Research Report

Visual spatial integrity in the absence of splenium

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ABSTRACT

Several lines of evidence have confirmed that visual integrity among the two hemifields is severely impaired following transection of posterior part of the corpus callosum (splenium). But the extent of this impairment differs for various visual functions. Here, in a posterior callosectomized patient (MD), interhemispheric visual spatial integrity is investigated in three experiments. In the first experiment, MD was asked to make decision about horizontal alignment of two balls presented simultaneously in one of three conditions: both in right or left hemifield, or each in one hemifield. We have previously shown that she is not able to perform a shape-matching task for stimuli presented to different hemifields. But in this task, MD was able to compare location of the two bilaterally presented stimuli significantly above chance level. Then we investigated whether attentive visual object tracking across vertical meridian of the visual field is possible in the absence of splenium. MD had to attentively track one bouncing ball among three identical balls, while it crossed the vertical midline in half of trials. Her performance in crossed conditions was significantly above chance level, but it was lower than uncrossed conditions. Finally, we investigated the contribution of simple interhemispheric temporal signals in performing the attentive tracking task. Results suggest that the patient was not using such temporal signals. Our results suggest that interhemispheric connections other than splenium can contribute in making an integral visual map across hemifields. Such an integrated map can be used for bilateral visual spatial comparisons and visual spatial attention.

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1. Introduction

Binding the two half-field representations of visual scene in the two hemispheres needs the normal functioning of the corpus callosum. Lesions of the corpus callosum have revealed that various parts of the corpus callosum make different contributions to provide this perceptual unity across the vertical midline (Gazzaniga, 2000). Areas such as temporal, parietal, and prefrontal cortices communicate with their analogous cortices on the other hemisphere through different parts of corpus callosum such as rostrum, genu, body, and isthmus. Although these cortical areas play an important role in higher visual functions, most of the visual information is transferred through the splenium, the largest part of the corpus callosum that interconnects the two occipital cortices (Pandya and Seltzer, 1986). Splenium resection severely impairs visual information transfer between the two hemispheres. For example, transection of splenium impairs

interhemispheric transfer of information about luminance, size and color of visual objects (Corballis and Corballis, 2001; Forster and Corballis, 2000), object shape (Forster and Corballis, 2000), reading digits (Corballis, 1994) and verbal reporting of letters, words and geographical names (Clarke et al., 2000).

But similar involvement of splenium has not been indicated for some other visual attributes. For example, it has been shown that interhemispheric transfer of orientation information is possible in the absence of the corpus callosum (Corballis, 1995). In addition, Clarke et al. have shown that bilateral cortical activation in a patient with lesion of the posterior two-thirds of the corpus callosum during unilateral presentation of apparent motion is similar compared to normal subjects (Clarke et al., 2000). These imaging data are in line with previous psychophysical findings indicating preserved perception of apparent motion (Naikar and Corballis, 1996; Ramachandran et al., 1986) and line-motion illusion (Corballis et al., 2004) across the vertical midline in split brain patients, although contrary evidence has also been reported (Gazzaniga, 1987).

Also there is evidence indicating that transfer of crude relative position information and spatial relations is possible in the absence of callosal connections. For example, Holtzman showed that split brain patients could redirect their eye gaze between corresponding spatial locations in the two visual fields (Holtzman, 1984). Also, Sergent showed that interhemispheric transfer of relative visuospatial information is possible in the absence of the corpus callosum (Sergent, 1991), although it has been discussed that her data do not necessarily indicate the transfer of high-level information about quantity or for sophisticated transfer at an implicit level (Corballis, 1995).

Previously, using a spatial crowding paradigm, Afraz et al. showed that distracters presented to one visual hemifield of split brain patient (MD) disturb target discrimination in the opposite visual hemifield in the absence of splenium (Afraz et al., 2003). This implicit spatial interaction occurred while MD performed a bilateral object-matching task just at chance level, suggesting that the intact anterior parts of corpus callosum play a major role in this type of implicit transfer of position information between hemispheres.

In summary, it is possible to conclude that spatial information in one hemisphere could take effect and also be implicitly utilized by the processes on the other side in the absence of the splenium. In his review, Michael Gazzaniga concludes that "spatial attention can be directed but not divided between the hemispheres" (Gazzaniga, 2000). However, all of the previous studies lack a direct quantitative measurement of the retained capacity for the transfer of spatial information between the two hemispheres in the absence of the splenium. On the other hand, it is still unknown whether the spared interhemispheric spatial interactions after resection of splenium can supply higher level functions, such as visual attention, which need explicit access to the extracted position information.

In the first experiment of the present article, we quantitatively measured the resolution for interhemispheric transfer of spatial information in a partial split brain patient without splenium (MD). In this experiment, the patient and normal subjects were asked to judge about horizontal alignment of two simultaneously presented visual stimuli. Using a staircase paradigm, we measured the accuracy of alignment/misalignment judgments in bilateral and unilateral presentations.

Then in another sets of experiments, we investigated the attentive tracking of moving visual objects across the vertical midline in MD. Attentive object-tracking paradigm is originally introduced by Pylyshyn and Storm (1988) and is widely used in the psychophysics literature to probe the top-down visual spatial attention (Pylyshyn and Storm, 1988; Pylyshyn, 1989; Scholl and Pylyshyn, 1999; Sears and Pylyshyn, 2000). To perform such an attentive task, one hemisphere needs to have an explicit access to the position information extracted from the other hemisphere's attentional system. In this study, we examined whether this explicit information could be transferred between hemispheres in the absence of the splenium.

2.   General discussion

Splenium of the corpus callosum is a thick neural bundle that interconnects occipital visual areas (de Lacoste et al., 1985). Several lines of evidence have shown that transection of splenium leads to severe problems in visual integration across hemifields (Gazzaniga et al., 1962, 1965). However, the amount of integration deficit is not necessarily equal for various visual functions. There are some studies revealing interhemispheric interactions in various visual functions such as simple orientation discriminations (Corballis, 1995), perception of apparent motion (Clarke et al., 2000; Naikar and Corballis, 1996; Ramachandran et al., 1986), and comparison of relative positions (Holtzman, 1984; Sergent, 1991) in the absence of splenium. Subcortical regions like superior colliculi and also remaining cortical commissures like more anterior parts of corpus callosum and anterior commissure may compensate the absent role of splenium in these visual functions.

In this article, we investigated visual spatial integration in a patient with posterior callosotomy. We first performed a fine measurement of spatial resolution for transferred data between hemispheres in our patient. The same patient has been examined previously with an object-matching task (Afraz et al., 2003), and her performance was at chance level when she was asked to judge whether two – bilaterally presented – T-shaped visual objects has the same orientation or not. In spite of her severe problem in object-matching experiment in our previous report (Afraz et al., 2003), results of experiment one of the current study revealed her well above chance level performance in a "position matching" task. Although perceptual difficulty level of position matching task used in this study is not necessarily comparable to the shape matching task (Afraz et al., 2003). However, her capability in position matching task was lower – but still above chance – in bilateral presentations compared to unilateral presentations. This experiment indicates that the patient is capable for visual spatial comparisons across the vertical visual midline, and that the "resolution" of such spatial comparisons is lower in contrast with within hemifield comparisons. This means that the remaining interhemispheric connections can provide a low-resolution but integral spatial map of visual field in this patient.

An important question arising here is whether the remaining interhemispheric connections can support higher level processes in which visual attention is involved? The simple misalignment detection task used in our study can be performed based on a low level subliminal position information transfer between the two cerebral cortices. There are several examples in cognitive neuroscience literature showing that simple decision makings in simple visuospatial tasks can be performed without explicit awareness about visual stimuli. Blind sight experiments are well-recognized examples that support this phenomenon (Marzi et al., 1986; Stoerig, 1993; Kentridge et al., 2004). Results of the first experiment indicate that in spite of splenium resection, the patient still has a "functional" integral map of visual space across hemifields. Nonetheless, this integrity of visual space is not necessarily available for the patient's conscious perception.

In the second step of the present study, using an attentive object-tracking task, we investigated whether the remaining interhemispheric connections in our patient contribute in shifting visual attention across visual hemifields. During attentive object tracking, it is impossible to discriminate the target item from distracters based on bottom-up visual cues. The only way to perform the task appropriately is that a top-down, persistent attentional tag follows the moving target from the beginning to the end of each trial. Such high level attentional tags have been interpreted as "fingers of instantiation" (Pylyshyn and Storm, 1988; Pylyshyn, 1989) or attentional pointers (Intriligator and Cavanagh, 2001). It is very unlikely to assume that such a top-down attentive task can be performed subliminally, without a direct explicit conscious access to the tracked item. What happens when the target is crossing the visual midline and goes to another hemifield? Proper tracking necessitates that the destination hemisphere's attentional system get some information about spatial coordination of the target from the other hemisphere's attentional system. Is it possible in the absence of the brain's major visual commissure, the splenium?

Comparing to the results of the first experiment, the second experiment did not provide clear answer to the abovementioned question. The patient clearly showed a deficit in interhemispheric object tracking compared to within hemifield tracking. However, her performance in interhemispheric tracking was well above chance level. As discussed in the discussion part of experiment two, even the patient's awareness to the target destination hemifield cannot explain her observed performance in interhemispheric tracking. What mechanism is underlying this "above chance" performance?

In the third experiment, we hypothesized two possible mechanisms to explain the patient's performance. On one hand, we hypothesized that the patient could use very low level "temporal" signals to alarm the arrival time of the target interhemispherically just at the time of midline crossing. On the other hand, it was possible that patient's attentional mechanisms could rely on the low-resolution spatial integrity among the hemispheres to support a "spatial" attentive integrity at low resolution. As discussed in experiment three, results indicated that the patient's performance is not affected by temporal offsets between crossing time of the target and a given distracter (temporal theory predicts lower performance for simultaneous crossings). On the other hand, the proper

performance in the tracking task was strongly dependent to the vertical distance between the target and the co-target distracter. As previously shown, the spatial tracking is very sensitive to the distance between visual objects that need to be individuated from each other by spatial attention (Intriligator and Cavanagh, 2001). Results of experiment three make the "temporal signal theory" very unlikely and supports the spatial tracking hypothesis. Although introspection is not always informative, but subjective experience of MD during performing these tasks is congruent with results of the third experiment. She reported that tracking became difficult when other balls got closer to the target one or when the target became farther from the fixation point. She did not report using any non-visual strategy for the tracking or alignment tasks. Also she did not report any sign of discontinuity or even report of disappearance of target ball at the point of midline crossing or any other point of the visual field in the tracking task.

If we assume the presence of a partial visual attentional integrity between hemispheres in the patient, what brain areas can provide it? Culham and her colleagues showed that attentive tracking is mediated by a network of areas that include parietal and frontal regions responsible for attention shifts and eye movements and the MT complex, thought to be responsible for motion perception (Culham et al., 1998). They observed bilateral activation in parietal cortex (intraparietal sulcus, postcentral sulcus, superior parietal lobule, and precuneus), frontal cortex (frontal eye fields and precentral sulcus) and the MT complex (including motion sensitive areas MT and MST) when they compared attentive tracking with passive viewing in their fMRI study.

In this study, we showed that splenium and posterior parts of corpus callosum which are interconnecting parietal and temporal visual areas are not necessary for tracking visual objects across hemifield. Other possible brain areas, which can be responsible for the observed attentional interactions, are frontal eye fields (FEF). Frontal eye fields are bilateral cortical areas that are interconnected by anterior parts of the corpus callosum (de Lacoste et al., 1985). Although their primary function is controlling eye movements (see Schall, 2002 for review), there are several lines of evidence revealing their involvement in top-down spatial attention (Moore and Fallah, 2001; Schall, 2004; Thompson and Bichot, 2005). In addition, microstimulation of frontal eye fields with very small electrical currents (below eye movement threshold) in monkeys will shift visual attention to the target field of the stimulated site (Moore and Fallah, 2004). The interconnection of frontal eye fields is intact in our patient and can be used for communication of spatial attentional systems of the two cerebral cortices. Repeating the same attentive tracking paradigm in patients with full callosotomy could yield valuable information about the role of frontal regions in visual spatial integrity.

Also, there is a possibility for involvement of subcortical visual structures in the mid-brain, such as superior colliculi, that are intact in our patient. Although the contribution of superior colliculi in visual attention is mostly shown in bottom-up attention tasks, top-down modulation of its response has also been shown, and it is suggested that this modulation is involved in the higher level target selection

process (Moschovakis et al., 1996; McPeek and Keller, 2002). In addition, it has been shown that microstimulation of the superior colliculi focuses attention without moving the eyes (Muller et al., 2005). Also previous experimenters have been suggested that remained integration of spatial attention in the split brain is controlled by subcortical (presumably collicular) mechanisms (Holtzman, 1984; Gazzaniga, 2000).

In summary, we suggest that resection of splenium differentially affects cross-hemifield visual integrity for various visual functions. And visual spatial integrity and visual spatial attention are partially spared in the absence of splenium.

3.   Experimental procedures

3.1.   Subjects

The split brain patient (MD) was a 25-year-old right-handed female who underwent a partial callosectomy surgery in 1996. She had an old scarring near the posterior part of her corpus callosum in the right hemisphere causing intractable generalized seizures. The scarred tissue and posterior parts of the corpus callosum were resected surgically to prevent seizures. Removal of the cicatricle led to transection of posterior parts of corpus callosum containing the splenium and trunk (Fig. 1). Just the anterior commissure and a small portion of the anterior part of the corpus callosum (containing rostrum and a small portion of the genu) remained intact.

Her generalized seizures are cured now, but she is still on low doses of anti-epileptic drugs. Clinical examinations did not show any neurological deficit in MD, except an occasional minor clumsiness in her left hand. She responded with her right hand in all experiments. Her visual acuity was normal. Threshold static automated perimetry did not show any deficit in her visual fields.
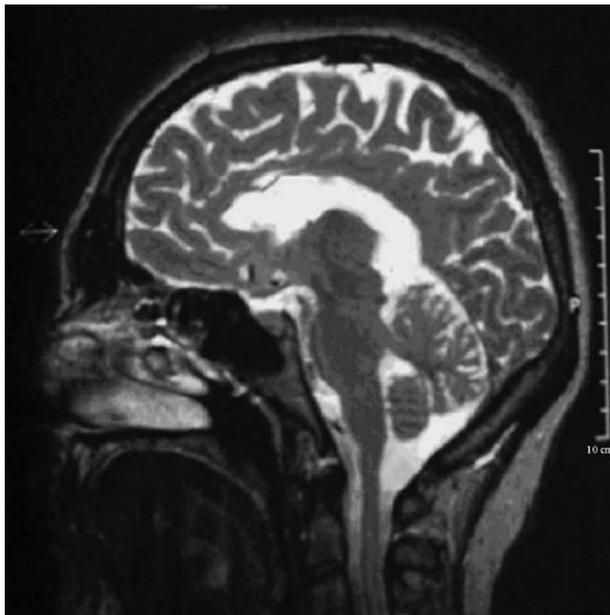
Fig. 1 – Sagittal T2W/TSE MRI section of MD's brain. The splenium and most of the corpus callosum are resected (filled with cerebrospinal fluid which is white for this MRI technique).

Normal controls were one right-handed male and two right-handed female subjects aged 24–29. All subjects participated voluntarily in experiments.

4.   Stimulus presentation setup

Images were displayed on a CRT monitor, 800 × 600 pixel resolution at 60 Hz refresh rate (17 in., 710 A, Hansol) using a Pentium III 633 MHz PC. Subjects were placed in a dimly lit room, and their heads were fixed on a chin and forehead rest. They viewed the displays binocularly. The distance between eyes and the screen was 57 cm. An infrared eye monitoring system was used for controlling the eye positions. A conventional computer mouse was used for response acquisition.

4.1.   Experiment I: alignment task

In this experiment, we investigated the capability of MD in comparing positions of two visual stimuli simultaneously presented to different hemifields. We used a modified version of alignment task used previously (Corballis and Trudel, 1993) to measure this capability.

We asked MD and three normal subjects to judge whether the two stimuli are horizontally aligned or not. We compared their performances when stimuli were presented in one or both sides of the vertical meridian. Their performance in this "misalignment detection task" was measured in three conditions: stimuli presented in right hemifield, left hemifield, or each in one hemifield.

4.1.1.   Methods

Visual stimuli were two small white balls (41.8 cd/m^2) 0.5° of visual angle in size. They were presented for 150 ms above a small bull's eye fixation point in a dark background (0 cd/m^2). Subjects were asked to fixate on the bull's eye and judge about the horizontal alignment of the stimuli and report it by pressing two mouse buttons with the index and middle fingers of their right hand. The two balls were positioned on the corners of an imaginary rectangle (Fig. 2) centered 6° away from the fixation point in the upper visual field. In the aligned condition, they appeared at the two top or two bottom corners; but in the misaligned condition, they were presented at the two diagonal corners. The horizontal side of this imaginary rectangle was always 4.5°. The size of the vertical side changed in a staircase paradigm during each block. This size was set at 16° at the beginning of each block. Regarding the subjects' responses in misaligned condition, the size of the vertical side halved following each correct response and doubled after wrong responses throughout the block. The maximum and minimum possible size of the vertical side was 16 and 0.5° respectively. Therefore, using such a staircase paradigm, the amount of misalignment of the two balls decreased gradually during each block, making the task more difficult for smaller sizes.

There were three conditions organized in separate blocks: one bilateral condition in which the center of the abovementioned imaginary rectangle (Fig. 2) was located on the vertical midline so that each stimulus fell in one hemifield, and two unilateral conditions in which the
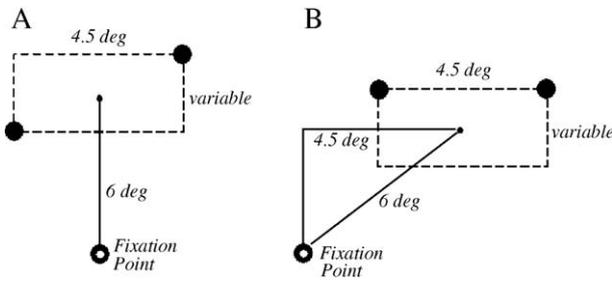
Fig. 2 – Presentation of stimuli in the first experiment is simulated by an imaginary rectangle in this figure. While horizontal distance between stimuli was constant during each block, their vertical distance was changed in a staircase paradigm. Panel A shows a misaligned trial in a bilateral condition, and panel B shows an aligned trial in a unilateral condition. All gray stuffs in this figure are just depicted here for better description and were not presented on the screen during the task.

center of the imaginary rectangle was placed 4.5° at the left or right of the vertical midline so that both stimuli fell within left or right hemifield. Each block consisted of 18 trials. Half of the trials in each block were misaligned, and the other half were aligned trials. The trials were presented in a pseudorandom order. MD performed 12 blocks for each condition. The same procedure was performed for three normal subjects. Each normal subject completed 6 blocks for each condition.

4.1.2. Results

Results of alignment task in bilateral and unilateral conditions are shown in Fig. 3 for both MD and normal controls. Since left and right unilateral results were not significantly different (logistic regression, Exp (B) = 0.838, $P = 0.390$), their data were pooled and were shown as an average in Fig. 3. MD's performance in spatial misalignment detection in the bilateral condition was well above chance level (50%) in most spatial offsets ($P < 0.05$ for all spatial offsets higher than 4°). However,

her performance in this condition was significantly lower than unilateral condition. Logistic regression shows significant effect both for spatial offset (Exp (B) = 1.304, $P = 0.001$) and presentation condition (unilateral/bilateral) of target stimuli (Exp (B) = 1.727, $P = 0.043$) on the MD's performance. In general, these results mean that MD could perform misalignment detection task in bilateral condition. Nevertheless, her visual–spatial resolution seems to be decreased comparing to unilateral presentations.

Normal subjects did not show any difference between the two presentation conditions (logistic regression, Exp (B) = 0.697, $P = 0.117$).

4.1.3. Discussion

Results of experiment one show that the split brain patient can perform spatial misalignment detection well above chance level in the bilateral presentation condition. This experiment provides a quantitative measurement of this ability in the absence of splenium. Our data are congruent with previous results of Corballis and Trudel which indicate above-chance transfer of orientation information in two split-brain subjects (Corballis and Trudel, 1993). The results clearly indicate that although the basic ability for spatial comparisons is saved in the absence of splenium, the resolution of interhemispheric spatial comparisons becomes much cruder. Normal subjects did not show any difference in misalignment detection performance between unilateral and bilateral presentations, thus, we suggest that the posterior corpus callosum provides rich interhemispheric visual–spatial communications that are necessary for misalignment detection at high resolutions. However, anterior parts of the corpus callosum, anterior commissure, and/or subcortical interhemispheric connections can transmit visual–spatial information between hemispheres at low resolutions.

The question arising here is whether such low-resolution interhemispheric channels of spatial information can be used for high level functions like visual spatial attention which require an explicit conscious access to the information of attended objects location? We examined this question in the following experiments.
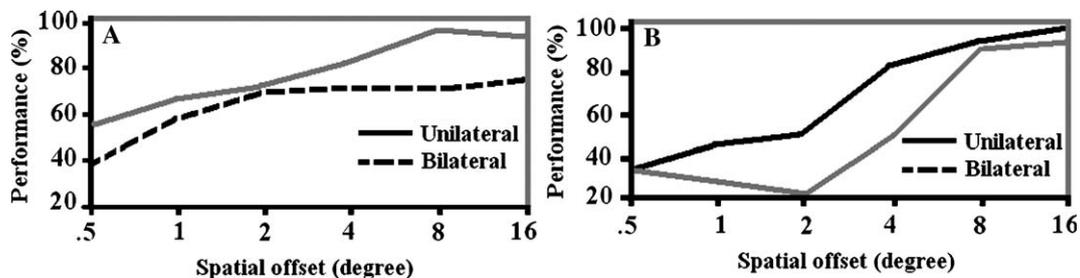
Fig. 3 – (A) Performance of MD in valid detection of spatial offset between two balls when they were both presented in one hemifield (solid gray line) is higher than when they were presented in two hemifields (dashed black line). Logistic regression shows significant effect both for spatial offset (Exp(B) = 1.304, P value = 0.001) and uni/bilateral presentation of target stimuli (Exp(B) = 1.727, P value = 0.043). (B) Performance of normal subjects in valid detection of spatial offset between two balls when they were both presented in one hemifield (red line) is lower than when they were presented in two hemifields (dashed green line). This effect is expected since in bilateral conditions the target stimuli were closer to vertical midline. Logistic regression shows significant effect both for spatial offset (Exp(B) = 1.131, $P = 0.000$) and uni/bilateral presentation of target stimuli (Exp(B) = 0.278, $P = 0.000$).

4.2. Experiment II: visual object tracking

Previous experiment showed that position information could be partially transferred between hemispheres in the absence of the splenium. It is still remained an open question whether the transferred crude position information could supply higher visual functions like spatial attention.

In visual object tracking explicit access to spatial location information of the tracked object is required. In this experiment, we asked our subjects, including the split brain patient, to attentively track one of the three identical moving objects when it was traveling across the vertical midline.

4.2.1. Methods

In this visual object-tracking task, subjects were asked to track one object among three. Objects were 0.5° white (181.1 cd/m2) "bouncing balls" moving for 10 s on a dark background (0 cd/m2). The balls were bouncing inside a rectangular frame 12 × 17° of visual angle (Fig. 4). Their motion direction and speed varied randomly throughout the trial so that subjects could not predict the motion trajectory of the stimuli. Tracked item was cued at the beginning of trial by its different color (yellow) which gradually turned white during the first 1 s of the trial. Objects did not cross over each other, and their minimal center to center distance was 1°, i.e., the distance between their margins was at least 0.5°. When the objects bumped to each other or to the borders of the frame, they simply bounced back and continued moving in their random trajectory.

The subjects were asked to track the cued object and keep on attentive tracking when it turned white until the end of the trial for the remaining 9 s. Throughout each trial, they were asked to keep their eye gaze on a fixation point, which was a small red bull's eye at the center of the motion field. Subjects had to maintain their fixation within a 1° × 1° window around the fixation point. Their eye movements were monitored using an infrared eye monitoring system. The importance of maintaining fixation was emphasized to subjects and trials with fixation errors were discarded from further analysis.

There were two different experimental conditions: in the uncrossed condition, the target started and ended its motion in the same hemifield without any midline crossing. In the crossed condition, target started its motion in one hemifield and crossed the vertical midline terminating its motion in the other hemifield. The target never crossed the midline during the cuing phase, and it became identical to other balls at least 3 s before the cross time. Each trial was randomly selected between two aforementioned conditions.

At the end of each trial, all the three stimuli stopped simultaneously. After 500 ms, their size doubled for convenient selection. Subjects were permitted to break their eye fixation and were asked to select the target item using the computer mouse cursor. Subjects were asked to click on the selected target with the index finger of their right hand. MD performed three blocks of 50 trials. Each normal subject completed two blocks of the same number of trials.

4.2.2. Results

As it is shown in Table 1 and Fig. 5, MD's performance in crossed condition was well above chance level (χ^2 (81, 1) = 41.524, $P < 0.001$). Chance level was set at 33.3% (tracking one among three). However, her performance in crossed condition was significantly lower than uncrossed condition (χ^2 (150, 1) = 4.922, $P = 0.027$).

It is possible that the split brain patient use an alternative strategy to compensate her information transfer disability. The patient may track the target in its starting hemifield up to the vertical midline and then just randomly select one of the objects in the other hemifield at the end of the trial. In other words, knowing the hemifield of the target could increase subject's performance by ruling out items on the opposite side. To deal with this problem, we compared the patient's performance in various crossed trials in which different number of stimuli exist in the target hemifield at the end of the trial. Her performance in crossed condition was not significantly different ($P > 0.1$) when various number of objects accompanied the target item in the destination hemifield (Fig. 6). This means the subject did not use an alternative strategy based on random selection of an object in the target destination hemifield.

To rule out the possibility that lower performance in crossed condition is due to other factors, such as larger tracking extent, we checked performance of three normal subjects in this task. The three normal subjects' performance in crossed (96, 87, 98%) and uncrossed conditions (87, 84, 93%) were not significantly different (Chi-square, $P = 0.147, 0.640, 0.646$).

4.2.3. Discussion

MD showed a lower performance when the tracked item crossed the midline, while normal subjects did not show significant difference in their performance in crossed and uncrossed conditions. But interestingly, she could track the crossed target item well above chance. This indicates that the spatial attentional systems in the two hemispheres did not
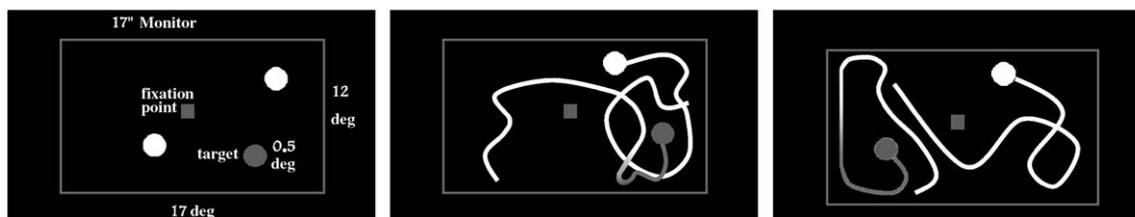
Fig. 4 – (Left panel) Schematic diagram of visual display which was shown to MD during the second experiment. (Middle panel) Schematic sample of paths of target (gray) and one distracter (white) ball in a crossed condition. The cued target gradually turns to white during the first second of the trial. (Right panel) Schematic sample of paths of target (gray) and one distracter (white) ball in an uncrossed condition.

Table 1 – Number of correct and wrong trials performed by MD for each condition in the first experiment					
Begin	End	Condition	Correct	Wrong	Total
Left	Left	Uncrossed	27	8	35
Right	Right	Uncrossed	30	4	34
Left	Right	Crossed	32	15	47
Right	Left	Crossed	22	12	34
Total			111	39	150

lose their communication, although this information transfer became impaired. This means that the transferred position information between the two hemispheres in the absence of the splenial connections can serve visual object tracking which needs explicit access to information about location information.

4.3. Experiment III: spatiotemporal interactions at the vertical midline

4.3.1. Introduction
In a visual object-tracking task, all objects' visual properties except their locations are identical, and the target object is differentiated from others just by an attentional tag which tracks the location of moving object during its motion. Such attentional pointers were referred to as "fingers of instantiation" (FINST) by Pylyshyn and his colleagues (Pylyshyn and Storm, 1988; Pylyshyn, 1989). Intriligator and Cavanagh (2001) described these pointers as small "attention windows" around tracked objects. They quantitatively showed lower tracking performance when objects are spaced closer to each other.

The question arising here is whether the attentional pointer is transferring properly and continuously between hemispheres – in our split brain patient – when the target object crosses the midline. The other possible mechanism is that one hemisphere tracks the target object properly up to the vertical midline and then alarms the arrival "time" of the target item to the other hemisphere by a simple binary signal, so that the destination hemisphere takes the first "incoming" object at that time and tracks it as "target" until the end of trial. This strategy may work based on "binary signals" at a certain time rather than holding an "attentional space selection label" on the target at the crossing moment. As suggested by Forster and Corballis, such binary signals may conceivably be developed by rapid external
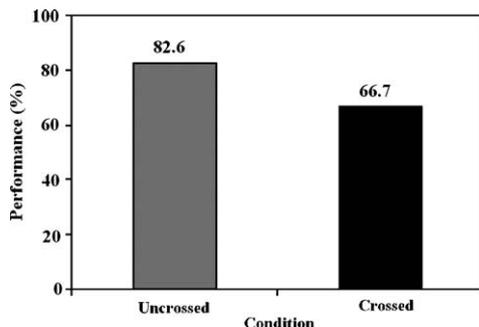
Fig. 5 – Comparison of MD's performance in crossed and uncrossed conditions at the second experiment.
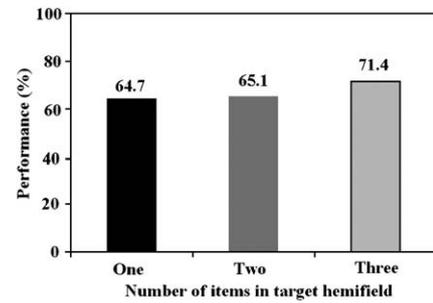
Fig. 6 – MD's performance for different crossed conditions when at the end of trial (response phase) different number of distracters accompanied the target stimulus in its hemifield. Horizontal axis indicates number of items in the hemifield of the target stimulus ranging from one (only the target stimulus was in one side) to three (all items were terminating their motion in one hemifield).

cross-cueing; for example, a binary decision might be signaled interhemispherically by raising or lowering the tongue (Forster and Corballis, 2000). Also using cross-cuing strategy could not be ruled out for the first experiment. One may claim that in the first experiment, the disks were presented at the corners of an imaginary rectangle centered at 6° from fixation. Perhaps MD could judge whether one of the disks was above or below 6°, communicates this position (above or below) with a cross-cuing strategy and then compares this signal to the position of the other disk. We designed the third experiment to rule out this possibility.

The "arrival time alarming" explanation predicts lower tracking performance in the case of simultaneous crossing of two objects (the target and a non-target object) across the midline. This explanation suggests a systematic increase in tracking performance when the difference between the crossing times of the two objects increases. On the other hand, in the case of transferring the attentional label properly between the two hemispheres, we expect that spatial distance between the crossing objects and not the temporal offset between the crossing of the two objects influence the tracking performance.

In this experiment, we asked the subject to perform the tracking task, but this time, another non-target object (will be referred to as "co-target") accompanied the target about the time of midline crossing. By analyzing the performance of the subject in different spatial and temporal offsets between the target and co-target, we investigated the spatio-temporal characteristics of object tracking at the vertical midline.

4.3.2. Methods
We asked the split brain subject to perform the same task as in the second experiment but this time with five bouncing balls, i.e., tracking one among four distracters (non-target balls). In addition, one of the distracters (co-target) crossed the vertical midline approximately the same time when the target crossed. The motion of this co-target was determined in a pseudoran-dom algorithm so that it accompanied the target ball in its
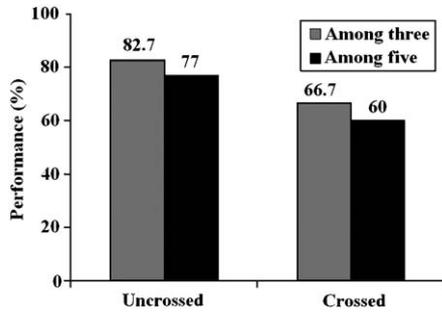
Fig. 7 – Comparison of MD's performance when she was asked to track one item among three or five objects when target item was crossing the vertical meridian (Crossed) or did not cross (Uncrossed).

Fig. 9 – Cumulative number of selection of presented items as a function of vertical distance between target and co-target at the point of midline crossing. It shows that most of the patient's errors are false selections of co-target item rather than other distracters and when the spatial offset between the target and co-target increases, the patient can resolve the target much better from the co-target. Dotted line represents average of cumulative count for all other three distracters.

midline crossing with different spatial and temporal offsets in spite of their different trajectories. Their spatial offset was defined as the vertical distance between the midline crossing positions of the target and co-target objects. Also their temporal offset was defined as absolute time difference between midline crossing times of target and co-target objects. To avoid artificial appearance of the co-target motion, the time of midline crossing was not completely the same as the target. MD performed 238 trials in this paradigm. We will refer to these trials as "co-target condition". Also she performed 136 more trials without any of distracters accompanying the target on the midline. These trials will be called "normal condition".

4.3.3. Results

For the normal condition, consistent with the second experiment, MD's performance in crossed condition was well above chance, the chance level being at 20% (χ^2 (112, 1) = 22.681, $P < 0.001$) or 29% (χ^2 (112, 1) = 4.799, $P = 0.028$) depending on the number of items in the destination hemifield (see Results section of experiment two). However, MD showed a lower performance in crossed conditions in comparison with uncrossed ones (χ^2 (136, 1) = 4.258, $P = 0.039$) (Fig. 7).

Results of the co-target condition show a significant decrease in tracking for crossed trials (average performance = 38%) in comparison with crossed trials of normal condition (χ^2 (175, 1) = 7.796, $P = 0.005$). To look for the source of

this huge decrease in the patient's performance in crossed trials of "co-target" condition, we analyzed the effect of "temporal offset" and "spatial offset" between the target and the co-target on the patient's performance using a logistic regression analysis. Interestingly, there was no effect of the temporal offsets of target and co-target on MD's performance (Exp (B) = 0.999, $P = 0.498$) while the spatial offset was found to be the determining factor in her performance (Exp (B) = 1.005, $P = 0.006$). As shown in Fig. 8, MD's performance increased when the spatial offset increased, but temporal offsets did not show the same effect.

Fig. 9 plots cumulative frequency of clicking on a ball – as the target – as a function of spatial offset in crossed trials of
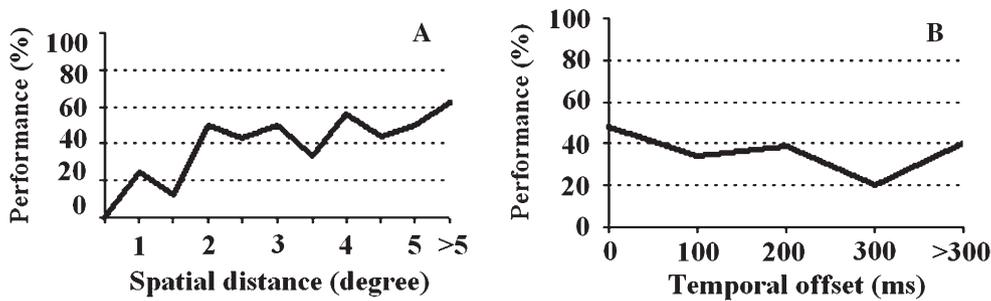
Fig. 8 – MD's responses shows different roles for spatial and temporal interactions between the target stimulus and the accompanied distracter (see the text). (A) As it is expected, the spatial distance between them influences the performance (Exp(B) = 1.005, P value = 0.006). (B) But temporal offset in the time of crossing the vertical meridian shows a non-significant effect (Exp(B) = 0.999, P value = 0.498).

co-target condition. This graph shows that wrong selection of the co-target is more probable than other distracters. Also, it indicates that in low spatial offsets, the patient mixed up the target and the co-target together. As the spatial offset increased the patient discrimination of the target from the co-target improved. Logistic regression shows that mistakes in discriminating target from co-target decreased as spatial offset was increased (Exp (B) = 0.994, P = 0.029) while variation in temporal offset does not affect it (Exp (B) = 0.997, P = 0.988).

4.3.4.   Discussion

Presence of a distracter (co-target), when it accompanied the target at the crossing moment, had a remarkable effect on the tracking performance. Tracking performance increased as a function of vertical spatial offset between the target and the co-target. Further analysis of spatiotemporal relations between the target and co-target revealed that the tracking performance was affected by the spatial parameters and not by the temporal ones.

These results indicate that the attentional selection mechanisms in the destination hemisphere have some crude information about the target location that leads to miss selection of the co-target instead of other distracters when it was placed close to the target at the crossing moment. On the other hand, results of the third experiment imply that "arrival time alarming" is the less probable explanation underlying the capability of the split brain patient in tracking visual objects across hemifields. The patient can perform the task in low temporal offsets as well as high temporal offsets (independent from spatial offset). This means that the patient does not perform the task on the basis of low level binary signaling of the target "crossing time".

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