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Virtual reality applications for the remapping of space in neglect patients

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Abstract. *Purpose:* The aims of the present article were the following: (i) to provide some evidence of the potential of virtual reality (VR) for the assessment, training and recovery of hemispatial neglect; (ii) to present data from our laboratory which seem to confirm that the clinical manifestation of neglect can be improved by using VR techniques; and (iii) to ascertain the neural bases of this improvement.
Methods: We used a VR device (DataGlove) interfaced with a specially designed computer program which allowed neglect patients to reach and grasp a real object while simultaneously observing the grasping of a virtual object located within a virtual environment by a virtual hand. The virtual hand was commanded in real time by their real hand.
Results: After a period of training, hemispatial neglect patients coded the visual stimuli within the neglected space in an identical fashion as those presented within the preserved portions of space. However it was also found that only patients with lesions that spared the inferior parietal/superior temporal regions were able to benefit from the virtual reality training.
Conclusions: It was concluded that using VR it is possible to re-create links between the affected and the nonaffected space in neglect patients. Furthermore, that specific regions may play a crucial role in the recovery of space that underlies the improvement of neglect patients when trained with virtual reality. The implications of these results for determining the neural bases of a higher order attentional and/or spatial representation, and for the treatment of patients with unilateral neglect are discussed.

Keywords: Visual neglect, rehabilitation, virtual reality, reach-to-grasp, space remapping

1. Introduction

Unilateral neglect is a common consequence of damage to the right hemisphere in humans [1]. The syndrome of neglect is characterised by a failure to respond to stimuli in the contralesional half of space, with patients often behaving as if these stimuli do not exist. Although neglect is most commonly seen after damage involving the right inferior parietal lobe near the temporal-parietal junction, it may also occur after damage to the frontal lobes, temporal lobes, or subcortical structures [1]. The real life implications of neglect can be devastating, with patients failing to eat food off the left side of the plate, only dressing the right half of their bodies, and often being unaware of half of their world. Understanding the functional and neurological bases of unilateral neglect has been an imposing task and in recent years several promising advances have been made in its treatment as reviewed by various authors within this special issue. Further, although improvements in unilateral neglect have been reported with a number of patients with various lesions, it remains to be seen precisely what spared tissue could be responsible for the recovery of space.

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Here we propose the use of virtual reality (VR) techniques as a mean for improving the visual representation of space deficits observed in hemispatial neglect patients and to ascertain possible neural loci for recovery. As explained below the impetus for using such techniques comes from recent VR applications which appear to be successful as to rehabilitate neglect.

1.1. Virtual reality applications and neglect

Virtual reality entails the use of advanced technologies, including computers and various multimedia peripherals, to produce a simulated (i.e., virtual) environment that users may perceive as comparable to real world objects and events. Users interact with displayed images, move and manipulate virtual objects, and perform other actions in a way that engenders a feeling of actual presence, and immerses their senses in the simulated environment. Virtual reality may be delivered to the user via a variety of different technologies (e.g., computer monitor, head-mounted display) that differ in their ability to determine a sense of immersion within the simulated environment. Until recently, the application of VR technology was limited by the lack of inexpensive, easy-to-maintain and easy-to-use VR systems, but recent technological developments have led to decreases in cost and increases in ease of use and in the availability of off-the-shelf programs.

An active area of research using VR is concerned with its use as an intervention tool in neurological rehabilitation [19,21]. In this respect, VR has the potential to assist current rehabilitation techniques in addressing the impairments associated with brain damage.

An essential part of the rehabilitation process is remediation of cognitive and motor deficits in order to improve the functional ability of the patient. The ultimate goal is to enable the patient to achieve greater independence in activities related to daily performance skills. In this respect, VR has the potential to be used as a novel modality in rehabilitation assessment and intervention due to a number of unique features. For one, the ability to objectively measure behaviour in challenging but safe and ecologically-valid environments, while maintaining strict experimental control over stimulus delivery. For another, the capacity to individualize treatment needs, while providing increased standardization of assessment and re-training protocols. Furthermore, virtual environments can provide repeated learning trials and offer the capacity to gradually increase the complexity of tasks while decreasing the support/feedback provided by the therapist.

Recently, a few attempts have been made to create VR environments which could be utilised for the rehabilitation of the neglect syndrome [13,26], but only a few experimental studies have been conducted. For example, Weiss and colleagues [27], see also [14] investigated the feasibility of using a PC-based, non-immersive VR system (i.e. a system in which the user has a reduced sense of actual presence in and control over the simulated environment) for training individuals with unilateral spatial neglect to cross streets in a safe and vigilant manner. A street crossing virtual environment was programmed as to run on a desktop computer, with successively graded levels of difficulty that provide users with an opportunity to decide when it is safe to cross a virtual street. The results indicated that the VR street crossing performance of neglect patients showed the effects of training. Specifically, there was improvement in the number of times participants looked to the left. More importantly, most patients made fewer accidents during the virtual street crossing. The results of this study clearly show that the VR intervention was effective both in terms of improving visual – spatial performance as measured in this study and for some improvement in the ability to cross a real street.

Kwanguk Kim and colleagues [11] deviced a virtual environment (VE) to assess and train unilateral neglect patients. This VE was composed by a branch road and a ball. A calibration and a main task were administered to patients. The patients' subjective visual middle line was measured during the calibration task whereas in the main task the participants had to detect the ball using their gaze (moving a small cross according to the subject's head motion). To measure the degree of visual neglect, the ball moved to a random direction with a specific velocity and distance. Visual and auditory cues helped the patients to detect the ball. The degree of difficulty was adjusted according to the result of the patient's achievement. The results suggest that in the VE patients could use a wider field of view. In particular, patients showed no difference in tracking the ball in both the right and left visual field.

All in all the above studies show that through VR programs it might be possibile to assess, train and rehabilitate hemispatial neglect. In the following sections we shall describe an experiment carried out with a VR methodology developed within our laboratory [3, 8] which might be used to rehabilitate neglect and to ascertain which brain areas might be implicated in such recovery. We created a real-time coincidence of the movement of the patients' real hand with the representation of a virtual hand moving within a virtual environment, so that the patient could be trained to use the virtual image of their hand to guide their real hand in the neglected space. The results indicate that after a period of training the patients coded in an identical fashion stimuli presented within the preserved and the neglected space.

2. Methods

2.1. Subjects

Subjects were six patients with left visual neglect following right hemisphere stroke (Table 1). Patients were classified on the basis of neurological assessment, behavioural observation, and standard clinical tests (Table 1). All patients were right-handed and had normal or corrected-to-normal vision with no signs of severe gaze palsy, dementia, or previous neurological illness. Lesions were confirmed by CT scan. Lesions were plotted (Fig. 1) using the template of Damasio and Damasio [4]. On the basis of lesion location we divided the patients into a dorsal fronto-parietal group (FP) and a ventral temporo-parietal group (TP). In addition three neurologically healthy control subjects were included. One-way analyses of variance (ANOVA) revealed that there was no significant difference ($F_{(2,2)} < 1$, ns) between the mean ages of the neglect patients for the FP group (69 years), the TP group (73 years) and the controls (73 years), or for the mean days after stroke for the FP and the TP neglect patients [FP: 59; TP: 58; $F_{(1,2)} < 1$, ns]. All subjects gave informed written consent before testing began.

The two groups of patients with neglect were well matched for degree of neglect (see Table 1). For example, on the star cancellation test the FP patients found a mean of only 17 targets (range, 12.2–21.2) out of 54, all on the right side of the sheet. Similarly, the TP patients found a mean of 13 out of 54 targets (range, 8–20), again all on the right side of the sheet.

2.2. Apparatus

The apparatus consisted of a monitor placed on top of a hollow box into which the subjects could reach (see Fig. 2). The computer screen was located approximately 50 cm from the subject's eyes. Vision of the reaching limb within the box was occluded by means of a black partition between the reaching limb and eyes. The targets for grasping consisted of either a) a real object (white polystyrene sphere 8 cm in diameter), resting on the table at a distance of 30 cm from a starting position located 20 cm in front of the subject, or b) a virtual object presented on the computer screen. The virtual object was an exact replica of the real object; its size was manipulated such that it had the same appearance as the target object for each given distance.

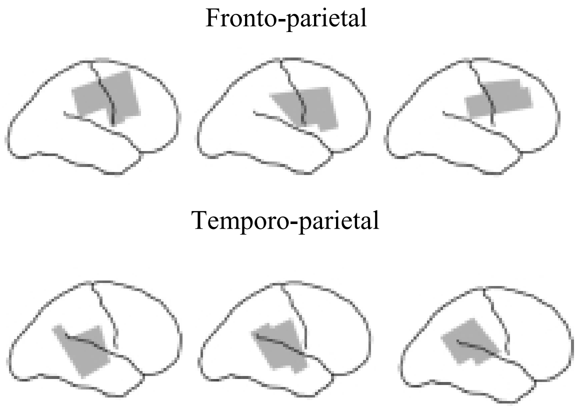

Fig. 1. Reconstruction of lesion location in the frontoparietal (FP) (top) and the temporo-parietal (TP) (bottom) patients who took part in this study.

2.3. Virtual reality devices and movement recordings

A data glove (Virtual Realities: Fifth Dimension Technologies, Irvine, CA) allowed the subjects to control the virtual hand that moved in real time within a computer-generated environment. The sampling rate was 200 Hz. All devices were operated via PC. We were able to resolve issues of real-virtual compatibility that can arise when the glove is worn by different subjects with different-sized hands. Reaching movements were recorded using a magnetic sensor placed on the wrist (Flock of Birds, Ascension Technology). Recordings of marker position were taken at 100 Hz, and stored in the computer for analysis offline. Following the testing, movement trajectories were computed from the stored data.

2.4. Procedure

Subjects sat at the table and reached to grasp either the real or the virtual object. As per Fig. 2, the real and virtual objects could be located either centrally (midsagittal plane), or 30° to the left or right of midline. The experiment was carried out in three sessions within the same day, one in the morning and two in the afternoon.

Table 1
Demographic and clinical data for the neglect patients who participated in the Experiment

Patient no.	Age	Sex	Lesion	Visual field	Post stroke (days)		Clinical tests		
							Line bisection test (mm)	Albert's line test (/36)	Star cancellation test(/54)
FP patients									
1	67	M	FP	Normal	56		12.2	15	13
2	69	M	FP	Normal	64		17.3	34	24
3	71	F	FP	Normal	58		21.2	26	14
						Mean	16.9	25	17
TP patients									
1	77	M	TP	Normal	59		10.8	22	8
2	70	M	TP	Normal	55		13.4	36	20
3	73	F	TP	Normal	61		18.7	32	13
						Mean	14.3	30	13

Notes. FP: fronto-parietal; TP: temporal-parietal.

2.4.1. Session 1: Baseline task

Subjects performed one of two types of task within either the real or virtual environment. An object (or its virtual counterpart) was presented in one of the three positions (midline or $+/-30°$ laterally), and in the 'sensory' task subjects were required to report the location in which the object appeared (left, right, or center). In the 'motor' task subjects had to reach out and grasp the object. Each participant performed four blocks, one of each combination of real/virtual and sensory/motor. The baseline task consisted of 10 trials at each location in each of four blocks. The total number of trials in the baseline task was thus 120. The experimental tasks were preceded by a block of randomly-determined 20 practice trials. Stimulus presentation was counterbalanced across participants.

2.4.2. Session 2: Training task

Subjects were required to reach for the real object located at one of the three locations within the real environment while simultaneously viewing the real-time virtual representation of the hand. While moving towards the real object, subjects observed the virtual hand moving toward the virtual object. This task consisted of two types of trial: a) congruent trials in which the real and virtual objects were spatially congruent (Fig. 3, top panels), or b) incongruent trials in which the real and virtual objects occupied different spatial locations (Fig. 3, lower panels). Crucial to the present study were the left incongruent trials (Fig. 3, panels f and g), in which the target was located to the left within the virtual environment whereas the real object appeared to the right or middle. We choose to give particular emphasis to this type of trials because we reasoned that the match between the 'good' proprioceptive input coming from the movement performed towards the object located in the preserved parts of the visual field (i.e., right and centre) and the visual input coming from the virtual hand moving towards the 'bad' portion of the visual field (i.e. left) would create a novel association. This novel association could be used later on to reach towards the 'bad' portion of space during the 'congruous left' trials and those incongruous trials in which a movement towards the real stimulus located on the left was required. Subjects performed 240 trials, 20 per each location/trial combination. Order of object presentation was counterbalanced. In order to avoid fatigue effects participants were given a 5 min. rest every 60 trials.

2.4.3. Session 3: Post-training sensory task

Subjects were required to perform the 'sensory' task in virtual and real conditions as in Session 1 to measure the effect of the training on performance of the sensory task.

2.4.4. Criteria for accuracy

Accuracy was analysed in the sensory and motor tasks (Sessions 1 and 3). Performance in the sensory task was considered correct when subjects successfully reported the location in which the object appeared within four seconds of its presentation. A correct movement was considered to be one in which the subject completed a successful reach and grasp, closing their hand around the target within four seconds of its appearance.

3. Results

3.1. Baseline tasks

For the baseline session (Session 1), the percentages of trials in which the object was successfully detected

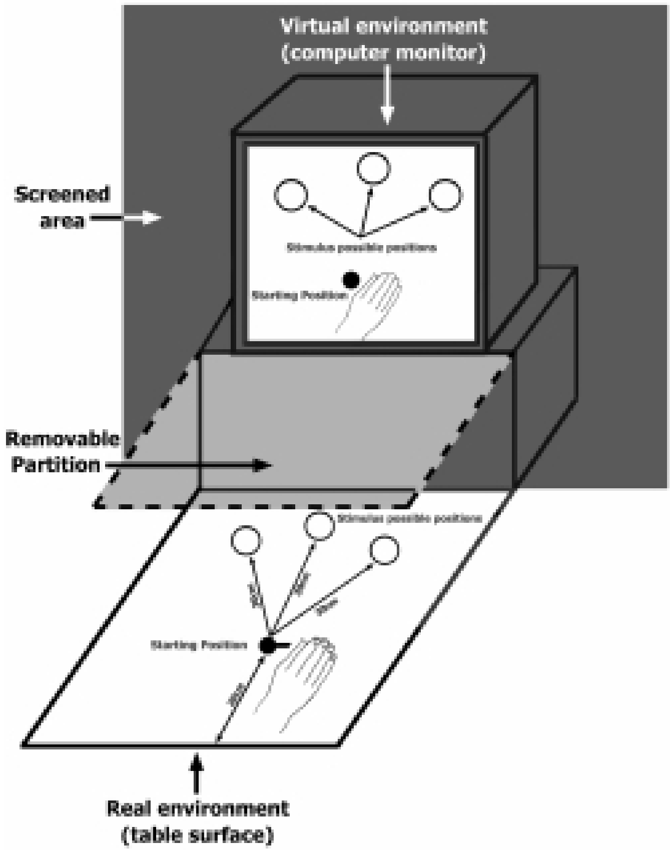

Fig. 2. Schematic of the experimental setup.

(sensory task) and in which the reaching movement was successfully carried out (motor tasks) were analyzed using ANOVA. The between-subjects factor was group (TP, FP, controls). The within-subjects factors were type of task (sensory, motor), environment (real, virtual), and location (left, middle, right). Post-hoc contrasts were performed using t-tests. Bonferroni corrections were applied (Alpha level, $p < 0.05$). For this analysis, the interaction group by location was significant ($F_{(1,2)} = 43.21, p < 0.0001$). Post-hoc contrasts revealed that both the FP and TP patients showed a clear inability to respond to leftward targets when compared to control subjects ($p_s < 0.01$). However, the performance for the neglect patients and the control subjects to targets presented to the right and to the centre in both the baseline sensory task and the baseline motor task was similar ($p_s > 0.5$). Similarly, for the right and the centre targets no differences in performance were found between the two neglect groups and the control groups ($p_s > 0.05$). These results confirmed the presence of similar severe unilateral neglect in both groups of patients prior to training with VR (see Fig. 4).

3.2. Training task

During the training task subjects were exposed to the spatially congruous and spatially incongruous trials (see Fig. 3). An ANOVA was carried out to test the effect of the left-incongruous trials (see Fig. 3f and 3g) on the performance for the left-congruous trials (see Fig. 3a) and the center-incongruous and right-incongruous trials (see Fig. 3d, 3e). In these latter two types of trials a movement towards the real stimulus located on the left was required. For this analysis the data for left-congruous trials and for center-incongruous and right-incongruous trials were divided based on occurrence (before or after) relative to the left-incongruous trials. Though the exact number varied,

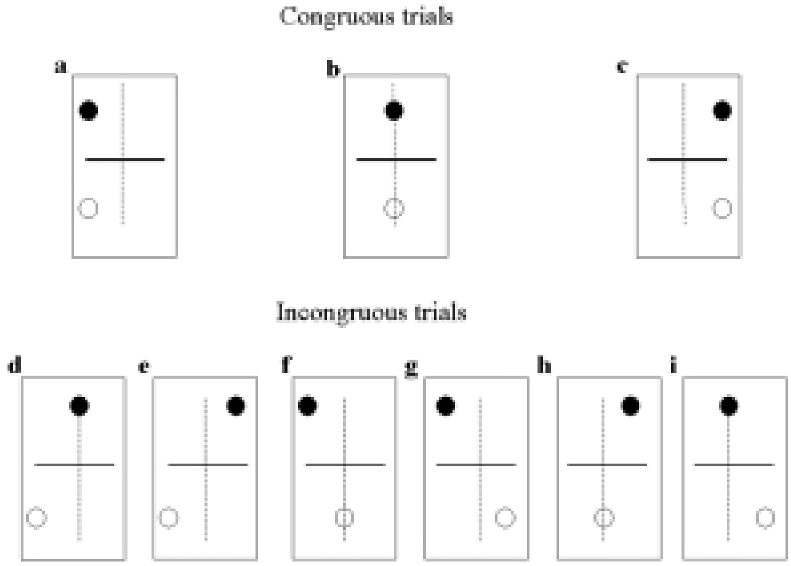

Fig. 3. Schematic of the various trial types in the training task. Virtual targets are shown as black circles, real targets as white circles. The top three panels represent congruent trials in which the location of real and virtual targets matched. The bottom six panels represent incongruent trials in which the locations of real and virtual targets did not match. The crucial left incongruent trials are represented in the third and fourth panels from the left – bottom row.

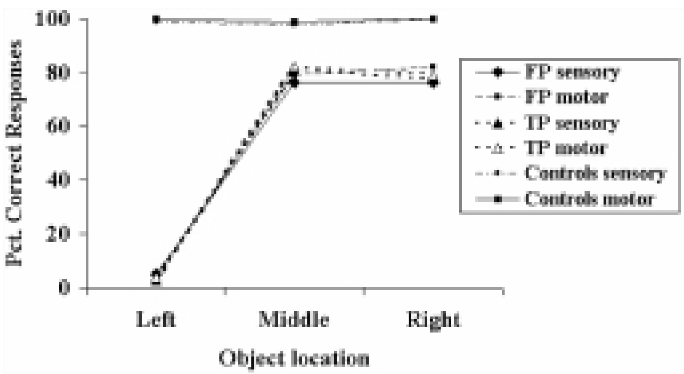

Fig. 4. Performance of patients and controls in baseline sensory and motor response tasks, real environment only. Percentage of correct responses is plotted as a function of group, location and task.

all subjects experienced at least 8 left-incongruous trials before the left-congruous, center-incongruous, and right-incongruous trials. Here, the between-subjects factor was group (FP, TP, controls) and the within-subjects factors were type of trial (congruous, incongruous), occurrence (before training vs. after training), and location (left, middle, right). Post-hoc contrasts were carried out using t-test. Bonferroni's corrections were applied (Alpha level $= p < 0.05$). The interaction between group, occurrence and location was significant ($F_{(1,2)} = 23.18$, $p < 0.0001$). Post-hoc contrasts revealed that there was a clear dissociation in performance for the training tasks for the FP and the TP patients (see Fig. 5). That is only the FP group show a significant improvement in their responses to leftward targets after training ($p_s < 0.01$). The lack of interaction between the main factor type of trial and the other measures signifies that the increase in percentage of correct responses for left trials was similar for both congruous and incongruous trials. In contrast, the TP group failed to show any signs of improvement after having experienced the left-incongruous trials ($p > 0.05$). Figure 5 shows that patients in the TP group hardly move at all towards the leftward target whenever it appeared on the left in virtual space, and failed to attain the leftward target even when it appeared in the central location in virtual space. The administration of right – and centre – incongruous trials did not bring to any sign of improvement on the performance for subsequent leftwards trials (congruous and incongruous; $p_s > 0.05$). Post – hoc analysis revealed also that there were no differences in the performance for the control group between congruous and incongruous trials, regardless of whether they experienced the incongruous left trials.

3.3. *Post-training sensory task*

In order to verify that an improvement also occurred for tests that did not require a motor response, in a third session FP and TP patients were asked to repeat the sensory task performed in the first session within the real space. This took place 1–2 hours after the training session. An ANOVA with group (FP, TP) as between subjects factor and session (first and third) and location (left, centre and right) as within-subjects factors was performed. The three way interaction group by session by location ($F_{(1,2)} = 24.12$, $p < 0.001$) revealed that the percentage of correct responses for the left trials was significantly greater for the third session than for the first session only for the FP group ($F_{(1,2)} = 24.12$, $p < 0.001$; 5% vs. 83%). No improvement was noticed for the TP group (4% vs. 5%; $p > 0.5$). This suggests that exposure to left-incongruous trials also had an effect on the perceptual component of neglect, but only for the FP group (Fig. 6).

4. Discussion

We examined the effect of VR manipulation in patients with left neglect. After being exposed to a certain number of trials in which the virtual object was located to the left within the virtual environment and the real object appeared to the right or in the middle in the real environment (i.e., left-incongruous trials), neglect patients were subsequently able to reach toward objects located to the portion of space of which they were previously unaware (i.e., the left hemifield). These results show an active process stimulated by VR resulting in the recalibration of visuomotor coordination and the ability to act on the organisation of high levels spatial representations such as those usually impaired in patients with visual neglect.

Further, the present study addressed the issue of the neurological bases of space recovery in unilateral neglect. We observed that patients with fronto-parietal lesions (the FP group), sparing the posterior inferior parietal and superior temporal regions, were able to acquire the ability to respond into the left visual field. However, this benefit did not accrue to patients with damage involving the posterior IPL and superior temporal lobe (the TP group). We now discuss these results in terms of the putative representational functions of areas of the posterior half of the brain.

To address this issue, it is worthwhile to consider what processes are required in the recovery of space and to examine what regions of the brain might subserve these processes. Bearing in mind that recovery of space can also occur after vestibular [2] and somatosensory stimulation, the most likely candidate would be a region that represents space in a multimodal fashion. At least two such areas are known to exist in the human brain, namely the prefrontal cortex and the posterior parietal cortex. Yet, only the latter area was affected in any of the patients studied here.

The inferior parietal lobes in humans acquire multimodal information from all of visual, somatosensory, and auditory senses and have been hypothesised to represent a region of higher order spatial representation [5, 12,17]. This region thus seems uniquely poised to perform a major role in the function of recovering space. Note also that in both the present and past studies, the recovery of space effected through a motor task has transferred rather easily to other, more sensory-based tasks (e.g., verbal response). This supports the contention that the recovery of space is at an attentional or representational level rather than a purely motor or purely perceptual level.

A second alternative explanation might be that damage to cells in the IPL region of the TP group remotely affected the functioning of cells in the SPL as a consequence of the intimate connectivity of these two regions [15,25]. This in turn may have impaired the SPL in what might be its normal function. Indeed, it is well known that naturally occurring brain damage can have effects on brain areas outside of the lesion [10]. However, if one accepts this contention then it becomes difficult to explain why damage to the premotor cortex in the FP group did not also lead to such a disruption, given that it also possesses strong connections with the SPL [16]. Further, both groups of patients showed intact on-line monitoring and control of their movements once initiated, a function ascribed to the SPL [7,9,18, 22], suggesting that at least one major function of the SPL remained intact. Thus, we are also confident in dismissing this argument.

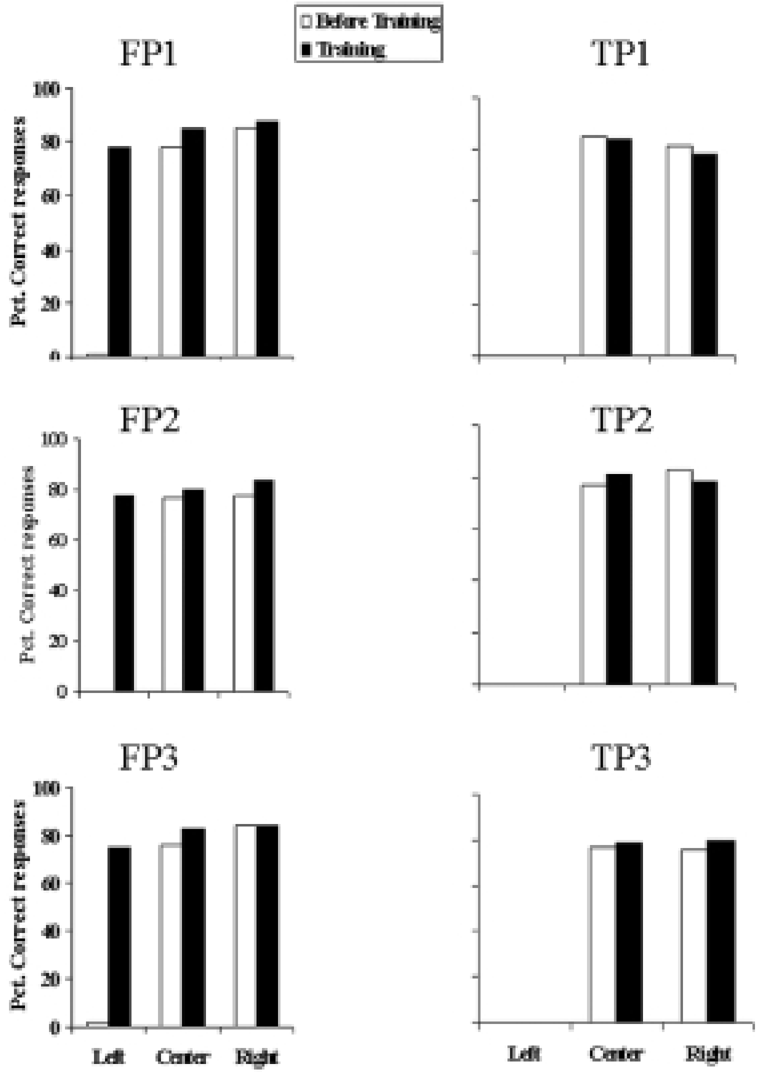

Fig. 5. Performance in the motor task prior to and after training. Correct responses to targets presented on the left, in the center, and on the right are plotted in the baseline (white bars) and post-training (black bars) sessions for individual patients in the FP (left column) and TP (right column) groups.

We suggest that the regions damaged in the TP group may play a crucial function in the specification of a target for an upcoming action in conjunction with attentional processes. In neglect, attention is typically diverted to the ipsilesional visual field and stimuli in the neglected field are ignored as targets for action. When these same stimuli are made to appear in central space, however, the attentional premotor requirement of target selection is enabled, allowing for the stimuli to be coded as the target of an upcoming action. However, when the inferior parietal/superior temporal regions are damaged, the result is an inability to recruit a motor plan for acting in the left side of space, despite the fact that the stimulus is now present in central vision.

The results of the present study suggest that attempts to treat unilateral neglect may be much more beneficial to those patients whose lesions spare the posterior IPL and possibly the superior aspects of the temporal lobe. A concern with this claim relates to the findings of previous studies involving attempts to improve unilateral neglect using prism adaptation [6,20,23]. In those studies, involving a similar shift in the perception of space as we engendered with our VR paradigm, some patients with temporo-parietal lesions did show improvements following training. Of those studies, precise localisa-

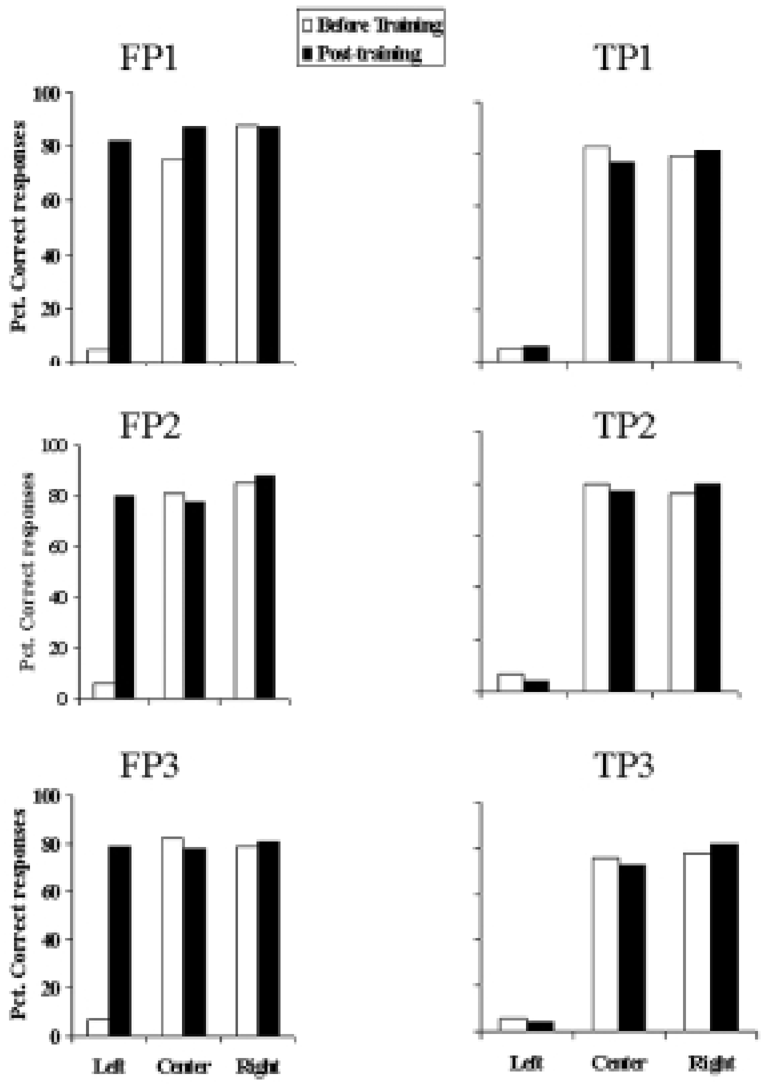

Fig. 6. Performance in the sensory task prior and after training. Conventions as in Fig. 5.

tion was only reported in Frassinetti et al. [6], however, in that case two of three patients whose lesions included the IPL did improve following training with prisms. One reason for the discrepancies across studies may have been the difficulty of the motor tasks involved (pointing in the prism studies versus reaching and grasping in the present study), or some more basic difference between the two techniques themselves. It would be beneficial to test our findings using larger samples of neglect patients, as well as to examine patients with varying lesion locations, and using different techniques, for the purpose of further clarifying these issues.

The question may also be raised as to why the VR training only led to improvement for leftward targets and not for targets presented in the center or right side of space. We suggest that the improvement in the former case resulted from the requirement to make movements into the previously neglected left side of space. Conversely, movements to the center or right side of space were not a novel occurrence, and so did not affect the ability to respond to these targets. Along these lines, it might be hypothesised that the VR training created a coincidence of the movement of the real hand and the hand's virtual image, allowing us to 'train' the patient to use the virtual image to guide their real hand in neglected space. This would presumably result in the formation of novel neural circuitry governing a novel mode of visuo-proprioceptive integration.

5. General conclusions

We here tested the ability of patients with unilateral neglect to recover space with the aid of virtual reality. The results of the present study suggest that space-recovery techniques such as virtual reality may lead to at least temporary relief for patients suffering from unilateral neglect. However, the usefulness of these techniques may depend, at least in part, on the integrity of structures in the inferior parietal/superior temporal lobe of the right hemisphere that may play a critical role in higher order attentional and/or spatial representation. Whereas FP patients showed a dramatic improvement in both motor and perceptual performance following training with virtual reality, TP patients did not benefit from the very same training. These results suggest that the recovery of space required for the recalibration of motor and perceptual responses into a neglected visual field may depend on the integrity of a multimodal attentional and/or spatial representation region in and around the right inferior parietal lobe. As the present study represents the first attempt to localise the areas responsible for the recovery of space, any conclusions reached must be cautious ones. Future studies using techniques such as virtual reality and prism adaptation will undoubtedly be needed to shed more light on both the treatment of neglect and the neural substrates responsible for its efficacy.

An important question is whether the improvement in the patients who took part in the current studies is transient or sustained. Various rehabilitation procedures using single applications of a variety of methods (caloric stimulation (e.g. [24]), neck vibration (e.g. [2]), optokinetic stimulation) have resulted in improvements lasting only a few minutes. Conversely, prism adaptation techniques can lead to improvements ranging from 2 hours to 5 weeks [6,23]. The patients of this study were given a pause ranging from 1 to 2 hours between the crucial second VR session and the final session in which the adaptation effects were still evident. Thus, we can be quite confident that the period of improvement produced by our VR manipulation lasted at least as long as the shortest period reported following prism adaptation and longer than the few minutes reported using other techniques. This suggests that VR techniques can potentially lead to long-lasting improvements in neglect patients, although the exact length of the amelioration will require further investigation.

Acknowledgements

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The presented data are part of a data set which has been published in full elsewhere (see [8]).

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