Multimodal Virtual Reality Application for the Study of Unilateral Spatial Neglect

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\textbf{ABSTRACT}

In the present paper, we describe a virtual reality application developed for the study of unilateral spatial neglect, a post-stroke neurological disorder that results in failure to respond to stimuli presented contralaterally to the damaged hemisphere. Recently, it has been proposed that patients with unilateral spatial neglect experience sensorimotor decorrelation in the affected space. Consequently, it is possible that since the sensorimotor experience in the affected space is perturbed, patients avoid this space, which results in neglect behavior. Here, we evaluate this hypothesis using a virtual reality application built on the base of the Stringed Haptic Workbench, a large-scale visuo-haptic system. The results provide support for the hypothesis and demonstrate that the proposed application is suitable for the envisioned goal.

\textbf{Keywords:} spatial neglect, multimodal virtual environments, neurological disorders, visuo-haptic display.

\textbf{Index terms:} H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems -- Artificial, augmented, and virtual realities; J.3 [Life and Medical Sciences]: Health; J.4 [Social and Behavioral Sciences]: Psychology.

1 INTRODUCTION

Unilateral spatial neglect (USN) is defined as the inability to respond to or orient towards stimuli located in the space contralateral to the damaged hemisphere, where these symptoms are not due to primary sensory or motor deficits. This disorder is found in almost 50\% of right-hemisphere damaged patients and the presence of USN in these patients has a well established negative impact on functional recovery \cite{1}. Patients with USN display a wide range of functional spatial deficits, such as bumping into objects while walking and dressing only one side of their body. In clinical tests, they frequently draw only one side of objects and bisect lines with large lateral biases (see Figure 1).

In last 30 years, different rehabilitation techniques have been proposed, however, none of them could completely rehabilitate USN \cite{2}. Understanding the causes of USN can greatly advance the development of new rehabilitation methods. Recently, Chokron et al. \cite{2} proposed that USN patients experience sensorimotor decorrelation in the contralesional space. Accordingly, patients’ sensorimotor experience in the contralesional space is perturbed due to the inability to link perception to actions. Consequently, spatial biases in USN could be the result of patients’ avoidance of the perturbed space.

This new hypothesis can be tested in healthy adults by perturbing sensorimotor actions in one hemisphere and measuring the resulting change in spatial perception (healthy populations are often used to study USN \cite{3}). Perturbations could be introduced as variable haptic or/and visual distortions making the task hard if not impossible to complete. Although, this experimental design is difficult to implement in a real environment, virtual reality (VR) could be used to provide a suitable system.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{An example of a patient with left USN performing (A) a copying task and (B) bisecting a line. Both tests indicate a strong rightward bias.}
\end{figure}

Here we describe an application built on the basis of the Stringed Haptic Workbench\cite{4}, which allows designing experiments with perturbed sensorimotor stimulation. An experiment is performed using our application in order to test the hypothesis that spatial biases typical to USN could result from avoidance of perturbed sensorimotor experience in one hemisphere.

2 RELATED WORK

2.1 VR in the assessment and rehabilitation of USN

Three main interconnected domains of VR applications for USN can be identified: assessment, rehabilitation and theoretical study. The first two domains have seen some development in the past years (see \cite{5} for a comprehensive review) but to our best knowledge, until now, no study proposed a VR application designed specifically for theoretical study of USN.

Several interesting applications were designed to rehabilitate USN. For example, a desktop application was proposed to extend action from unaffected to affected space in USN patients \cite{6}. The system includes a monitor and a data glove to control the motion of a virtual hand. Patients reach and grasp a real object while observing the grasping of a virtual object by a virtual hand. The remapping of space is induced by an incongruent trial in which the virtual object is located to the left of the center while the real one is in the center or to the right. After a period of adaptation with the application, improvement in spatial biases is observed.

Baheux et al. \cite{7} proposed a VR environment which combines visual, haptic and audio devices and provides eye, head and hand tracking. It consists of a virtual world where patients can interact with a 3-D rotating sushi bar using a PHANTOM. Audio and visual cueing is provided to direct the patients’ attention towards the goal. This application can be used to train patients in simple spatial tasks and to assess their level of impairment.

Several studies proposed VR techniques for diagnosis of USN using head mounted displays (HMDs) \cite{8, 9}. They use the standard USN assessment tasks such as line bisection and object naming in a computerized form. The head and eye tracking...
capabilities are used to detect any abnormalities in head orientation and search patterns. This allows characterizing the spatial deficits of each patient better. Moreover, visual cues are given in some of the applications in order to direct subjects’ attention suggesting a possible rehabilitation technique.

A novel assessment technique using a virtual wheelchair was proposed by Buxbaum et al. [10]. The subjects had to navigate the virtual wheelchair through a VR environment displayed on a large screen, while naming the objects seen on the sides of the road. This test shows good predictability of navigation dysfunction and sensitivity to mild USN, which is not detected on conventional pen and paper tests.

2.2 Visuo-Haptic VR systems

Majority of visuo-haptic VR applications designed for USN use small-scale systems combining a computer display with a haptic device such as the PHANToM [5]. The disadvantages of such systems are the obstruction of the visual input by the body of the haptic devices and the small operational space. Using large-scale displays can solve the latter problem. Several such systems integrating large-scale haptic and visual displays were proposed. The displays used in these systems are either projection-based such as CAVEs [11], workbenches [12] or HMDs [13]. Single screen workbenches can be combined with PHANToMs installed above the screen in an upside down fashion [14, 15]. These setups allow collocation of the visual and haptic space, however the size of the haptic working space is smaller than that of the visual working space, and the body of the PHANToM obstructs the view. Similar problems are found in a setup with a large display and an Argonne ARM [16]. In other cases, haptic devices such as the PHANToM and the Cybernet Spacepen are positioned beside the large visual displays, resolving the problem of occlusion, but as a result co-location is not achieved [17, 18].

The integration of HMDs and large-scale haptic devices is easier to accomplish since the devices are hidden from the user [17]. Moreover, due to the small size of the HMDs, the haptic devices can be positioned in front of the user, thus allowing for co-location. However, many HMDs provide a limited field of view, smaller than that of large projection-based displays.

The Stringed Haptic Workbench [4] resolves the problems of co-location gracefully. It combines a two-screen workbench [12] with the SPIDAR [19], a string based haptic device. The visual and haptic working spaces are co-located and are of comparable size. Moreover, the lightweight nature of SPIDAR prevents occlusion of virtual objects.

3 SENSORIMOTOR STIMULATION APPLICATION

To evaluate the hypothesis on the cause of USN presented in the Introduction we wanted to use a simple sensorimotor task, perturbed by variable haptic and/or visual distortions. Such a task is difficult to design in a real environment; hence we searched for an appropriate VR system with the following properties:

- First person viewpoint and stereovision - to make the experience as close to the real world as possible.
- Visual and haptic information – to create a multimodal environment, which provides profound sensorimotor stimulation.
- Co-location of the visual and haptic operational spaces – to simulate sensorimotor activity veridically and to avoid effects caused by the dissociation of the visual and motor spaces.
- Large field of view and working space – to allow extensive exploration of space.

The Stringed Haptic Workbench fulfills all these criteria. Using this system we built an application for the evaluation of the perturbed sensorimotor experience hypothesis and for any further questions built on the basis of this hypothesis.

Figure 2. Our application in use. The subject is tracing a line appearing left-to-right on a surface using a mixed-prop shown in detail in the inset. The real part held in the hand is a Fastrak stylus and the virtual part is a ray shooting out of the tip of the stylus.

3.1 VR System

The Stringed Haptic Workbench we used is described in detail elsewhere [4, 20]. To make the VR interaction as natural as possible we used a prop to simulate a writing device in conjunction with the SPIDAR. However, props can occlude the virtual objects in the scene. Hence we used a mixed-prop [20] that consists of a Fastrak stylus attached to the SPIDAR, and a virtual ray shooting out of the stylus. Together the mixed prop represents an elongated writing stick.

Using the Fastrak stylus as a prop solves another problem in our application as it also provides tracking of both position and orientation of the hand. The SPIDAR can track the hand as well, however since only four strings are used (for translational forces) only the position information is available from the SPIDAR. The orientation of the mixed-prop is needed to compute the exact position of the mixed-prop tip, which interacts with the rigid writing surface. Hence, we used the Fastrak coordinates to properly synchronize the haptic feedback with the movements of the virtual tip of the mixed-prop.

The head position and orientation is tracked with a small Fastrak receiver attached to the stereo goggles. Another small receiver is placed on the subject’s shoulder to track the trunk rotation.

3.2 Application details

The task employed in our application is a simple sensorimotor task where users have to trace a curved line, appearing gradually on top of a virtual surface (box), using the mixed-prop. The lines start appearing on one end of the surface and terminate on the opposite end. The users have to finish tracing the line before it disappears. The users feel the writing surface as rigid, due to the haptic feedback, and can see the trace they are creating (see Figure 2).

Variable haptic perturbations can be introduced to make the sensorimotor task hard to complete. The variability is created by randomizing the perturbations’ magnitude, type and duration.

The system logs the trace of the lines and head and shoulder positions and rotations to subsequently evaluate the effects the task has on the user’s posture and body orientation.

All the different options outlined below can be easily set in a configuration file, which is read by the software at start up. This
allowed non-expert personnel to use the application to run subjects in the psychophysical experiments.

3.2.1 Task lines

We chose Bézier curves to model the curved lines. The application allows controlling several parameters of the task lines: **The direction of the line** – the lines can appear left-to-right or right-to-left. This feature is useful for spatial variation of the sensorimotor adaptation. **The speed of the appearance of the line** – how fast the line appears on the surface. This allows the experimenters to control the speed of the movement of the subject’s hand. **The shape of the line** – the curvature, length and height of the curves can be adjusted as necessary. This option allows adjusting the difficulty of the task since curvier lines are harder to trace especially with haptic perturbations.

3.2.2 Haptic perturbations

The perturbations are created by applying forces using the SPIDAR haptic display. We implemented three types of haptic perturbations: **Vertical perturbations** – forces normal to the writing surface. **Horizontal perturbations** – forces parallel to the writing surface. **Friction-like perturbations** – forces applied only opposite to the direction of the movement of the line. The magnitude of the perturbation force is randomly chosen but does not exceed an upper limit. The application allows for several parameters to be adjusted as necessary: **Upper limit of the force** – it can be set offline and modulated online according to the location of the user’s hand. **Area affected by perturbations** – perturbations can be introduced in any part of the writing surface. **Types of perturbations** – all three types of force can be used separately or simultaneously. In the simultaneous mode, order and the duration of each type of perturbations is randomly selected.

4 INDUCING SPATIAL BIASES IN HEALTHY SUBJECTS USING THE APPLICATION

The application presented above was used in a complex experimental design aimed to induce spatial biases in healthy subjects. We wanted to test the hypothesis that spatial biases typical to USN could result from avoidance of perturbed sensorimotor experience in one side of space.

4.1 Experimental setup

4.1.1 Subjects

Fifteen healthy adults (7 f. and 8 m.), 23-38 years of age, participated in the study. All were right-handed and left-to-right readers and naïve as to the purpose of this study.

4.1.2 Procedure

Subjects participated in several sessions. Each session started with a pre-test. Next, the subject performed the sensorimotor stimulation task followed by a post-test, which was identical to the pre-test. This sequence (pre-test, sensorimotor stimulation, post-test) was repeated 3 times for each condition. The comparison of the pre-test and the post-test was used to reveal spatial biases induced by the sensorimotor stimulation.

4.1.3 Pre/Post tests

To guarantee that the induced spatial biases are not caused by a purely motor bias due to repetitive movement or muscular fatigue, a task completely devoid of any motor component was used in the pre- and post-tests. Subjects had to judge whether lines were transected to the left or to the right of the actual middle. The line stimuli were pre-bisected either in the middle or at various positions to the right or the left of the middle. The lines were displayed on a computer screen and subjects responded by using a button pad. The bisection error both in patients and healthy subjects was shown to be modulated by line position and length. Consequently, to probe the effects of the treatment in the best way we used 2 line lengths - 200 & 300mm, and 3 line positions – center (0mm) and 31 mm left or right.

4.1.4 Sensorimotor stimulation

This task was performed using the VR application described above. The subjects traced a curved line gradually appearing on the surface with the mixed prop. There were 4 different conditions in this experiment: 2 control and 2 experimental conditions. In the control conditions, there were no perturbations during the task. In one condition, the direction of the line was from left-to-right (LR) and in the other from right-to-left (RL). In the experimental conditions, the directions were the same but perturbations were introduced in the right hemispace in the LR condition and in the left hemispace in the RL condition. The perturbations started from the midline of the writing surface and became gradually stronger as the subject’s hand progressed towards the edge of the surface. All three types of perturbations (horizontal, vertical and friction-like) were used simultaneously to create a strongly incoherent environment.

![Figure 3](image-url)

Figure 3. Experimental results. The ordinate shows the different conditions and the abscissa shows the mean differences between pre- and post-test PSE’s. The top panel of the graph shows the RL conditions and the bottom panel the LR conditions. Each panel shows the mean differences for each type of line tested. The error bars show +/- 1 standard errors of the mean.
4.2 Results

To verify the presence of a spatial bias we computed the subjective midpoint of the judged lines in pre- and post-tests. This was done by fitting a psychometric functions to the data and obtaining the point of subjective equality (PSE) where the percent leftward responses was equal to percent rightward responses (see [21] for more details). The mean differences between pre- and post-test PSE’s for each condition are presented in Figure 3.

We analyzed the mean difference of the PSE’s between pretest and post-test by repeated measures ANOVA with Direction (RL or LR), Test (pre vs. post), Perturbation (perturbation vs. no perturbation), Location (left, centre, right) and Length (200, 300 mm) of the lines as within-subject factors.

The ANOVA revealed a significant main effect of the Test \( F(1, 14) = 14.99, p < 0.005 \), and an interaction of Test with Direction and Perturbation \( F(1, 14) = 6.67, p < 0.05 \). The decomposition of this interaction revealed a significant effect of perturbation for the LR condition where the line was traced left-to-right \( F(1, 14) = 5.24, p < 0.05 \). Therefore, as compared to the post-effect of the control condition, perturbations in the right space induced a significant leftward bias. No significant effect of perturbation was found for the RL condition \( F < 1 \).

5 Discussion

Using our VR application we wanted to evaluate a hypothesis about the causes of USN. The hypothesis states that patients’ sensorimotor experience in the contralateral hemispace is perturbed which leads to an avoidance and neglect of the affected space. We tested this hypothesis by perturbing one side of the space while the subjects performed a simple sensorimotor task, and measuring the post-test effect of the perturbation on spatial perception. Data showed that imposing perturbations in the right hemispace when the subjects traced the line from left-to-right induced a significant bias to the left. Similarly to the spatial biases observed in USN, the direction of this bias is away from the perturbed hemispace. These results offer support to the hypothesis that spatial biases in USN are the result of avoidance of perturbed sensorimotor experience in the contralateral hemispace.

When the subjects traced the lines right-to-left, no significant bias was observed. This asymmetry could be related to the everyday sensorimotor experience of the subjects. Since all subjects were left-to-right writers, the perturbed experience could have affected the subjects’ spatial perception most when the direction of the tracing corresponded to the writing direction the subjects use everyday [22].

Our application shows that VR can be a useful tool in the theoretical study of USN. The application permitted testing a hypothesis, which would otherwise be hard to evaluate with conventional laboratory tools. So far our application is unique since to the best of our knowledge it is the first one specifically designed for the theoretical study of USN. Moreover, it is the first USN related VR application to use large-scale haptic and visual displays [5]. In the future, researchers of USN and other neurological diseases should consider VR as an alternative to the conventional research techniques since it provides great flexibility and innovative methods.

In the future, we could verify whether visual perturbations or the combination of visual and haptic perturbations could produce similar biases as haptic perturbation alone. This will further clarify the mechanisms behind USN and will assist in the design of possible rehabilitation methods based on our application.

REFERENCES