Uses of Virtual Reality for Diagnosis, Rehabilitation and Study of Unilateral Spatial Neglect: Review and Analysis

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Abstract

Unilateral spatial neglect is a disabling condition frequently occurring after stroke. People with neglect suffer from various spatial deficits in several modalities, which in many cases impair everyday functioning. A successful treatment is yet to be found. Several techniques have been proposed in the last decades, but only a few showed long-lasting effects and none could completely rehabilitate the condition. Diagnostic methods of neglect could be improved as well. The disorder is normally diagnosed with pen-and-paper methods, which generally do not assess patients in everyday tasks and do not address some forms of the disorder. Recently, promising new methods based on virtual reality have emerged. Virtual reality technologies hold great opportunities for the development of effective assessment and treatment techniques for neglect because they provide rich, multimodal, and highly controllable environments. In order to stimulate advancements in this domain, we present a review and an analysis of the current work. We describe past and ongoing research of virtual reality applications for unilateral neglect and discuss the existing problems and new directions for development.

Introduction

Unilateral spatial neglect (USN) is a disorder frequently observed after unilateral brain damage such as stroke. It is defined as the inability to respond to or to orient toward stimuli located in the hemispace contralateral to the lesion of one of the cerebral hemispheres, where these symptoms are not due to primary sensory or motor deficits.1 This disabling condition is found in almost 50% of people with right-hemisphere stroke, and the presence of left USN in these patients has a well-established negative impact on functional recovery.2 People with USN display a wide range of functional spatial deficits, such as bumping into objects when walking, shoving only one side of their face, and eating food from only one side of the plate. In experimental tests, they frequently draw only one side of objects and bisect lines with large lateral biases (see Figure 1). USN is a heterogeneous syndrome that can manifest in several sensorimotor modalities and parts of space. Patients can neglect visual,3 tactile,4 and auditory5 stimuli presented contralaterally to the lesion. USN can also affect motor function6 and mental imagery.7 The disorder can affect the space pertaining only to the body of the patient,8 the space within arm’s reach,9 or the space beyond the arm’s reach.9

The complexity of USN makes it a difficult condition to diagnose and treat. While many rehabilitation methods have been proposed and applied with various degrees of success,10 there is still a great need for effective treatment. Diagnostic techniques could also be improved and extended. In the last decade, promising new methods using virtual reality (VR) technologies have emerged.

VR technology provides tools that immerse the user in rich, multimodal, 3D worlds using computer-generated environments. VR is an important tool for psychology and neuropsychology.11,12 It delivers interactive, realistic environments with a high level of control over their parameters and applications that can be easily adjusted for each user. Scenarios that are too dangerous or expensive in the real world can be re-created in VR with relative ease and cost efficiency. For instance, VR has been used to treat posttraumatic stress disorder13 and different phobias14 and to assess memory and executive functions.15

In the domain of USN, VR is a relatively new tool that has

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Assessment of USN

Conventional methods

USN is normally assessed by bedside pen-and-paper tests. Line bisection requires patients to indicate the middle point of horizontal lines. People with USN usually exhibit a strong deviation to the ipsilesional side of space, as in Figure 1B. In cancellation tests, patients are required to cross out target objects sometimes embedded in distracters. The proportion of omitted target objects on the contralesional side signals the degree of USN. In object copying tests, patients are asked to copy a picture. Patients omit details on the contralesional side of the drawing and/or contralesional-sidged details of the objects, as in Figure 1A.

Although these tests are convenient and easy to administer, most of them do not assess important everyday tasks in natural environments and hence potentially lack sensitivity to the degree of impairment of the patients. Moreover, some forms of the disorder, such as extrapersonal and auditory USN, are not addressed by these tests.

VR methods

Several studies have proposed VR versions of the pen-and-paper tests that augment existing conventional techniques. Gupta et al. designed the VREye system that consists of a head-mounted display (HMD) equipped with an eye tracker. In the first task, 10 different objects were positioned in rows from left to right, and observers were asked to name all the objects they could identify. In the second task, the observers viewed an image of a clock and were asked to tell the time. Four controls had no trouble performing the tasks, and their eye movements covered the entire space. Two participants with USN omitted objects located contralaterally to their lesion and misread the clock. Their eye movements were primarily restricted to the ipsilesional side of the viewed scene. Interestingly, one of the participants had aphasia in addition to USN and was unable to recall the names of all the objects. In hospital environments, similar tasks, such as naming objects around the room, are sometimes used to assess USN.

In those conventional settings, the aphasia could have made it harder to determine how far the observer’s gaze moved into the contralesional side, since the score would be determined solely on the basis of the number of objects the participant named. In the VR setting, eye tracking allowed precise estimation of the extent of the observer’s spatial exploration deficit.

In another study, an HMD-based system with a digital camera was used with line and star cancellation tests. The digital camera photographed a sheet of paper containing the test. The image was then altered, by either increasing (zoom-in condition) or reducing (zoom-out condition) its size, and displayed in the HMD. The participants were evaluated on the conventional line and star cancellation tests, activities of daily living such as dressing and grooming, and the VR tests. The assessment on the daily activities showed that most of participants exhibited one or more behavioral deficits typical to USN. However, only three out of eight scored lower than the cutoff on the conventional cancellation tests. The VR cancellation tests were more sensitive. They showed lower scores and greater differences between the scores on the left and the right parts of the test sheets than did the conventional tests, especially in the zoom-in condition. The authors proposed that the limited field of view of the HMD causes the participants to concentrate their attention on the task and thus aggravates the neglect behavior.

Broeren et al. replicated the conventional cancellation task using a desktop setup with 3D stereo vision coupled with a PHANToM haptic device. The observers were presented with a scene with targets and distracters. They had to press each target they could find using the PHANToM. Those with USN omitted targets mostly on the left, while others with stroke and healthy controls marked all the targets correctly. Hand movement of those with USN was slower than that of the other participants. Both groups had irregular search patterns and repeatedly marked other targets.

These applications augment conventional methods by providing tracking information. People with USN exhibit postural deviations as well as lack of exploratory eye and hand movement toward the neglected hemispace. Conventional tests can provide only limited information about patients’ gaze and search patterns. Transferring conventional methods to VR could allow more precise assessment of USN. Moreover, diagnosis based on multiple parameters could be more robust than that based on a single factor alone.

Other VR applications include novel diagnostic tasks. Kim et al. designed a VR test using an HMD with head tracking. Observers were asked to track a virtual ball moving in random directions. The system was evaluated in a study with three groups: 12 participants with USN and two control groups of 20 experienced and 20 inexperienced computer users. Results showed that the performance of the two control groups did not differ significantly on all parameters, while the USN group performed significantly worse. They required longer time periods to scan the scene, and
they failed more trials. They also showed a larger deviation in their head position and the ratio of right-to-left scanning was significantly higher than for the control groups. Significant differences were found between the scanning time and the number of cues corresponding to the left and right parts of the scene for the USN group but not for the control groups. These results show that the method could be used to diagnose USN. Since the virtual ball that has to be tracked in the task can move in depth as well as laterally, this task can be extended to diagnose extrapersonal neglect.

Myers and Bierig designed an application for diagnosis and treatment of USN consisting of a virtual house presented in an HMD. A preliminary trial with five USN patients showed that the maximal angle of rotation of the head to the left was smaller than to the right. This kind of diagnostic task could be interesting because it assesses the behavior of patients in a natural environment.

A multimodal VR system for treatment and diagnosis of USN was developed in Japan. The system included visual, haptic, and audio displays. A 3D stereo display was combined with a PHANToM haptic device, eye tracker, and sound system. The virtual world consisted of a rotating sushi bar, where the task was to grab a target sushi with virtual chopsticks (controlled by the PHANToM) and place it in a designated location. The authors have tested this system with several hemiplegic patients and controls and found that the kinematics of the hand differed between the two groups. In controls, the approach trajectory started with an acceleration followed by a succession of decelerations. Patients’ approach trajectory was much more variable, with many acceleration and deceleration areas.

An interesting assessment technique using a virtual wheelchair was proposed by Buxbaum et al. The observers, seated in a wheelchair treadmill, had to navigate the virtual wheelchair through a VR environment while naming objects seen on the sides of the road. The performance of nine USN patients on the virtual task was compared with their performance on real wheelchair navigation and with a battery of conventional USN tests. In the virtual wheelchair task, the patients named significantly fewer objects on the left than on the right side. Moreover, although a strong correlation was found between performance on the virtual task and performance on the other tests employed in the study, the virtual task revealed functional deficiencies in three participants who performed within norms on the standard battery of USN tests.

The last three applications emphasize the real strength of VR, the ability to replicate and alter the surrounding world. Future assessment applications could focus more on this feature of VR. Methods could be designed to evaluate patients on important activities of daily living, such as driving, cooking, and shopping. Such tasks have been successfully used for the diagnosis of other disorders. Virtual environments could provide a safe testing ground for tasks that cannot be assessed in the real world without putting the patient in danger. Moreover, such methods could be more sensitive to mild USN than are pen-and-paper tests, as was demonstrated by the virtual wheelchair application.

Future methods could also address the poorly diagnosed aspects of USN. Current VR techniques have mostly focused on the visual deficits of USN, localized in peripersonal space. In the future, VR tests could concentrate on other, less explored aspects of the disorder. Three-dimensional stereovision in VR provides an opportunity to diagnose extrapersonal USN. Such tests could be oriented toward activities of everyday life such as crossing the street, driving, and watching performance in these activities. Many VR systems are equipped with audio displays that can be used to assess auditory USN. VR can provide 3D sound displays that enable placement of sounds anywhere within the environment.

The VR methods described here are promising, but they require a more rigorous evaluation. Standardized performance thresholds should be established on novel assessment tests in order to allow diagnosis of USN. Evaluation studies of VR tests that come to replace conventional methods should compare the sensitivity of the two tests in order to justify the use of VR.

One potential drawback of VR is the presence of perceptual deformations of space in some virtual environments. For example, it has been shown in multiple studies that the egocentric distance beyond two meters is underestimated in virtual worlds presented in HMDs. Consequently, the observers might show decreased performance on the VR assessment tests in comparison to conventional tests due to the nature of the VR setup. The perceptual biases are being carefully studied and corrected. However, before all perceptual artifacts are eliminated, VR assessment tests should also be evaluated with healthy controls and preferably with patients with stroke but without USN to ensure that VR artifacts do not affect their performance.

**Rehabilitation of USN**

**Conventional methods**

Many rehabilitation methods of USN have been proposed in the last few decades, but few showed long-term effects on the symptoms of USN. Spatial exploration training encourages patients to make eye movements to the contralesional hemispace by providing tasks that require visual search in both sides of space. This method was one of the earliest rehabilitation techniques of USN, but its ability to ameliorate USN symptoms is still under debate. Patching of a visual hemifield (one half of each eye) reduces the visual input to the contralesional superior colliculus, thus increasing the effectiveness of the ipsilesional colliculus in making eye movements into the contralesional visual field. After eye patching treatment, patients show improvement in daily activities, visual exploration, and visuo-spatial tasks.

Vestibular stimulation (neck muscle vibration or ear irrigation) and optokinetic stimulation (movement of luminous dots) cause a motion of the eyes to the contralesional side. These techniques were shown to temporarily improve some symptoms of USN.

Together with spatial deficits, patients with USN also exhibit a nonlateralized deficit of sustained attention. Consequently, auditory stimulation, whether lateralized or not, can improve the general alertness of patients as well as direct their attention toward the neglected stimulus.

The most successful rehabilitation technique to date is prism adaptation. Adaptation to wedge prisms creates a lateralized reorganization in visuomotor mapping. This
method showed long-lasting effects on series of behavioral and ecological visuospatial tasks.38

**VR methods**

Several VR-based methods for rehabilitation of USN have been proposed recently, but there is little experimental data documenting their effectiveness in ameliorating USN symptoms. Nevertheless, we describe them here to illustrate the possibilities of VR for rehabilitation of USN.

Castiello et al.\textsuperscript{39–41} tried to extend action from unaffected to affected space in patients with USN. They used a PC screen for visual display combined with a DataGlove for hand-motion tracking. Six USN patients and six healthy controls had 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. Their real hand and the real object were not visible to them. The remapping of space was induced by incongruent trials in which the virtual object was located to the left of center while the real one was in the center or to the right. After a period of adaptation to the incongruent trials, participants with USN made significantly fewer errors with targets appearing in the neglected hemispace. The authors suggested that the virtual hand was incorporated as part of the body and thus space representation was extended to include the virtual space (even the neglected side of it). This application highlights two important features of VR technologies: the ability to easily dissociate between different modalities and the ability to introduce alterations that are impossible or difficult to achieve in the real world. Decorrelation of modalities can become an efficient rehabilitation technique, as has been demonstrated with prism adaptation. Chokron et al.\textsuperscript{10} recently proposed that patients with USN suffer from a sensorimotor decorrelation or a loss of sensorimotor mappings. Consequently, methods based on the dissociation between different modalities or on those altering the sensorimotor mappings may decrease USN symptoms by inducing a recorrelation of sensorimotor information.

Katz et al.\textsuperscript{42} examined the efficiency of a virtual street-crossing application for training patients with USN to cross the street in comparison with standard computer-based visual scanning training. The 3D graphics application was presented on a PC screen. After nine hours of training (distributed over 4 weeks), both control and experimental groups of participants with USN improved on standard USN measures. The experimental group also showed significant improvement on the VR street-crossing test, while the control group did not. On real street crossing, the experimental group looked more to the left than they did before the VR training, while the control group showed no change. These results are encouraging, since even such a simple system, located on the lower end of the immersion spectrum, equaled and in some cases surpassed the conventional method in its rehabilitative abilities. Such ecologically valid rehabilitation can be of great value to patients. VR can re-create the living environment of the patient, which will lead to better generalization of the therapy to everyday life.11

A rehabilitation application was developed on the basis of the Mandala Gesture Extreme system, which captures the user’s movements and displays a virtual avatar on a screen with other virtual objects.43 Using this system, four partici-
monitoring the progress of the patient, such as changes in the range and speed of motion.

Visual exploration can also be easily transferred to VR. Tasks can be designed that require patients to follow an object moving toward the neglected side. For example, a task might be to determine whether a golf ball was successfully aimed at a cup while watching a virtual golf game or playing it. Other tasks can involve active exploration of the environment, such as searching for a particular object hidden in a virtual room.

Like the VR assessment methods, the rehabilitation techniques proposed must be properly assessed in further studies before clinical engagement. Methods enhancing the conventional rehabilitation should be compared with their prototype, and similarly to conventional methods of rehabilitation, VR rehabilitation methods should be evaluated not only for short-term improvements but also for long-term gains.

### VR in Theoretical Study of USN

VR has been used for the assessment and therapy of USN, but only a single published study utilized VR for theoretical research. Castiello et al. used their remapping VR application to show that only patients with intact inferior parietal and superior temporal regions can benefit from their VR treatment. They speculated that these brain structures might be responsible for the recovery of space in people with USN.

The theoretical direction of VR application to USN is an exciting one. VR provides possibilities not readily available in psychological laboratory environments. VR applications can help solve some of the open questions about USN. For example, according to Kerkhoff, one such question is the nature of the interplay among the different modalities. Creating a discrepancy among the modalities might aid the understanding of their relationship and contribution to the disorder. In VR, this can be easily achieved.

It is often difficult to get patients with USN to participate in experiments that are conducted in VR labs outside of medical facilities. However, theoretical studies of USN could also be performed with healthy populations. It has been shown that some rehabilitation methods of USN, such as prism adaptation and caloric stimulation, induce spatial biases in healthy participants. These biases are qualitatively similar to those present in patients with USN. Using VR to create and study such spatial biases in healthy people, and thereby simulating USN, could help our understanding of the mechanisms involved in USN and spatial cognition in general. Using the same reasoning, Dupierrix et al. recently showed the effects of a lateralized sensorimotor experience on spatial perception among healthy adults before testing this procedure on USN patients.

### Conclusions

Evidence shows that VR has the capacity to enhance current methods of diagnosis, treatment, and theoretical study of USN and to provide new methods. We have highlighted many of the features of VR that make it an especially attractive tool for USN. VR can improve existing assessment methods by providing information about head and eye movements, postural deviations, and limb kinematics. Patients can be diagnosed and trained on tasks that are relevant to everyday life and potentially dangerous to perform in the real world. Because of 3D vision technology and the versatility of virtual worlds, rehabilitation could be made more engaging and consequently more effective. The multimodality of virtual environments and the high level of control over their parameters allows researchers to easily decorrelate the senses. Such decorrelation has potential rehabilitative power, and it can answer pending questions about USN.

However, several characteristics of current VR technologies can pose a challenge to the development of new applications for USN. The ergonomic aspects of VR systems should be carefully evaluated. In the early poststroke stage, many patients are bed bound or have reduced mobility. In later stages, many suffer from postural disorders or paralysis and have to use a wheelchair for locomotion. Consequently, mobile, lightweight VR systems that allow for wheelchair access and do not require the observers to stand are preferable.

Because of their complexity, VR systems might require the presence of a professional for their operation. By designing intuitive and easy-to-use applications and providing training, developers could ensure that medical personnel could manage the systems independently.

Many VR setups are expensive. To justify the cost, several different tests and rehabilitation techniques can be designed on the same platform. Ideally, one VR system could offer a battery of multimodal diagnostic measures and rehabilitation applications. This could also allow testing of the whole spectrum of USN-related disorders in one setting.

Collaboration between clinicians, neuropsychologists, researchers, and computer scientists is needed to move this promising domain forward. Such collaboration will unite the technical knowledge required to create and operate VR environments with the theoretical and clinical knowledge needed to envision and assess new paradigms. Through productive collaboration, VR methods could become the answer to current problems surrounding USN.

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