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Review

The contribution of virtual reality to the diagnosis of spatial navigation disorders and to the study of the role of navigational aids: A systematic literature review

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ABSTRACT

Introduction: Spatial navigation, which involves higher cognitive functions, is frequently implemented in daily activities, and is critical to the participation of human beings in mainstream environments. Virtual reality is an expanding tool, which enables on one hand the assessment of the cognitive functions involved in spatial navigation, and on the other the rehabilitation of patients with spatial navigation difficulties. Topographical disorientation is a frequent deficit among patients suffering from neurological diseases. The use of virtual environments enables the information incorporated into the virtual environment to be manipulated empirically. But the impact of manipulations seems differ according to their nature (quantity, occurrence, and characteristics of the stimuli) and the target population.
Methods: We performed a systematic review of research on virtual spatial navigation covering the period from 2005 to 2015. We focused first on the contribution of virtual spatial navigation for patients with brain injury or schizophrenia, or in the context of ageing and dementia, and then on the impact of visual or auditory stimuli on virtual spatial navigation.
Results: On the basis of 6521 abstracts identified in 2 databases (Pubmed and Scopus) with the keywords « navigation » and « virtual », 1103 abstracts were selected by adding the keywords "ageing", "dementia", "brain injury", "stroke", "schizophrenia", "aid", "help", "stimulus" and "cue"; Among these, 63 articles were included in the present qualitative analysis.
Conclusion: Unlike pencil-and-paper tests, virtual reality is useful to assess large-scale navigation strategies in patients with brain injury or schizophrenia, or in the context of ageing and dementia. Better knowledge about both the impact of the different aids and the cognitive processes involved is essential for the use of aids in neurorehabilitation.

1. Introduction

Finding one's way around an environment, whether or not it is familiar, is a common situation for humans. People frequently need to move from one point to another, according to a trajectory that may or may not be known in advance, using different elements – external aids, landmarks or other sources of relevant information. This ability is essential, because it underpins the person's autonomy and his or her participation in society. Spatial navigation has raised interest, and has been the subject of much research in mammals (including humans) on account of its particular integrative role in linking functions in the areas of neurophysiology, learning, memory and cognition [1].

For a number of years, numerous clinical descriptions of brain-injured patients presenting selective losses of the ability to find their way have been undertaken. This disorder has been termed "topographical disorientation" [2]. But there is wide diversity in the types of topographical disorientation observed in these

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patients, and also in the type of brain injury incurred [3]. In addition, the evaluations used to characterise the disorders have been diverse and non-standardised [4].

To start with, tests of spatial cognition on a small scale were elaborated, in the form of "pencil-and-paper" tests, such as the Rotation Mental Test [5] or the Guilford and Zimmermann spatial orientation test. Hegarty et al. [6] showed only partial correlation between paper-and-pencil visuo-spatial tests on a small scale and tests in large-scale virtual or real environments. Spatial navigation in large spaces thus seems to require skills other than those assessed in paper-and-pencil tests. This study concluded to poor ecological validity of pencil-and-paper tests, and confirmed the usefulness of assessing spatial navigation in a large-scale environment, whether real of virtual. Indeed, several authors, among whom Cushman et al. [7], have shown a correlation in navigation performances between real and virtual environments.

The progress in computing and its widespread use from the 1990s have enabled the modelling of simulated environments that are close to reality, known as virtual reality environments. Virtual reality rapidly demonstrated its potential usefulness in clinical practice, in particular in the areas of cognitive evaluation and rehabilitation, and well as for the study of cognitive processes in humans [4]. The evaluation of navigation in a virtual environment has various advantages over evaluation in real situations [8]: it enables better scientific monitoring, it can allow for deficits and disabilities that sometimes make evaluation problematic in real situations, it is less costly, and also safer. From a functional and behavioural viewpoint, it enables immediate feedback on performances in various sensory forms and modes, controlled administration of cues so as to improve performances in a learning approach, and it also enables "time-out" to make room for discussion and the inclusion of different methods.

Following the publication of numerous studies that have shown the advantages of the virtual setting in the area of spatial cognition, it seemed important to us to perform an up-to-date review on the contributions of the use of virtual reality in the exploration of spatial navigation, especially in populations with cognitive impairments. These patients are particularly likely to present spatial cognition disorders, which are highly damaging for social participation in their ordinary environments [2,3]. In addition, the clinical use of virtual environments, because it enables more strict experimental control than working in a real environment, makes it possible to measure the influence of different components brought into play on spatial navigation performances. Thus environmental cues are used as sensory cues of the bottom-up type, and provide scope for investigation, where the use of virtual reality has much to contribute. The review presented here has two objectives: the first is to detail the clinical use of virtual reality in spatial navigation in populations with cognitive disorders; the second is to provide an update on the literature on the impact on virtual spatial navigation of using visual and auditory environmental cues.

2. Methods

This review was conducted on two medical databases, PubMed and Scopus (for the Scopus database, only articles in the area of the health sciences were searched). The following Mesh keywords were used: "navigation", "virtual", "ageing", "dementia", "brain injury", "schizophrenia", "stroke", "cue", "help", "aid", and "stimulus". The basic search algorithm was "navigation AND virtual" to which all the other keywords were associated in turn. The processing of results was performed according to Prisma guidelines. Articles published in English in the area of the life sciences from 2005 to June 2015 were retained. The articles were selected on the basis of title and abstract. The final selection was discussed by the three authors of the present article (MC, PAJ, ES) with respect to the two objectives defined above. A flow diagram (Fig. 1) illustrates the article selection procedure.

In all, 44 articles complying with the first objective and 19 with the second objective were retained. The main characteristics of these articles are summed up in Tables 1 and 2 using the following characteristics: first author, virtual environment used, population (numbers and type) study objective and main result.

3. Results

3.1. Contributions of spatial navigation in virtual reality in different populations presenting cognitive disturbances

3.1.1. Spatial navigation and normal ageing

The effect of ageing on navigation skills in large spaces has been widely described [9]. Generally speaking, the remembrance of spatial configurations and landmarks during navigation loses precision with age [10], while paradoxically, learning a route from an aerial view appears, according to certain authors, to be preserved [11]. More specifically, different studies in virtual reality setting have shown alterations in the allocentric processing of information (i.e. spatial configurations) among elderly subjects using a virtual water maze [12], other maze models (wall maze, radial maze) [13–16], or virtual city districts [17,18]. Similarly, other studies using mazes or other virtual environments evidence difficulties in acquiring spatial representations thought to result from an age-linked decline in hippocampus function, which appears to spontaneously direct elderly subjects towards the use of egocentric strategies [19–23]. A recent study comparing a virtual and a real city district however showed that elderly subjects encounter greater difficulties than young subjects in finding their way, this being related to decline in executive functions, while the spatial knowledge acquired in the virtual environment did not significantly differ between the two groups. This age-linked executive decline, affecting planning and the choice of appropriate navigation strategies, is confirmed by different studies [9,12]. However certain elderly subjects retain better abilities to adapt their strategies [14]. This observation is not however confirmed in the study by Carelli et al. [13]. Finally, for certain authors, failure to efficiently integrate sensory-motor information could also be implicated in the deterioration of spatial navigation skills [25–28]. Overall, virtual reality studies indicate that navigation disturbances in the course of normal ageing is multi-determined, and has origins that can be mnesic (allocentric processing associated with hippocampus function), executive (strategic processing associated with front-lobe function) or related to sensory-motor integration (integration of the itinerary associated with the retrosplenial cortex).

3.1.2. Spatial navigation and Alzheimer-type dementia

Altered large-scale spatial cognition in Alzheimer-type dementia (ATD) has been described in different studies using virtual reality [7,17,29,30]. The study by Ballassen et al. [31] suggests that memory of the temporal type in the course of a navigation task, which tends to be related to allocentric strategies, is a selective behavioural marker for ATD. Topographical disorientation is often considered to be a prodromal sign of this pathology, and has led authors to use virtual environments in order to objectify the early signs and evidence the underlying neurological correlates [32–34]. Weniger et al. [30] retrospectively compared the spatial navigation performances of a group of patients with mild cognitive impairment (MCI) that evolved towards ATD and a group of MCI patients who did not evolve towards ATD. The authors did not

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