Fig. 1 shows the individual scans and an overlap image of the individual lesions.

Case 1 is a 66 year-old man who suffered an ischemic stroke in the right middle cerebral artery (MCA) territory, who had presented with transient sensory symptoms in his left hand, three years prior to the time of testing. The infarction left a small lesion involving the horizontal segment of the IPCx and cortex surrounding the post-central sulcus. Case 1 displayed no deficits at neurological examination.

Case 2 is a 29 year-old woman who underwent surgery to remove a right parietal cerebral arteriovenous malformation five years previous to the time of testing. Her lesion involves the cuneus of the occipital lobe, the precuneus, most of the inferior and superior parietal lobules including the supramarginal and angular gyri. The lesion has destroyed parietal cortex along the full extent of the IPCx both medially and laterally, sparing only the most caudal part and the lateral part of the horizontal IPCx, and extends to the post-central sulcus rostrally. She suffered left inferior quadrantanopsia affecting her peripheral vision, although detection and awareness of moving objects was preserved (Riddoch's Syndrome, Riddoch, 1917; Zeki & ffytche, 1998). By the time of testing for this study, she had regained some ability to discriminate shapes and colors in the affected quadrant, but still reported that these images were indistinct. Because of this visual field defect, trials presented in the bottom left visual field were discarded from analyses.

Case 3 is a 57 year-old man who suffered an ischemic infarction in the left MCA territory ten years prior to the time of testing. His lesion involves the temporo-parietal junctions (TPJ; Wernicke's area), lateral temporal occipital cortex, posterior superior temporal gyrus, supramarginal gyrus, angular gyrus, inferior

parietal lobule and extends to the lateral border of the IPCx. Case 3 suffers from word finding difficulties, occasional phonemic paraphasias and impaired repetition but preserved comprehension.
Case 4 is a 59 year-old man who suffered an ischemic infarction in the left MCA territory four years prior to the time of testing. His lesion involves the middle temporal gyrus, the superior temoral gyrus including Heschl's gyrus and the TPJ (Wernicke's area) with gliosis of deep temporal white matter. There is also damage to the inferior parietal lobule extending to the lateral border of the rostral IPCx and horizontal segment of the IPCx. Neurological examination reveals a subtle loss of proprioception and tactile extinction in his right hand. He also suffers impaired naming and repetition, with phonemic paraphrasias.
Case 5 is a 68 year-old woman who suffered a traumatic brain injury following a fall six years prior to testing. A CT scan showed a large intracerebral hematoma in the right parietal lobe that required surgical excision. She has a dense residual left hemiplegia and hemisensory loss. She demonstrated dense hemispatial neglect for several months after the injury, but had then recovered. MRI reveals an extensive lesion of much of the right parietal lobe including the parietal operculum, supramarginal gyrus and superior parietal lobule and all of the cortex surrounding the IPCx except in the most caudal part. The lesion involves the temporal pole and middle part of the superior temporal gyrus, and the pre- and post-central gyri, but spares the frontal eye field.

None of the patients had additional neurological or psychiatric illness. All participants are living at home leading active lives and had capacity to give informed consent. The research and consent procedures were approved by the Ethics Committees of both the University and NHS and were in accordance with the standards of the Declaration of Helsinki.

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 advertised to have a spatial resolution of 0.01°. 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 the experiment in a sound-attenuated setting, viewing a display monitor from a distance of 57 cm.

2.3. Stimuli and procedure

2.3.1. Double step task

Participants viewed a display containing a gray fixation cross (1.1 × 1.1°) on a black background in the center of the display. The fixation cross was removed after a random interval of 400–900 ms. Subsequently, after a gap period of 100 ms in which no stimulus was presented, one red filled disc with a radius of 0.86° was presented. The disc was positioned on one of the four principal axes (in polar coordinates: 45°, 135°, 225°, and 315°) on an imaginary circle around the central fixation point (radius: 9.35°). This location will be termed 'T1'. In two-thirds of the trials (*step trials*), the disc jumped to a location at ±20° on the same imaginary circle from the location at which the disc was initially presented (e.g. towards 25° or 65° when the disc was initially presented at 45°). This location will be termed 'T2'. The time between the onset of the disc and the jump was either 110 or 160 ms. On the remaining one-third of the trials, the disc did not jump (*no-step trials*). The target display was presented for 2000 ms after which the stimulus was removed from the display.

Participants were instructed to fixate on the central fixation cross and to move their eyes to the stimulus on the monitor as quickly as possible. The experiment consisted of 480 experimental trials with 24 training trials. The experiment started with a nine-point grid calibration procedure. The sequence of trials was randomized.

2.3.2. Temporal order judgment

A temporal order judgment task was used to investigate possible attentional differences between the right and left visual field. In this task, a red and a green equiluminant square (0.54° × 0.54°) were presented 7.19° to the right or left of fixation. One of these two squares was presented earlier. Participants had to indicate manually whether the green or red square was presented earlier. The temporal offset between the two squares was adjusted according to a three-down-one-up staircase procedure. Two interleaving staircases were used with an initial temporal asynchrony of 150 ms: one starting with the contralesional square appearing first, and the other with the ipsilesional square appearing first. The temporal offset was multiplied by 0.5 when three correct answers were given in a row and by 1.5 when one incorrect answer was given. The staircases were terminated after 100 trials.

2.4. Data analysis of double step task

2.4.1. Initial saccades inclusion criteria

For the initial saccade, we measured saccade deviation and saccade latency. The first eye movement with an amplitude larger than 2° was taken into account. The trial was excluded from analyses when the amplitude of this first saccade was smaller than 5° (too short initial saccade).

Saccade deviation was computed as the angle (in deg.) between the saccade endpoint and T1. The location of T1 was therefore used as a null-reference.

Eye movements sometimes portrayed a small drift from fixation at the start of the saccade. Since this influences the relative position of the stimuli in relation to the start of the saccade, the deviation score was calculated relative to the actual starting point of the saccade. Saccades had to be initiated within 2° of the central fixation point, else the trial was removed from the analyses.

Initial saccades landing outside the quadrant in which T1 was presented were removed from analysis. Furthermore, if a landing position in any of the conditions was further than two and a half standard deviations away from the average landing position per condition of the participant the trial was marked as an outlier and removed from the analysis.

Saccade latency was defined as the interval between target onset and the initiation of the saccadic eye movement. Trials with a saccadic latency lower than 80 ms (anticipatory saccades) or higher than 800 ms (too slow saccades) were excluded.

The exclusion criteria described above resulted in 11.7% excluded trials; the majority of those were inaccurate fixations.

2.4.2. Corrected vs. uncorrected initial saccades

Specifically for the analyses of the error correction in the step condition, trials were excluded in which saccade latency was shorter than 40 ms after the step occurred (i.e. shorter than 150 ms in trials in which the step occurred 110 ms after the onset of T1). This was done to make sure that participants had enough time to correct their initial saccade to the T2 location.

Trials in the step condition were subsequently divided into *corrected* and *uncorrected* saccades. A representation of the different saccade types is shown in Fig. 2. To take the normal variation of saccade endpoints into account, *the no-step condition* was taken as a baseline to compute whether saccades were corrected or uncorrected:

- *Uncorrected* saccades were initial saccades that landed within one and a half standard deviation of the average saccade deviation *in the no-step condition* for that particular T1, suggesting that the eye movement trajectory was *not* updated to take account of the new target location.
- *Corrected* saccades were initial saccades that landed within one and a half standard deviation of the average saccade deviation *in the no-step condition* for that particular T1, but now transposed 20° in polar coordinates to the location of T2 (i.e. the same baseline as for the uncorrected saccades, but now 'placed' upon the location of T2). This criterion suggests that the eye movement trajectory *was* updated to take account of the new target location.

For each visual field, we analyzed percentage corrected and uncorrected saccades and compared the percentage between the contra- and ipsilesional visual field.

2.4.3. Second saccade

When the initial saccade was uncorrected, we investigated the second saccade when the endpoint of this second saccade was closer to T2 than to T1. This was considered to be a *corrective second saccade* (see Fig. 2). For these saccades, we measured the time necessary to initiate this second saccade after the end of the

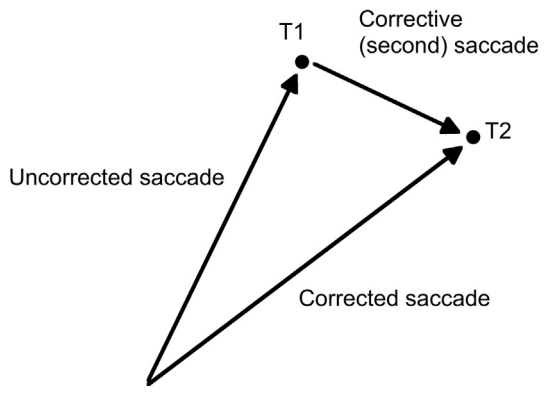

Fig. 2. A representation of the three possible saccade types that were analyzed for the step trials.

initial uncorrected saccade. Furthermore, we measured the endpoint error (in terms of the absolute distance between the endpoint of the corrected second saccade and the location of T2 in degrees of visual angle).

2.4.4. Analysis

To test the hypothesis that IPS lesions alter saccadic performance the unaggregated data were submitted to simultaneous entry multiple regression analyses using JMP software (SAS Institute 2012). The saccadic latencies for no-step trials, corrected step trials and uncorrected step trials underwent separate regression analyses with patient and field entered as predictors along with the interaction term patient by field. The regression analyses for saccadic latencies and endpoint errors for the second saccades included the predictors patient, field and step direction as well as four interaction terms: patient by field, patient by step direction, field by step direction and patient by field by step direction. This regression approach enabled the evaluation of field and step direction effects on trial-to-trial variability in saccadic latencies, whereas a more traditional repeated measures approach was not feasible due to the low number of patients. Including patient and its interaction terms in these analyses allowed the evaluation of the independent contribution of field and step direction (as indicated by partial *F*-tests) to the prediction of saccade latency or endpoint error. Between-patient contrasts will not be reported because they are uninformative.

2.5. Data analysis of temporal order judgment task

The temporal order judgment data was analyzed within each patient to determine whether any individual demonstrated an attentional biases between the visual fields. For each participant the temporal offsets of the last eight turning points were examined. Temporal offsets for which the contralesional target appeared first were expressed as negative numbers. The turning point data were averaged to determine the Point of Subjective Simultaneity (PSS) and single-sample *t*-tests were used to compare each patient's data to zero.

3. Results

3.1. Double step task

The number of valid no-step, and uncorrected and corrected step trials for each participant is shown in Table 1. This illustrates that each patient had enough trials to include in the analyses, except for Cases 3 and 5, who were excluded from the analyses of corrected saccades due to having fewer than ten trials in one or both visual fields in which the saccade was corrected.

3.1.1. No-step trials

Field was a significant independent predictor of saccade latency for no-step trials (Table 2). Saccades made to the contralesional visual fields were 9 ms slower than saccades made to the ipsilesional field (contralesional: $M=216$, $SEM=2.9$; ipsilesional: $M=207$, $SEM=2.7$). Three of the five patients had longer contralesional RTs (see Fig. 3).

3.1.2. Step trials

3.1.2.1. First saccades. Of the step trials, 43.1% were corrected in the contralesional visual field (46.9% uncorrected), and 40.6% were corrected in the ipsilesional field (59.4% uncorrected). This difference was not significant (Pearson chi-square=0.46, $p=0.280$).

Table 1
Number of trials for no-step and uncorrected and corrected step trials for each patient.

Case	Contra			Ipsi		
	No step	Uncorrected	Corrected	No step	Uncorrected	Corrected
1	67	38	42	67	38	34
2	32	18	10	61	24	27
3	70	34	10	74	36	8
4	63	48	63	48	45	47
5	73	35	6	74	27	0
Total	305	173	131	324	170	116

Table 2
Regression of saccade latency for no-step trials on patient and field.

Variable	Df	SS	Partial *F*
Patient	4	1,764,905	189.45*
Field	1	12,183	5.23*
Patient × Field	4	33,903	3.64*

Note: R2=0.57, adj. R2=0.56, $F(9,618)=90.18$*. * $p<0.05$.

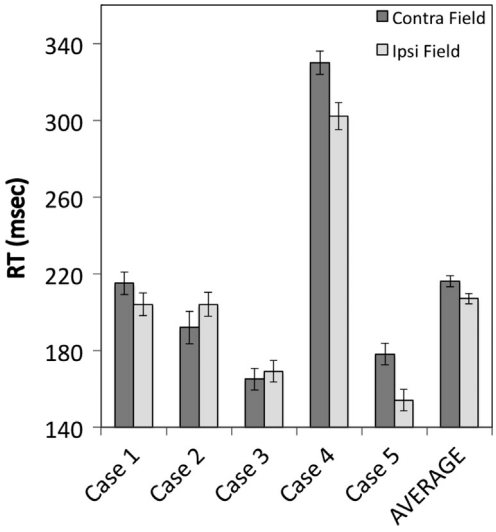

Fig. 3. Individual and average saccade latencies for no-step trials in the contralesional and ipsilesional fields.

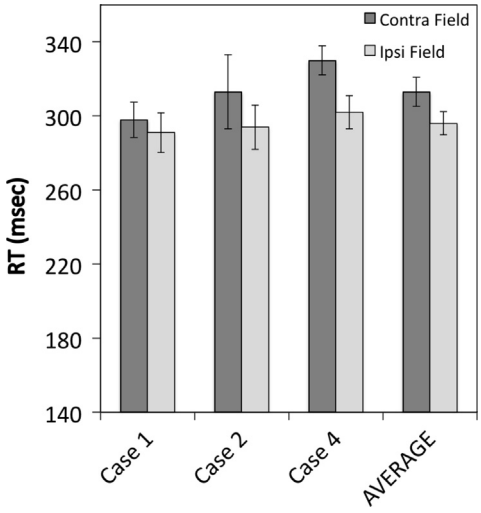

Fig. 4. Individual and average saccade latencies for corrected step trials in the contralesional and ipsilesional fields.

Corrected saccades were 105 ms slower than uncorrected saccades (corrected: $M=294$, $SEM=3.8$; uncorrected: $M=189$, $SEM=2.5$; $F(1, 588)=699$, $p<0.001$). This difference did not vary across field ($F(1, 584)=0.9$, $p=0.34$)).

Two patients had a low number of corrected trials and were excluded from further analyses of *corrected* saccade latencies. The remaining three patients each had slower RTs for saccades made to the contralesional compared to ipsilesional field (see Fig. 4), with an average difference of 17 ms (contralesional: $M=313$, $SEM=7.8$; ipsilateral: $M=296$, $SEM=6.2$). The regression analysis

Table 3
Regression of saccade latency for corrected step trials on patient and field.

Variable	df	SS	Partial *F*
Patient	2	21,551	2.76†
Field	1	12,464	3.19†
Patient × Field	2	5119	0.66

Note. R2 = 0.058, adj. R2 = 0.036, $F(5,216) = 2.67$*. Two patients were excluded from this analysis due to insufficient data. * $p < 0.05$.
† $p < 0.08$.

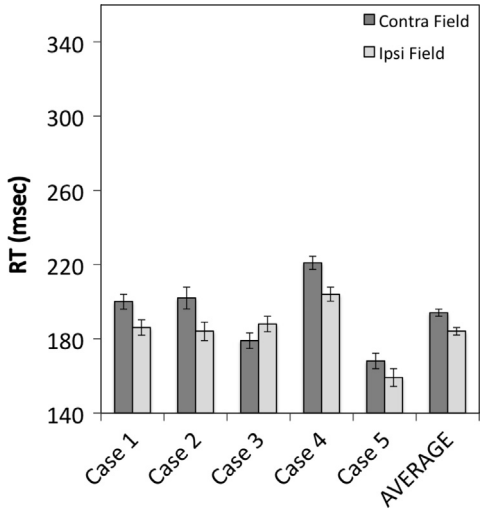

Fig. 5. Individual and average saccade latencies for uncorrected step trials in the contralesional and ipsilesional fields.

revealed that the independent contribution of field in predicting Saccade Latency was at trend level (see Table 3).

With the exception of case 3, all patients showed slower latencies for *uncorrected* saccades in the contralesional compared to ipsilesional field (Fig. 5). The regression analysis indicated that field was a significant independent predictor of saccade latency (Table 4), with an average of 10 ms slower than to the ipsilesional field (contralesional: $M = 194$, $SEM = 2.2$; ipsilateral: $M = 184$, $SEM = 2.2$).

3.1.2.2. Second saccades. Of the corrective second saccades, 50.6% were made in the contralesional field (49.4% in ipsilesional field), and 50.6% were involved a correction in the contralesional direction (49.4% in the ipsilesional direction). These differences were not significant (Pearson chi-square = 0.20, $p = 0.888$).

The results of the analysis of latencies for corrective second saccades are shown in Table 5. Field, step direction and the interaction of field by step direction are significant independent predictors of saccadic latency.

As shown in Fig. 6, these results reflect a specific slowness in initiating corrective saccades in a contralesional direction within the contralesional visual field. It took an average of 20 ms more time for patients to initiate these saccades than those in the ipsilesional direction in the contralesional field (contralesional: $M = 159$, $SEM = 3.3$; ipsilesional: $M = 139$, $SEM = 3.3$). Average latencies for corrective saccades in the ipsilesional field were both smaller than those in the contralesional field, and did not vary by direction of correction (contralesional direction: $M = 131$, $SEM = 3.3$; ipsilesional direction: $M = 132$, $SEM = 3.4$).

The analysis of endpoint error for the second saccade relative to the T2 location indicated that there were no significant

Table 4
Regression of saccade latency for uncorrected step trials on patient and field.

Variable	df	SS	Partial *F*
Patient	4	93,287	37.3*
Field	1	7368	11.7*
Patient × Field	4	8324	3.3*

Note. R2 = 0.34, adj. R2 = 0.33, $F(9,332) = 19.27$*. * $p < 0.05$.

Table 5
Regression of saccade latency for second saccades on patient, field and step direction.

Variable	Df	SS	Partial *F*	*t*
Patient	4	68,897	11.3*	
Field	1	21,125	13.8*	
Step direction	1	6253	4.1*	
Patient × Field	4	40,100	6.8*	
Patient × Step direction	1	7361	4.8*	
Field × Step direction	4	21,884	3.6*	
Contra field: contra vs ipsi direction		13,695		3.0*
Ipsi field: contra vs ipsi direction		22		0.1
Patient × Field × Step direction	4	31,816	5.2*	

Note. R2 = 0.31, adj. R2 = 0.26, $F(19,296) = 7.1$*. * $p < 0.05$.

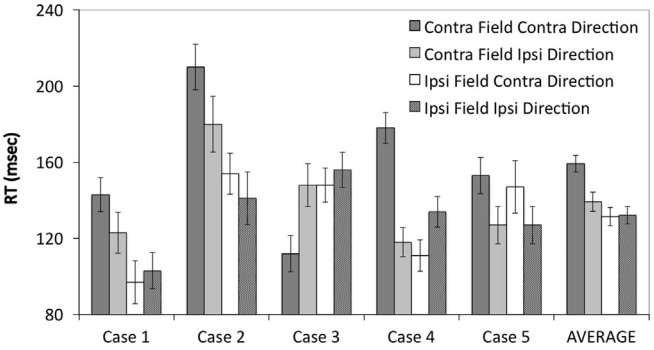

Fig. 6. Individual and average saccade latencies for corrective second saccades.

Table 6
Regression of saccadic errors for second saccades on patient, field and step direction.

Variable	df	SS	Partial *F*
Patient	4	7.8	2.1
Field	1	3.3	3.6
Step direction	1	0.0	0.0
Patient × Field	4	3.4	3.4*
Patient × Step direction	1	4.8	4.8*
Field × Step direction	4	0.5	0.5
Patient × Field × Step direction	4	6.4	6.4*

Note. R2 = 0.22, adj. R2 = 0.16, $F(19,282) = 4.1$*. * $p < 0.05$.

independent contributions of Field, Step Direction or the interaction of these two terms in the prediction of saccadic errors ($ps > 0.05$). The only significant independent predictors involved interactions with patient (see Table 6). Inspection of pairwise comparisons of parameter estimates for these interactions revealed that these interactions were driven by the substantially larger endpoint errors made by case 4 for contralesional saccades made in a contralesional direction (see Fig. 7).

Overall, the analyses of the double-step task indicate that latencies for all trial types (no-step, uncorrected and corrected)

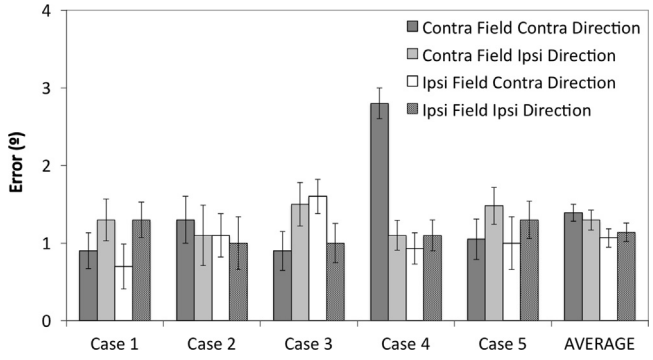

Fig. 7. Individual and average saccade errors for corrective second saccades.

Table 7
Results of the temporal order judgment task.

Case	PSS Mean	SEM	*T*(7)	*P*
1	−1.63	16.86	0.10	0.93
2	−15.5	20.80	0.75	0.48
3	−13.00	25.65	0.51	0.63
4	−8.50	19.41	0.44	0.67
5	47.75	29.58	1.61	0.15

were larger when saccades were directed to the contralesional versus the ipsilesional field. Furthermore, patients took longer to initiate a corrective second saccade after making an uncorrected first saccade in their contralesional compared to ipsilesional field. With the exception of case 4, there were no differences in the ultimate landing positions of the eye movements for such corrected saccades.

3.2. Temporal order judgment

The results of the temporal order judgment task are provided in Table 7. The PSS did not significantly differ from zero for any of the patients, indicating that there was no bias in the distribution of attention between the two visual fields.

4. Discussion

The present study investigated the role of the intra-parietal cortex in the rapid, online, updating of a saccade program. To this end, we employed a double step saccade task in which the target location in a subset of trials changed shortly before the saccade was executed. Participants were not required to program a sequence, but were instructed to execute a single eye movement to the location of the target. This set-up results in three types of initial saccades: saccades to the target on no-step trials, uncorrected saccades to the original target location on step trials and corrected saccades to the new target location on step trials. Furthermore, the uncorrected saccades were frequently followed by a corrective second saccade. The results of the different saccade types will now be discussed.

On no-step trials, patients were simply executing a saccade to a non-dynamic target. On average, patients were slower to initiate a saccade to a contralesional target than to an ipsilesional target, although this effect was not consistent across patients. As there were no differences in the temporal order judgment task, this effect cannot be attributed to an attentional imbalance between the two visual fields. Interestingly, the literature is inconsistent on whether the speed of saccade execution is impaired after a lesion to the IPCx: whereas a contralesional increase was observed for memory-guided saccades (Pierrot-Deseilligny, Rivaud, Gaymard, & Agid, 1991), such an effect was not present for visually summoned saccades to the contralesional visual field (Machado & Rafal, 2004; Rafal, 2006). Also in our patient group, results were mixed with only two patients showing a strong imbalance in saccade latency between the two visual fields. In two patients, a reversed trend was observed.

The effect of an increased saccade latency to the contralesional visual field was more robust for the step trials, in which latencies for both corrected and uncorrected saccades towards the contralesional visual field were increased compared to the ipsilesional visual field. This imbalance in saccade latency was especially robust for the corrected saccades, in which the difference between the contra- and ipsilesional field was around twice as large as the uncorrected saccades. The finding that the latency imbalance was strongest for corrected saccades leads to an interesting speculation: it might be that a contralesional increase in saccade latency for patients with a lesion to IPCx is only observed when saccade execution requires a top-down component. It might be argued that corrected saccades, as observed in the current study, and memory-guided saccades (Pierrot-Deseilligny et al., 1991) are under stronger top-down influence than visually summoned saccades (Machado & Rafal, 2004).

As expected, corrected saccades had longer latencies than uncorrected saccades, reflecting the fact that the updating of a saccade program is a time-consuming process. Although both types of saccades had longer latencies when initiated towards the contralesional visual field than to the ipsilesional field, this does not point to a deficit in updating of a saccade program, but rather to a delay in oculomotor programming as explained in the previous paragraph. A deficit in updating of a saccade program should have resulted in different updating costs between the two visual fields. This was not observed. Furthermore, the number of updated saccades was similar for the two visual fields. It therefore seems that simple updating of a saccade program given new exogenous information is not impaired after a lesion to the IPCx. Whenever a saccade is programmed, but not yet executed, it can therefore still be successfully updated when the target location is shifted.

There was a clear contralesional deficit for the corrective second saccade performed after the first saccade was initiated to the old location of the target. In these trials, the time necessary to correct the endpoint position by the execution of a second saccade was longer for targets in the contralesional field than the ipsilesional field. Interestingly, this effect in the contralesional field was only observed when the target was moved in the contralesional direction. No deficit was observed for a shift in the contralesional field when the target was moved in the ipsilesional direction. It is important to notice that this effect cannot be explained by a general contralesional delay: the corrective saccade was not slower when patients performed a corrective saccade in the contralesional direction when the target was positioned in the ipsilesional field.

The results of the present study therefore extend previous findings with respect to the role of the IPCx in the updating of saccade programs: this area only seems to be crucially involved when updating has to occur after the gaze has been shifted to the new location. This conclusion follows from the finding that only corrective saccades were affected in the present study. In previous double step paradigms, the new T2 saccadic targets always occurred after gaze had already been shifted to the T1 location (Heide et al., 1995; Heide & Kompf, 1998; Pisella et al., 2011). These paradigms could therefore not disentangle between the rapid updating required when the target location shifts to a new

location *before* the saccade is initiated and the updating required *after* a saccade had already been initiated. The results of the present study imply that the IPCx is only involved in the latter type of updating, as there were no deficits in updating before the saccade was initiated. Indeed, neurons in the IPCx maintain target coordinates between saccades, enabling a stable visual scene for the observer (Duhamel et al., 1992). Therefore, after a saccade has been executed, the current (environmentally based) reference frame of the observer has to be updated. This sensory information based on the updated reference frame is subsequently transformed into a representation of use to the motor system (Sapir, Hayes, Henik, Danziger, & Rafal, 2004). The results of the present study suggest that the integration of sensory information about the new location of the target is impaired after a lesion to the IPCx, but only when information in the current reference frame needs to be updated.

Interestingly, the deficits in spatial updating were only present in the reaction time of the corrective second saccade and not in the endpoint error. Furthermore, the proportions of corrective saccades were not different between the two visual fields. This therefore implies that the deficits after a lesion to the IPCx in this fast double step task are only reflected in timing of the updating signal and not in the accuracy of the signal itself. Although this might seem inconsistent with the results of previous studies using the slower double step task (Heide et al., 1995; Heide & Kompf, 1998; Pisella et al., 2011), this discrepancy is easily explained by the differences between the tasks: in these previous studies, patients had to execute the second saccade fully based on information held in memory, whereas the updating in the current study was based on a visual signal: the target object was visible at the moment of the programming of the corrective saccade. This visibility might have given enough visual information to successfully update the eye movement program and to overcome possible problems in the accuracy in the updating process. Our results therefore suggest that the accuracy deficits in updating are only observed when there is no, or weak, visual information about the location that should be updated.

In conclusion, the paradigm deployed in the current study allows for a refinement of the role of the intra-parietal cortex in the updating of saccade programs. Deficits in updating of saccade programs only seem to be present if the updating must occur after the gaze has shifted to a new location, pointing to a role of intra-parietal cortex in the processes involved in updating information when the current reference frame has to be updated.

Acknowledgments

This research was funded by Grant 451-09-019 from the NWO (Netherlands organization for Scientific Research) to SvdS. We thank Dr. Lesa Hoffman, Mr. Adam Thomas and Dr. Thomas Nichols for statistical advice.

References

Becker, W., & Jürgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. *Vision Research*, *19*, 967–983.
Duhamel, J.-R., Colby, C. L., & Goldberg, M. E. (1992). The updating of the representation of visual space in parietal cortex by intended eye movements. *Science*, *255*, 90–92.
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.
Heide, W., Blankenburg, M., Zimmerman, E., & Kompf, D. (1995). Cortical control of double-step saccades: implications for spatial orientation. *Annals of Neurology*, *38*, 739–748.
Heide, W., & Kompf, D. (1998). Combined deficits of saccades and visuo-spatial orientation after cortical lesions. *Experimental Brain Research*, *123*, 164–171.
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.
Machado, L., & Rafal, R. (2004). Control of fixation and saccades in humans with chronic lesions of oculomotor cortex. *Neuropsychology*, *18*(1), 115–123.
Meeter, M., Van der Stigchel, S., & Theeuwes, J. (2010). A competitive integration model of exogenous and endogenous eye movements. *Biological Cybernetics*, *102*, 271–291.
Morris, A. P., Chambers, C. D., & Mattingley, J. B. (2007). Parietal stimulation destabilizes spatial updating across saccadic eye movements. *Proceedings of the National Academy of Sciences*, *104*(21), 9069–9074.
Pierrot-Deseilligny, C., Rivaud, S., Gaymard, B., & Agid, Y. (1991). Cortical control of memory-guided saccades in man. *Experimental Brain Research*, *83*, 607–617.
Pisella, L., Alahyane, N., Blangero, A., Thery, F., Blanc, S., & Pelisson, D. (2011). Right-hemisperic dominance for visual remapping in humans. *Philosophical Transactions of the Royal Society: B*, *366*, 572–585.
Rafal, R. D. (2006). Oculomotor functions of the parietal lobe: Effects of chronic lesions to humans. *Cortex*, *42*, 730–739.
Riddoch, G. (1917). On the relative perceptions of movement and a stationary object in certain visual disturbances due to occipital injuries. *Proceedings of the Royal Society of Medicine10*(Neurol Sect), 13–34.
Rorden, C., Mattingley, J. B., Karnath, H. O., & Driver, J. (1997). Visual extinction and prior entry: Impaired perception of temporal order with intact motion perception after unilateral parietal damage. *Neuropsychologia*, *35*, 421–433.
Sapir, A., Hayes, A., Henik, A., Danziger, S., & Rafal, R. (2004). Parietal lobe lesions disrupt saccadic remapping of inhibitory location tagging. *Journal of Cognitive Neuroscience*, *16*(4), 503–509.
van Donkelaar, P., & Muri, R. (2002). Craniotopic updating of visual space across saccades in the human posterior parietal cortex. *Proceedings of the Royal Society of London. Series B, Biological Sciences*, *269*(1492), 735–739.
Zeki, S., & ffytche, D. H. (1998). The Riddoch syndrome: Insights into the neurobiology of conscious vision. *Brain*, *121*, 25–45.