Virtual reality for cognitive rehabilitation: from new use of computers to better knowledge of brain black box?

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ABSTRACT

Virtual reality based technologies are one of the emerging tools that appear to have great potential for use in cognitive rehabilitation but it still is unclear how brain capacities are involved and what is the best approach to such training. At first, virtual reality was mainly used in single user virtual environments, but social interaction should also be addressed using collaborative virtual environments (CVE). In a CVE, multiple users can interact and collaborate with each other, solve complex tasks and learn with each other. Regarding to impact of behavioral disturbances in family stress and social re-entry, such tools need to have a wider use in future years.

Quantitative aspects are encouraging as some improvement have been shown after few training sessions. Home retraining or telerehabilitation based on VR may bridge the gap between lack of specialized resources and growing number of patients. Qualitative design of VR tools is more questionable. Choice of errorless or errorfull designs may depend on the severity of disturbances. Most VR tools emphasize the explicit component of tasks, even procedural aspects are a main strength of VR retraining programs. VR and augmented reality tools give various stimuli and indicators but their best modalities stay unclear, as most data are coming from learning studies in normal subjects more than rehabilitation studies in brain injured patients. Specific research studies to explore impact of sensorial transmodal effects and emotional involvement in VR tasks are requested. Rehabilitation protocols utilizing virtual environments are moving from single applications to cognitive impairment (i.e. alert, memory, neglect, language, executive functions) to comprehensive rehabilitation programs with the aim of efficient improvement in autonomy and transfer of benefits in real life conditions. A core issue that presents challenges to rehabilitation is decreased ability of persons with brain injury to transfer learning from one situation or context to another. The multicontext approach to cognitive rehabilitation proposes treatment methods for teaching use of strategies across a wide range of meaningful activities to promote generalization and enhance functional performance.

VR offers a very promising and exciting support for cognitive rehabilitation but we have to move from mimicking “in room” or desk rehabilitation practice to specific VR programs to maximize benefits and to get optimal improvement in cognitive and behavioral autonomy of patients.

1. INTRODUCTION

At first, virtual reality (VR) based tools were developed from an educational perspective. Then VR systems had targeted a wide range of physical, cognitive, psychological rehabilitation concerns. Virtual environments can be developed to present simulations that assess and rehabilitate cognitive functional performance under a range of conditions that are not easily deliverable and controllable in the real world. By providing a safe setting in which users may interact and develop goal-oriented activities within a virtual environment, VR allows the delivery of controlled multisensory stimuli and the creation of innovative learning and training approaches. VR offers the potential to create systematic human testing, training, and treatment environments that allow for the precise control of complex, immersive, dynamic stimulus presentations, within which sophisticated interaction, behavioural tracking, and performance recording is possible (Rizzo & Kim 2005).
The use of virtual-reality technologies in the areas of rehabilitation and therapy continues to grow, with encouraging results being reported for applications that address human physical, cognitive, and psychological functioning. However, there is currently little information from clinical trials about their effectiveness (Laver et al. 2011). The studies involved small numbers of participants and intervention approaches in the studies were predominantly designed to improve motor function rather than cognitive function or activity performance (Klinger et al. 2010).

2. STRENGTH AND WEAKNESSES OF VR TECHNOLOGIES REGARDING COGNITIVE REHABILITATION

Immersion and interaction are two fundamental functionalities of VR that can be exploited at different levels: sensorimotor, cognitive and functional (Fuchs et al. 2006; Klinger 2006). VR situations substantially change the information-processing capacities of the cognitive system and that warrants investigation and understanding. VR is used for cognitive learning by way of repetition, feedback which can be augmented in VR, errorless training with explicit or implicit cues.

2.1 A Way to Improve Self Awareness in Cognitive Deficits

Anosognosia and less dramatic disturbances in self-awareness observed in various brain disorders are weakly addressed by conventional rehabilitation (Prigatano 2009). VR may support patients’ improvement of self awareness and better understanding of mistakes and inadequate strategies, by way of easier assisted sequential tasks (e.g. step by step or cues during process) or replay after exercise. Motivation in virtual environments is reinforced by making sense and a feeling of success, allowing the high number of repetitions necessary to achieve learning.

2.2 From Hospital Acute Phase to Home-based Rehabilitation even in Severely Handicapped

Even subjects with severe motor or sensorial deficits, who cannot cope with many of the difficulties of conventional rehabilitation session, may practice exercises in VR environment. It enables patient to practice skill in ways he cannot achieve in the physical world. A wide range of virtual reality programs are used and most of the programs require only small movements by the person using the program, such as moving a joystick or as utilizing a keyboard, in a sitting position. Even patients who are not familiar with computers can perform rehabilitative exercises.

2.3 Low Incidence of Side Effects

Very few people using virtual reality in brain injury patients reported pain, headaches, epileptic seizures or dizziness and no serious adverse events were reported. These side effects mainly occur with Head Mounted Displays (HMD) and large screen driving simulators, and are much less relevant for desktop or video capture systems that are mainly used in VR-based rehabilitation.

2.4 A Holistic Rehabilitation which makes sense for Real Life and Activities of Daily Living

The tremendous advances in technologies over the past two decades have focused primarily on the realism of the virtual environment tools, and the complexity and performance of simulations and data collection. However, real time interactivity of the device is the key point for immersion more than realism. Cognitive rehabilitation programs are focused on single process such as memory, attention, executive functions, visuo-spatial abilities, neglect, etc… These approaches have shown some efficacy regarding trained domains but effects in real life conditions are still poor and lack the ability to develop efficient autonomy. Understanding performance and training in VR conditions involve not only a single cognitive process or network but the whole activity system which comprises a group of human actors, their tools and environment, in a distributed cognitive perspective, and is organized by a particular history of goal-directed action and interaction. Brain damaged patients may exploit “intelligence” from objects when they use them instrumentally in VR activities, that is to say bottom-up abilities and implicit holistic know-how.

Consequences in daily life of cognitive deficits are still difficult to identify and VR testing is promising in that way. VR systems appear to be perceived to be closer to real activities than conventional exercises, by the way of delivery and control of ecological and appropriate multimodal stimuli within a significant and familiar context (e.g., classroom, office, supermarket or street). Patients have to cope with more dynamic stimuli, as is the case for real world challenges. VR allows patients to practice everyday activities that are not or cannot be practiced within the hospital or day living center environment. Home retraining or telerehabilitation based on VR may bridge the gap between a lack of specialized resources and a growing...
number of patients. In cognitive brain impaired people, VR makes activities feasible for more patients, allowing them to respond to and perform tasks in less complex ways that entail a simplified cognitive load with minor simultaneous motor control requirements. The multicontext approach to cognitive rehabilitation proposes treatment methods for teaching use of strategies across a wide range of meaningful activities to promote generalization and enhance functional performance (Abreu & Toglia1987).

2.5 A New Way to Cope with Emotional and Behavioural Disturbances

Emotions play a key role in the user experience, in the development of more engaging rehabilitation programs, and increasing attention and learning. A significant effort has to be made in the modeling of emotions, their generation and their effects in VR cognitive rehabilitation. Many advances have been made in machine recognition of emotions over the past 10 years (Hudlicka 2009). This progress allows the implementation of affective game engine functionalities to support the development of affect-adaptative rehabilitation programs. Once diagnosed, treatment of depression and other emotional disorders can greatly improve rehabilitation outcomes (Kimura 2000, Wiart 2000).

2.6 What are we doing? More Concerns about Procedural Processes and Bottom-up Learning

Most VR tools emphasize the explicit component of tasks, even procedural aspects are a main strength of VR retraining programs. VR and augmented reality tools give various stimuli and indicators but their best modalities stay unclear, as most data are coming from educational in normal subjects more than rehabilitation studies in brain injured patients.

Observation of patient behavior thanks to various recorded data for performance review and construction of adapted interventions – the tasks in which the patient is involved – allow clinicians to collect detailed information about the process of patient performance rather than focusing primarily on a final product (e.g., the juxtaposition of types of errors to task requirements versus only an overall total error score). An analysis of these “learning tracks” leads to suggestions for further intervention adapted to the patient’s capacities or to the therapeutic challenge. Construction of new intervention paradigms – VR allows clinicians to manipulate a variety of features, such as space, 3D entities, time, physical laws, information (via texts, icons or sounds), – leads to the provision of standardized and repeatable experiments, or personalized and gradable ones.

3. WHAT DO WE LEARN FROM CONVENTIONAL REHABILITATION AND COGNITIVE REORGANIZATION?

Cognitive deficits after brain diseases are very common. Although there are anecdotal and large case studies supporting the benefits of cognitive remediation, evidence-based research is lacking and most research has been in the traumatic brain injury population. The data supports a thorough assessment of cognitive functioning as well as treatment of patients with several areas of cognitive impairment via multiple disciplines (Bates 2005). There is substantial evidence to support cognitive-linguistic therapies for people with language deficits after left hemisphere stroke. Specific interventions for functional communication deficits, including pragmatic conversational skills are recommended for persons with TBI. Some evidence supports training for apraxia after stroke. The evidence supports visuospatial rehabilitation for deficits associated with visual neglect after right hemisphere stroke. There is substantial evidence to support cognitive rehabilitation for traumatic brain injured patients, including compensatory strategy training for mild memory impairment, strategy training for post acute attention deficits, and interventions for functional communication deficits (Cicerone et al. 2000, 2005). Use of memory notebooks or other external aids to facilitate acquisition of specific skills and knowledge may be considered for persons with moderate to severe memory impairments after traumatic brain injury; these devices should directly apply to functional activities, rather than as an attempt to improve memory function per se. Training in formal problem-solving strategies and their application to everyday situations and functional activities are recommended during post acute rehabilitation for persons with stroke or traumatic brain injury. Comprehensive-holistic neuropsychological rehabilitation is recommended to reduce cognitive, behavioral and functional disability after TBI. Memory stimulation programs used in the treatment of Alzheimer’s disease (AD) are using visual imagery, errorless learning, dyadic approaches, spaced retrieval techniques, encoding specificity with cognitive support at retrieval, and external memory aids were the memory stimulation programs used alone or in combination in patients with AD. Preliminary evidence suggests that the errorless learning, spaced retrieval, and vanishing cues techniques and the dyadic approach, used alone or in combination, are efficacious in stimulating memory in patients with AD (Grandmaison, 2003).

Cognitive rehabilitation typically relies on individually tailored interventions to provide the best available treatment within a clinical setting. For many, the real work of recovery begins after formal rehabilitation...
when the patient attempts to use newly learned skills without the support of the rehabilitation environment or team. Adequate support from family and caregivers is critical to a successful outcome. A holistic approach that has, as its basic philosophy, a belief that cognitive functions cannot be divorced from emotion, motivation, or other non-cognitive functions, and consequently all aspects of functioning should be addressed in rehabilitation programs (Wilson 1997). Long-term follow-up and late rehabilitation can improve performance in some cases and reduce the risk of deterioration in these abilities in many people (Outpatients Service Trialists 2004, Cicerone et al. 2005).

3.1 Quantitative Aspects in Cognitive Rehabilitation

Therapy is most effective in treating cognitive disorders when provided intensely; less intensive therapy given over a longer period of time does not provide a statistically significant benefit, although some clinical benefit may be achieved (Wilson 1997, Robbey 1998, Cicerone et al. 2005). The recent Cochrane update (Kelly et al. 2010) in stroke aphasics rehabilitation reported that intensive therapy was associated with improved outcome when compared to conventional treatment; however, more participants withdrew from intensive therapy conditions than conventional. By progressive training and greater repetition VR is an efficient way to give more training and to complete adequate care from the beginning of illness, during hospitalization, to the long term in home environment.

A promising result regarding VR applications to cognitive deficits is that short treatment programs of 3 or 4-week interventions with three sessions per week have shown some effectiveness (Klinger et al. 2010). Training post effects were observed and follow-up assessments argue for transfer of gain in VR environment to real life settings. Present data are encouraging, especially regarding spatial learning, but have to be confirmed in larger controlled studies. VR applications permit some containment of costs, in terms of staff time, and risks to both patients and staff, which are incurred when training in real world situations.

3.2 Qualitative Aspects in Cognitive Rehabilitation

Cognitive rehabilitation is usually presented from an information processing perspective (Abreu & Toglia 1984). Cognitive trainings involve:

- processing of information: ability to receive, elaborate, and monitor incoming information;
- generalization of learning: flexibility to use and apply one’s analysis of information across task boundaries;
- the use of metacognitive skills (higher level skills or executive functions) including self awareness, goal formation, planning, and monitoring during task performance.

Several cognitive remediation or stimulation programs have been developed to compensate for the impairments associated with some necessary skills involved in the process of learning, such as the encoding and retrieval capacities. These capacities are typically altered in classical amnesic syndromes and in cases of brain damage, causing severe memory problems and other cognitive deficits. The theoretical goal of the strategies reported in the literature is to improve or support damaged functions in order to facilitate new learning. These different strategies have not yet been used to strengthen or improve areas not damaged, but they can partially rely on these undamaged areas (such as implicit memory) to carry on the training and improve learning capacity. Visual imagery techniques or encoding specificity strategies with cognitive support in episodic remembering necessitate sufficient residual cognitive abilities; the errorless learning approach and vanishing cues techniques have been developed for more impaired subjects. The training programs can be used individually or in combination. Choice of errorless or errorfull designs may depend of severity of disturbances. Specific skill training follows a hierarchy: orientation and arousal, attention, visual processing and language, motor planning and sequencing, memory, categorization and concept formation, and problem solving in task performance.

Errorless learning, a procedure introduced by Terrace (1963), is a type of discrimination learning that decreases or eliminates the opportunity for incorrect choice selection, therefore maximizing the possibility of a correct response. Errorless learning allows learning to occur with few or no negative stimuli. Errorless learning has been contrasted with trial and error learning in which the learner attempts a task and then benefits from feedback, whether the attempt was correct or incorrect. Trial and error learning may have the added advantage of producing deeper understanding – but only for those individuals who remember the learning experience (Sharp et al. 2011). The finding that patients with amnesia retain the ability to learn certain procedural skills has provided compelling evidence of multiple memory systems in the human brain, but the scope, defining features and ecological significance of the preserved mnemonic abilities have not yet been explored. Subjects with amnesia would be able to learn and retain a broad range of procedural skills.
Errorless learning minimizes the number of errors, increases overall time available for instruction, reduces the likelihood that errors will be repeated in future trials and should also reduce frustration and the occurrence of inappropriate emotional behaviors by increasing opportunities for reinforcement. Learning on the basis of predictable stimulus-outcome associations enables the brain to reduce resources in association with the processes of prediction (K Koch et al. 2008) so errorless learning appears to be more efficient than reward-related learning in severe cognitive deficit. Errorless learning strategies have been applied to a variety of fields with success, including learning, memory, aphasia and apraxia.

Usually, cues are gradually introduced. By way of giving assistance as sparsely as possible, the therapist encourages an effortful approach which enhances patient’s chance to perform it later on. But the high opportunity to make errors may be disadvantageous. As an alternative, the method of vanishing cues (Glisky, Schacter & Tulving 1986, Abel et al. 2005), which was initially designed for treatment of memory disorders, provides as much assistance as needed, thereby helping patients to avoid errors. The vanishing cues technique consists of several attempts to recall information, using prompts that are gradually decreased until recall is successfully achieved. Cue hierarchy progresses from most potent to least potent until failure, then increases again. This method is mainly based on two well-established and related principles: the backward chaining procedure of behavioral modification and some preservation of implicit memory in subjects with amnesia. Some authors view the vanishing cues technique as a complementary method to achieve an errorless learning training.

Strategies have been developed to provide supportive conditions at both encoding and retrieval phases of episodic learning. The encoding specificity paradigm necessitates the use of similar cues for acquisition (or encoding) and retrieval, since this paradigm holds that the amount of informational overlap between a cue presented at retrieval and the memory representation established at encoding is critical to episodic memory proficiency (Tulving &Thomson 1973, Diesfeldt 1984, Nieuwenhuis et al. 2005). In other words, the more congruent a cue is with the context prevailing during encoding or with the cognitive operations associated with encoding, the more effective it will be at retrieval. Being able to learn from feedback or reward and to adapt behavior accordingly is an important capability in everyday life. There is increasing evidence that the mesolimbic dopamine system (MDS) is critically involved in the processing of reward and reward-related learning (McClure et al. 2003). Activation in orbital/medial frontal and MDS regions has been found to be inversely related to the likelihood to receive positive feedback or reward. Therefore, activation in these regions is assumed to constitute the neural correlate of the so-called prediction error that describes the difference between the expected and the received outcome or reward (K Koch et al. 2008). Learning with and without reinforcement has been found to go along with practice-associated cortical activation decreases. These decreases are assumed to reflect a learning-related increase in automated processing, demanding fewer processing resources. Nevertheless such remediation is cognitive resource intensive and so relevant only in slightly impaired patients. Strategies aiming to maximize cues in virtual environments may fail when used in more damaged subjects.

To process information in the environment to meet our survival and personal needs, we need to process sensory information. This begins with a relay of visual, auditory, tactile and olfactory information from the sense organs (eye, ear, skin, nose) to primary sensory cells in the cortex (A1, V1 and S1 and the olfactory lobe respectively). Thereafter, sensory information is processed by more complex unimodal associations and ultimately, transmodal projections to other modality associations, allow integration of stimuli into multimodal concepts, like words which can be processed auditorily and visually. Sensory information undergoes extensive associative elaboration and attentional modulation as it becomes incorporated into the texture of cognition. All cognitive processes arise from analogous associative transformations of similar sets of sensory inputs. The human brain contains at least five anatomically distinct networks. The network for spatial awareness is based on transmodal epicentres in the posterior parietal cortex and the frontal eye fields; the language network on epicentres in Wernicke’s and Broca’s areas; the explicit memory/emotion network on epicentres in the hippocampal-entorhinal complex and the amygdala; the face-object recognition network on epicentres in the midtemporal and temporopolar cortices; and the working memory-executive function network on epicentres in the lateral prefrontal cortex and perhaps the posterior parietal cortex. Individual sensory modalities give rise to streams of processing directed to transmodal nodes belonging to each of these networks (Messulam, 1998, Riddoch & Humphrey 2001).

Usually only a few sensory modalities are provided in virtual environments (most commonly visual and auditory); recent efforts aim to integrate other modalities including haptics, smell and proprioception. But contradictory multisensory stimuli may lead to conflicts which, in turn, often lead to cybersickness side effects. No study has demonstrated greater effectiveness of the multisensory system for cognitive rehabilitation and in fact, it may be deleterious. Sensory inputs in VR cannot be regarding as additive or only associated with brain speed of processing; they are highly integrative and context dependent. Two
mechanisms of bottom-up processing versus top-down processing are involved in sensory processing. Perception must be largely data-driven because it must accurately reflect events in the outside world. In many situations, however, our knowledge or expectations will influence perception. This is called schema-driven or top-down processing. ‘Top-down’ processes describe knowledge-driven mechanisms. Bottom-up perspectives attempt to explain a subject’s ability to detect targets and target-triggered attentional processing largely by the sensory salience of the targets, and their ability to trigger attentional processing by recruiting ‘higher’ cortical areas in a bottom-up manner (e.g., from overlaps and differences the processing of a visual target in the primary visual cortex to temporal regions for object identification and to parietal regions for location). Importantly, ‘top-down’ and ‘bottom-up’ processes represent overlapping organizational principles rather than dichotomous constructs, and in most situations, top-down and bottom-up processes interact to optimize attentional performance (Egeth & Yantis 1997, Sarter et al. 2001). Top down processing – processing based on previous knowledge or schemata – allows us to make inferences: to “perceive” or “know” more than is contained in the data. The bottom-up approach of visuo-motor adaptation appears to interact with higher order brain functions related to multisensory integration and can have beneficial effects on sensory processing in different modalities. These findings should stimulate the development of therapeutic approaches aimed at bypassing the affected sensory processing modality by adapting other sensory modalities (Jacquin-Courtois et al. 2010).

Training should include specific strategies designed to help clients compensate for attention deficits and improve performance. Examples of strategies include:

- verbal mediation: whereby patients talk themselves through tasks (e.g., verbalize the stimulus dimension to which they are responding on an alternating attention task);
- rehearsal of specific strategies: such as repeating what they are looking for (e.g., descending number sequences on a sustained attention task);
- self-pacing: to reduce the impact of information overload caused by decreased processing speed, teach people to slow down on tasks and to pause between tasks.

The use of positive self-statements intends to reduce frustration and fatigue (Sohlberg &. Mateer 1987, Brain Injury Interdisciplinary Special Interest Group 2002).

Even if permanent damage is present, the individual can be taught to capitalize on existing potentials and strengths and to use strategies to substitute or compensate for limitations. Performance can be enhanced if the environment or the task is modified to accommodate limitations, which can be allowed by VR environments.

4. CONCLUSIONS

Cognitive rehabilitation is a system of therapeutic activities, based on brain-behavior relationships, directed to achieve functional change by re-establishing or reinforcing previously learned patterns of behavior, establishing new patterns of cognitive activity through compensatory cognitive mechanisms, establishing new patterns of activity through external compensatory mechanisms, enabling persons to adapt to their cognitive disability to improve overall functioning.

Virtual reality has the potential to assist current rehabilitation techniques by offering new opportunities for learning and transfer in brain damage rehabilitation. The main focus of much of the exploratory research performed to date has been to investigate the use of VR in the assessment of cognitive abilities, but there is now a trend for more studies to encompass rehabilitation training strategies. There is considerable potential for using VR in cognitive learning rehabilitation which is only just beginning to be realized. PC-based virtual environments are currently preferred for this purpose, rather than the more immersive virtual environments, because they are relatively inexpensive and portable, and easy to use for patients.

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5. REFERENCES


