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VIRTUAL REALITY IN NEUROSCIENCE: A SURVEY

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Abstract. Some research projects have begun to test the possibility of using Virtual Environments (VEs) for research in neuroscience, neurosurgery and for the study and rehabilitation of human cognitive and functional activities. In fact, VEs let users navigate and interact with computer-generated 3-D environments in real time, allowing for the control of complex stimulus presentations. VEs enable the neuroscientist to present a wide variety of controlled stimuli and to measure and monitor a wide variety of responses made by the user.
This paper highlights recent and ongoing research related to the applications of VEs in the neuroscience arena. In particular it focuses on the European and US applications in this field.

1. Introduction

Neuroscience research involves a great range of scientific endeavors [1]: describing electrophysiological events, tracking receptor binding, and the monitoring of brain structure and function. These include everything from the examination of histological preparations to in vivo functional brain activation measurements.

As noted by Merril [1], “Given our increasingly comprehensive understanding of the dynamic complexity of the brain, we require increasingly sophisticated computer hardware and software to both contribute to and communicate our understanding of the brain.” (p.230).

To face this challenge, researchers need the full power of new technologies. In fact, new technology can provide more complete and concise descriptions of neuroscience models as well as capabilities that can transform the scientist’s observations into models that can be explored in new ways [2]. Computer technology also offers new opportunities for creating more powerful clinical tools. Virtual reality software and hardware, as well as networking applications deploying 3-D are trends that could contribute to a richer understanding of the brain and enable sharing and exploration of conceptual models in ways never before possible [1].

Virtual environments (VEs) have recently attracted much attention in neuro-psycho-physiology [3,9]. VEs can play an important role in reducing the cognitive demands on health care practitioners by helping them to manage, filter and analyze multiple sources of information.

This paper highlights recent and ongoing research related to applications of virtual environments and related technologies in the neuroscience arena. In particular it focuses on the American and European initiatives in this field. The paper also provides a general introduction to virtual reality as it relates to its impact on cognitive and functional abilities.

2. Virtual Reality in neuropsychological assessment and rehabilitation

2.1 Basic definitions

Virtual reality (VR) is an emerging technology that alters the way individuals interact with computers. It can be described as “...a fully three-dimensional computer-generated ‘world’ in which a person can move about and interact as if he actually were in an imaginary place. This is accomplished by totally immersing the person’s senses... using a head-mounted display (HMD)" or some other immersive display device, and an interaction device such as a DataGlove or a joystick [10, p. 111]. However, it is the user immersion in a synthetic environment that characterizes VR as being different from interactive computer graphics or multimedia. In fact, the *sense of presence* in a virtual world elicited by immersive VR technology indicates that VR applications may differ fundamentally from those commonly associated with graphics and multimedia systems [11]

VEs present a unified workspace allowing more or less complete functionality without requiring that all the functions be located in the same physical space. According to Ellis [12, p. 17], VEs can be defined "...as interactive, virtual image displays enhanced by special processing and by nonvisual display modalities, such as auditory and haptic, to convince users that they are immersed in a synthetic space". Less technically, a virtual world can be described as an application that lets users navigate and interact with a computer-generated 3-D environment in real time. This type of system has three major elements: interaction, 3-D graphics, and immersion [13].

The VE may be displayed on a desktop monitor, a wide field-of-view display such as a projection screen, or on a head-mounted display. A virtual environment displayed on a wide field-of-view display which is fixed in space is referred to as partially immersive virtual reality. A fully immersive virtual reality environment utilises a head-mounted display, with a head position sensor to control the displayed images so that they appear to remain stable in space when turning the head or moving through the virtual environment. A see-through head-mounted display and head position sensor may be employed to augment the user's experience of the real world by superimposing space-stabilised computer-generated images of virtual objects on the user's view of the outside world.

2.2 The rationale

The ability to control a VE and then to introduce a predetermined set of stimuli can in theory enhance the standard approach used in neuropsychological assessment, whose main goal is to evaluate how specific activities in the brain are expressed in observable behaviors [14]. Moreover, the additional capabilities that are inherent in VEs can lead to greater flexibility in the adaptation to the patient's individual problems, improving the efficacy of the rehabilitation process.

VEs are highly flexible and programmable. They enable the therapist to present a wide variety of controlled stimuli and to measure and monitor a wide variety of responses made by the user. Both the synthetic environment itself and the manner in which this environment is modified by the user's responses can be tailored to the needs of each client and/or therapeutic application [15]. It is also possible for the therapist to accompany the user into the synthesised world.

More specifically, there are *three* important characteristics of VR systems that can offer new methods to neuropsychological assessment and rehabilitation [16].

1. *How They Are Controlled*: Present alternate computer access systems accept only one or at most, two modes of input at a time. A computer can be controlled by single modes such as pressing keys on a keyboard, pointing to an on-screen keyboard with a head pointer, or hitting a switch when the computer presents the desired choice. Present computers do not recognize facial expressions, idiosyncratic gestures, or monitor actions from several body parts at a time. Most computer interfaces accept only precise, discrete input. Thus, many communicative acts are ignored and the subtleness and richness of human communicative gestures are lost. This results in slow, energy-intensive computer interfacing. VR systems open the input channel: VR systems have the potential to monitor movements or actions from any body part, or many body parts at the same time. All properties of a movement, not just contact of a body part with an effector, could be monitored.

2. *Feedback*: VR systems are capable of displaying feedback in multiple modes; thus feedback and prompts can be translated into alternate senses. The environment could be reduced to achieve a larger or overall perspective (without the "looking through a straw effect" usually experienced when using screen readers or tactile displays). Sounds could be translated into vibrations while environmental noises could be selectively filtered out. Vision is the primary feedback channel of present-day computers; frequently, a

displayed message is further distorted and alienated by text representation. It is very difficult to represent force, resistance, density, temperature, pitch, etc., through vision alone. For the individual multimodal feedback ensures that the visual channel is not overloaded.

3. *What Is Controlled*: Until the last decade, computers were used to control numbers and text by entering numbers and text using a keyboard. Recent direct-manipulation interfaces have allowed the manipulation of iconic representations of text files, or two dimensional graphic representations of objects, through pointing devices such as the mouse. The objective of direct-manipulation environments was to provide an interface that mimics object manipulation in the real world. The latest step in that trend, virtual reality systems, allows the manipulation of multisensory representations of entire environments by natural actions and gestures.

3. VR in Neuroscience: the applications

3.1. VR in research

VR offers new opportunities and challenges for collaboration and sharing of information to build increasingly comprehensive models of the brain [1]. Using VEs, multi-modal data can be simultaneously displayed, enabling different types of data to be merged to create a more comprehensive understanding of the brain. For example, the dynamic processes observed by the electrophysiologist can be combined with the receptor binding studies and histological information obtained by other researchers. This capability provides an opportunity for both scientific discovery (in detecting new patterns and relationships between investigations) as well as misinterpretation (observing patterns which are artifacts of the techniques employed).

Ghahramani *et al.* [17] used VR to investigate modular decomposition in visuomotor learning. Using a VR system, subjects were exposed to opposite prism-like visuomotor remappings-discrepancies between actual and visually perceived hand locations- for movements starting from two distinct locations. Despite this conflicting pairing between visual and motor space, subjects learned the two starting-point-dependent visuomotor mappings and the generalization of this learning to intermediate starting locations demonstrated an interpolation of the two learned maps. The obtained results provided evidence that the brain may employ a modular decomposition strategy during learning.

Aguirre *et al.* [18] used functional magnetic resonance imaging (MRI) and VR to localize the neural substrates of human topographic spatial learning within the human hippocampal system to address the conflicting evidence on the regional function of the medial-temporal lobes in rodents and primates. VR was used to allow 9 male subjects to engage in an allocentric learning of a spatially extended place.

Pekel *et al.* [19] used VR with a macaque monkey to investigate neuronal responses in the motion pathway to natural optic flow stimuli. Neurones in higher visual motion areas in the superior temporal sulcus (STS) of the macaque monkey respond to abstract random dot optic flow stimuli. Higher motion areas may not only represent, but in a next computational stage also analyse the flow field to determine, for instance, the direction of heading for navigation purposes. Real world visual scenes differ in several aspects from these abstract optic flow stimuli. So, the researchers tested the neuronal response to naturalistic optic flow stimuli in different virtual environments and contained different numbers of visual cues.

Finally, Accornero *et al.* [20] used VR electromagnetic tracking devices as a new technical approach to multisegmental posturography. The VR-based device was used to study age-related differences in normal subjects in the control of upright posture. Body sway was studied by recording the oscillations of two trackers placed on the head and the hip during the Romberg test. The VR device allowed researchers to detect age-related differences in postural stance strategies.

3.2. VR in assessment and rehabilitation

Development of a VR system specifically designed for the assessment and cognitive rehabilitation of cognitive functions in persons with acquired brain injuries began in Italy

[21,22]. Using a standard tool (Wisconsin Card Sorting Test-WCST) of neuropsychological assessment as a model, these researchers have created a virtual building which requires the person to use environmental clues in the selection of appropriate choices (doorways) to navigate through the building. The doorway choices vary according to the categories of shape, color, and number of portholes. The patient is required to refer to the previous doorway for clues to appropriately make his/her next choice. After the choice criteria is changed, the patient must shift the cognitive set, analyze clues, and devise a new choice strategy. The parameters of this system are fully adjustable so that training applications can follow initial standardised assessments.

Although this VE is not regarded as a substitute for diagnostic neuropsychological tests, it was used to diagnose brain dysfunction in selected cases. For instance, the VE was used to document failures in everyday life coping in a patient with an anterior thalamic stroke [23]. In particular, it produced objective clinical evidence of a persisting frontal dysfunction in spite of unremarkable result in traditional neuropsychological tests tapping frontal functions.

Kuhlen *et al.* [24] are checking the possibility of using VEs for improving the diagnosis and therapy of sensorimotor disturbances. Usual examination of sensorimotor disturbances is based on various functional tests: patients must perform motor tasks which are subsequently analysed for diagnostic purposes and therapy planning. In clinical practice, the motor disturbances resulting from cortical and subcortical lesions are distinguished, but quantitative comparisons are scarce. Even if cortical and subcortical brain areas extensively exchange information, little is known about this mutual interaction in the control of sensorimotor integration. Therefore, as noted by Kuhlen *et al.* [24, p.186] "complex situations are necessary to examine this sensorimotor network to bring out even subtle impairments [involving] the use of 3D space information". This has become only recently possible by using VEs.

Attree *et al.* [25] are currently developing VEs aimed at attention/memory assessment and training . As noted by Rizzo & Buckwalter [26] these efforts would be particularly informative as results using traditional methods for memory rehabilitation have been inconsistent due to the inability to maintain a patient's motivation when confronting them with a repetitive series of memory training challenges. VR training could potentially address this problem by providing environments which initially utilize gaming incentives followed by the gradual fading in of functional environments with the aim of developing domain-specific memory [27].

The preliminary results [28] support the view that positive transfer can occur between virtual and real environments. When investigating the transfer of training from a simple sensorimotor virtual task (a "steadiness tester") to performance on the real-world equivalent it was found that final performance on the real-world task benefited as much from virtual as from real practice. However, it is not sufficient to simply demonstrate that training transfers in a given situation. Researchers need to understand the precise conditions (immersive versus non-immersive; degree of similarity between virtual and real tasks; temporal factors, etc.) which are necessary for transfer to occur.

The two leading VE research groups in the United Stated of America are: the Human Interface Technology Laboratory at the University of Washington, Seattle, and the Alzheimer's Disease Research Center at the University of Southern California, Los Angeles, California. Researchers at HITL use a field-multiplexed head-up video display to simulate an effect, called *kinesia paradoxia*, to trigger near-normal walking in akinetic Parkinson's patients [29,30]. In particular, normal walking behavior could be elicited by presenting virtual objects and abstract visual cues moving through the patient's visual field at speeds that emulate normal walking (see Reiss chapter in this book). The research team is currently identifying the most important design parameters of the physical display and dynamic graphics presented.

Researchers at ADRC are working on a VE to be used for the assessment and rehabilitation of visuospatial cognitive functions. This VE is referred to as *Mental Rotation* [26]. Mental rotation is designed to present, within a VR environment, a target stimulus that consists of a specific configuration of 3-D blocks. After presentation of the target stimuli, the participant is presented with the same set of blocks that need to be rotated to the orientation of the target and then superimposed upon it. This approach will supposedly improve the reliability and validity of Mental Rotation assessment, as well as provide an efficient training and rehabilitation option for this aspect of cognition.

3.3. VR in neurosurgery

Significant advances in the management of neurosurgical disorders during the past decade have enhanced the safety of intracranial surgery, resulting in the ability of most patients with brain tumors to undergo successful resection now. Among these advances are stereotactic surgical procedures and VR-based intraoperative monitoring devices [31,34].

For instance, Giorgi *et al.* [35,36] used a VR system to guide surgery in stereotactic space. Stereotactic neuroanatomical images are acquired, and the same reference system is employed to represent the position of the toolholder on the monitor. The surgeon can check the orientation of different approach trajectories, moving the toolholder in a situation of virtual reality. Angular values expressed by high precision encoders on the five joints of the toolholder modify "on line" the representation of the configuration of the toolholder within the three dimensional representation of the patient's anatomy.

A different approach was used by Gleason *et al.* [37]. They have combined three-dimensional (3D) computer-reconstructed neuroimages with a novel video registration technique for virtual reality-based, image-guided surgery of the brain and spine. This technique allows the surgeon to localize cerebral and spinal lesions by superimposing a 3D-reconstructed MR or CT scan on a live video image of the patient (augmented reality). Once the patient's scan has been segmented into the relevant components (e.g., tumor, edema, ventricles, arteries, brain and skin), the surgeon studies the 3D anatomy to determine the optimal surgical approach. The proposed intraoperative surgeon's perspective is displayed in the operating room at the time of surgery using a portable workstation.

Augmented reality is also playing an important role in neurosurgical endoscopy. Widespread use of neurosurgical endoscopy has been hampered by the necessity of looking up from the surgical field to view the endoscopic image on a video monitor. McGregor [38] demonstrated a simple, lightweight headpiece with a small, built-in video monitor that reflects the video image to the dominant eye, thus allowing the operator to continuously observe the surgical field either via peripheral vision or via the non-dominant eye.

4. The VREPAR projects

4.1 Aims of the projects

If we analyze the results and the devices used by the researches described above, we can find at least three technical problems that limit their actual application:

- *Cost:* Although some attempts have been made to use PC-based virtual reality systems, the majority of the existing VEs are based on RISC platforms whose cost is beyond the possibilities of a therapist.
- *Lack of reference standards*: Almost all of the applications in this sector can be considered "one-off" creations tied to their development hardware and software, which have been tuned by a process of trial and error. This makes them difficult to use in contexts other than those in which they were developed.
- *Non-interoperability of the systems*: Although it is theoretically possible to use a single virtual reality system in many different applications, none of the existing systems can be easily adapted to different tasks. This means that two different departments within the same organisation may find themselves having to use two different VR systems because of the impossibility of adapting one single system to their different needs.

In order to overcome these shortcomings, the European Commission recently funded the VREPAR - Virtual Reality Environment for Psycho-neuro-physiological Assessment and rehabilitation - projects (HC 1053 and HC 1055). Putting together researchers from Italy, Great Britain, France and Germany, the projects aim at:

- the development of an hardware/software Virtual Reality Modular System (VRMS) based on the low cost PC architecture (INTEL processor, Windows 95/NT operating system).

- the development of three VRMS modules to be used for the assessment and treatment of Movement, Stroke and Body Perception disorders.

4.2 The VR applications

The research group from Politecnico di Milano, Milan, Italy, developed a VE for the study of the relationship between visual sensory information and the control of movement being performed in patients with movement disorders [39,40].

In order to analyze this relationship, they used a simple touch task, studied under four different conditions:

a) *Quick Movement*. After hearing an acoustic signal (or seeing a visual signal) the subject is asked to reach a target as quickly as possible.

b) *Guided Quick Movement*. After hearing an acoustic signal (or seeing a visual signal) the subject is asked to reach a target as quickly as possible. He/she is asked to exercise the least force possible on the target while maintaining a direct visual control over the task being performed.

c) *Virtual Reality Guided Movement*. This condition differs from the previous one in the nature of the visual information about the task being performed. The subject does not maintain direct visual control over the real test station but interacts with a virtual representation of the station.

d) *Unguided Controlled Quick Movement*. This condition differs from the previous two in the fact that the subject has neither real nor virtual visual control over the task being performed.

During each task the patient touches the tip of his/her index finger to a lamina equipped with strain gauge. Only the movements of retraction-extension of the index finger of the hand are examined. The radial distance between the position of the metacarpophalangeal articulation and the lamina can be regulated according to the length of the phalanxes of the patient's finger.

The preliminary results obtained from the Milan group [39] show that this approach is suitable for testing both the effectiveness of various types of visual control, and individual performances in manipulation. An initial therapeutic application could be the assessment and rehabilitation of patients suffering from spinal cord injuries.

A second VR module was developed by researchers from University of Reading, Great Britain, to be used with subjects exhibiting attentional disorders (neglect) [41,43] and movement disorders (hemiparesis, cerebral palsy) [42,43]. The settings of this module consist of a series of open or enclosed VEs that the patient can navigate using a bicycle interface. This allows the clinician to set tasks at a level appropriate for the patient and to scale the task difficulty as they become accustomed to the requirements. The tasks used range from simply following an object, to tasks that may require sequencing skills, recognition skills or semantic tasks. The researchers at University of Reading present the interesting concept that the training will also improve the patient's fitness level [41] which is hypothesised to improve brain activation as well as other variables relevant to rehabilitative concerns. Experiments using clinical subjects are currently underway, with results expected shortly.

Researchers from Istituto Auxologico Italiano, Verbania, Italy, developed the latest VR module. Its main goals are the assessment [16,44] and rehabilitation of subjects with body experience disturbances associated with eating-and weight-related problems [44,47].

In an immersive VE the researchers integrated the two methods (cognitive-behavioural and visual-motorial) commonly used in the treatment of body experience disturbances. This approach made it possible to use the psycho-physiological effects provoked by the virtual experience for therapeutical purposes. As we have seen above, in every VR system, the human operator's normal sensorimotor loops are altered by the presence of distortions, time delays and noise in the system.

Such effects, attributable to the reorganisational and reconstructive mechanisms necessary to adapt the subjects to the qualitatively distorted world of VEs, could be of great help during the course of a therapy aimed at influencing the way the body is experienced, because they lead to a greater awareness of the perceptual and sensory/motorial processes. The developed module was tested in two different studies on non-clinical subjects: a first uncontrolled study on 72 male and female subjects [45]; a second controlled study on 48 female subjects [47]. The results of both studies show that even a short-term application of the developed VE is able to modify the body experience disturbances of the subjects tested.

The next steps of the project will be the testing of both the effects of the virtual environment on a clinical sample and how long the influence of the VE will last.

6. Conclusions

Virtual reality technology could have a strong impact on neuroscience. The key characteristic of VEs is the high level of control of the interaction with the tool without the constrains usually found in computer systems. VEs are highly flexible and programmable. They enable the therapist to present a wide variety of controlled stimuli and to measure and monitor a wide variety of responses made by the user. However, at this stage, a number of obstacles exist which have impeded the development of active research specifically testing persons with cognitive impairments. These obstacles include problems with acquiring funding for an almost untested new treatment modality, the lack of reference standards, the non-interoperability of the VR systems and, last but not least, the relative lack of familiarity with the technology on the part of researchers in these fields.

The VREPAR project was a first step towards a solution of some of these problems. Defining as its reference platform a relatively low-cost hardware/software solution based on PCs, it could allow a wider diffusion of this approach. However, the possible use of VEs in neuroscience is not linked to the solution of technical problems only. Actually, the impact of VEs on cognition is not fully understood. Many questions about the structure of human cognitive processes, motion sickness concerns, and computing parameters will need to be considered by future studies. Such research will require the active involvement of a variety of disciplines including neurology, psychology, engineering, medicine, and computer science.

In closing, this review underlined that VEs offer a unique set of advantages for research in neuroscience, for neurosurgery and for the delivery of assessment and rehabilitative strategies to persons with cognitive impairments. However, as underlined recently by Rizzo & Buckwalter [26], the "what if" questions in the theoretical musings will now need to be replaced with "what is" answers based on objective studies of the critical issues.

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