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Virtual Reality and Spatial Cognition

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Abstract:

With this article the significance of Virtual Reality within the field of spatial cognition is outlined. The role of Virtual Reality is grouped in three sections addressing (i) the current and latest technology of Virtual Reality regarding the two main functions within Virtual Reality, i.e., technology to interact with Virtuality (input devices used to record observer actions and output devices used to simulate sensory stimuli) and technology for presenting the virtual environments to the user, (ii) the usage of this technology for the purpose of research in the field of spatial cognition regarding behavioral and neuronal processes (discussing advantages and disadvantages of Virtual Reality), and (iii) Virtual Reality experiments and their results relevant in current research of spatial cognition covering place memory, wayfinding in large scale spaces, and the neural representations of spatial features.

Keywords:

immersion, navigation, place memory, presence, spatial cognition, Virtual Reality, wayfinding

Body text:

The term Virtual Reality was first used and introduced by Jaron Lanier in 1989. By definition, Virtual Reality is a collection of technologies for generating a human-computer-interface that allows people to interact efficiently with, become immersed in, and to feel present in computerized 3D environments, while using their natural senses and motor skills in real time. Here, immersion refers to the technical capability of the system to deliver a surrounding and convincing environment with which the user can interact. Presence is the sense of being (embodied) in a virtual environment rather than in the physical space where the real user's body is actually located.
During the last years, computer technology has improved substantially and with it factors supporting immersion and presence. Improvements concern the complexity and richness of detail of the virtual environments displayed or the diversity and fidelity of sensory and motor interactions involved in the Virtuality. The next sections will address these advancements and discuss their application within the field of spatial cognition.

1. The technology of Virtual Reality

Virtual Reality is largely based on computer graphics. The quality of computer graphics increased substantially within the last years affecting features such as the size of virtual environments, their level of detail, the realism of surface texture, the modeling of illumination, shading, and shadowing, and the animation of objects and avatars. At the same time, the fidelity of sound and the speed of rendering (i.e., the process of computing a 2D image from a 3D database) have improved. Through these advancements, virtual environments are now able to closely approximate real world conditions. As result of a development mostly driven by the computer game industry, graphics engines are now frequently available as Open-Source-Software (e.g., Unreal Engine 3, CryENGINE 3, OpenSceneGraph, and Ogre3D) and run on cheap, custom hardware with satisfactory results, i.e., engines enable rendering of and allow interactions with virtual environments in real-time and in a highly realistic manner.

In terms of interaction with virtual environments, users can rely on classical devices like the computer mouse, joystick, and gamepad (Figure 1a) to act in the virtual space. In addition, a large number of more sophisticated devices have been developed for special purposes. The flystick is an extended joystick where the position is tracked in 6 degrees of freedom; Figure 1b). The Phantom® device combines position sensing of a single finger with force feedback to that finger to create a closed loop of haptic interaction. Motion capture with devices such as the Kinect controller (Microsoft®) is now common even in the consumer market. High-precision motion capturing of the head, the hand (e.g., dataglove; Figure 1c), or the whole body allows the use of real body movements to alter the viewing direction, to manipulate objects, to change the body position, or to do all these actions together in the Virtual Reality. Furthermore, body capturing can be used to animate an avatar (a virtual agent), usually a person who is visible within a virtual environment and can interact with it. Movement devices such as the VirtuSphere (Figure 1d) or the omnidirectional 'Cyberwalk' treadmill (Figure 1e) allow users to walk for unlimited distances within a virtual environment thus expanding the physical limitations of a restricted tracking space in laboratory rooms. Furthermore, such movement devices facilitate the sense of real walking and provide movement tracking at the same time - a combination hardly to realize in reality.

<Figure 1 near here>

Concerning visual stimulation, today a huge amount of devices is available which allow the presentation of virtual sceneries to the user. In most cases stimuli are presented on flat desktop screens, covering just a restricted part of the human field of view. Usually, users have to rely on a mouse or a keyboard to interact. A more direct interaction becomes possible when using head tracking together with a head mounted display (Figure 1a). In a head mounted display stimuli are presented by the use of two small LCD-screens placed in front of the eyes in order to interlink real head movements with rotations and translations in the virtual world. Such head mounted displays are also applied when walking on treadmills or in walking spheres (see above). Stimulating the entire field of view of a human subject requires large projection screens (curved or flat; Figure 2) or the combination of multiple such screens in a so called Cave. Furthermore, stereoscopic stimulation can increase the feeling of immersion by providing realistic binocular depth cues. Stereoscopic 3D effects are produced by means of head mounted displays, anaglyph glasses, shutter glasses, polarization glasses, or by special 3D displays.

<Figure 2 near here>

2. The application of Virtual Reality in spatial cognition

In the field of spatial cognition researchers investigate behavioral and neuronal processes associated with the perception, representation, revision, and utilization of knowledge about spatial environments or conditions and the behaviors bearing on such knowledge. Spatial knowledge is apparently associated with locations of something in relation to a spatial reference. Research on behavior attainments focuses on orienting in spatial layouts, homing (i.e., the ability to find the way back to a certain home place), pointing towards goals in an environment, extracting visuo-spatial information by head and eye movements, navigating in large scale (urban or cluttered) environments or mazes, and the communication about spatial facts. Concerning neuronal processes, questions about brain areas involved in spatial cognition, the representational format as well as the metrics of spatial codes, the involvement of different senses (i.e., multisensory processing), and the characteristics of spatial features crucial for spatial behavior are examined.

Spatial cognition research is often closely related to Virtual Reality technology. In fact, for the majority of research questions, the simulation of spatial conditions is a requirement that at least substantially simplifies the experimental procedures. Imagine a navigational experiment where subjects have to find certain routes within a town or another large scale terrain. Here, it would be hardly possible to ensure repeatability in a highly controlled manner when performing such a task in a real urban environment. Furthermore, manipulations of the spatial layout or metrics, objects within the scenery, or the sensorimotor processing cannot be realized. Consequently, spatial cognition profits greatly from the advancements in Virtual Reality technology:

- Virtual Reality is highly controllable and makes procedures repeatable with respect to the design of the environment and the way of interacting with it.
- Body position, pointing direction, and exploration movements can be measured with high precision in real time.
- Manipulations of the environment, of viewpoints or metrics of the virtual space (e.g., physical inconsistencies or non-Euclidean metrics), and of interactions with the Virtual Reality are possible in real time.
- Different sensory modalities related to spatial perception can be tested selectively and can be brought into competition with one another in order to estimate their relative contributions for a given task.
- Virtual Reality enables the measurement of spatial behavior in large-scale environments also under real walking conditions (e.g., treadmill or walking sphere)
- Virtual Reality enables recordings of neuronal activities during spatial performance (e.g., by use of EEG or fMRI). Single or multi-cell recordings are done in rats or mice using an adapted version of the walking sphere (e.g., Hölscher et al., 2005; Figure 4).
- Experiments in the real space may be inappropriate or impossible because of inaccessibility, cost, excessive danger, security requirements, etc. These limitations can be bypassed when using Virtual Reality.

On the other hand, Virtual Reality entails some disadvantages or attentions the user must take into consideration. Cyber- or simulator sickness is one of them (Stanney et al., 1998). It can be caused by temporal interrupts or delays in the interaction and stimulation due to hard- or software processes or by cross-sensory conflicts between vestibular and visual stimuli. For example, the perception of self-movement (vection)

can be induced purely visually without stimulating the vestibular or the proprioceptive system, yielding a conflict which might result in simulator sickness. The symptoms of this sickness include disorientation, disequilibrium, drowsiness, salivation, sweating, and vomiting. Another aspect when using Virtual Reality is the conflict between the virtual and the physical reality. Both environments might be represented partially at the same time and generate conflict between each other, for example, when a virtual and a real room differ in orientation (cf., May, 2004). Just like with simulator sickness, the amount of disturbance will depend on the used setup and the task at hand.
In Virtual Reality the user is always confronted with virtual stimuli, generated by a certain technology to simulate the reality. The degree of realism in Virtual Reality as well as the way of presentation and interaction has to be chosen with respect to the scientific question or the kind of task to investigate. Hence, experimenters need the knowledge about the range of possibilities when simulating real conditions. Additionally, when applying virtual environments, the user needs a certain amount of training to get familiar with the simulated realism. Setups for Virtual Reality can also be very expensive and need a high amount of engineering power for successful running (e.g., Cave or treadmill setup).

3. Spatial Cognition: Experiments in Virtual Reality

Virtual Reality is applied in various research areas including spatial cognition. The following experiments in human and animal navigation will show how virtual reality can contribute to examining such a field. These examples address (i) the contribution of different information sources, (ii) the selection of environmental features, and (iii) the neuronal implementation in the brain.

Virtual Reality can help to identifying whether humans integrate and memorize their paths walked and/or rather rely on visual information such as landmarks (i.e., environmental, salient objects - easy to recognize) encountered. Foo et al. (2004) had participants physically walk through a hall while displaying a virtual environment to them via a head mounted display. When putting spatial information derived from paths walked before and visual landmarks into conflict, participants heavily relied on visual landmarks and tended to ignore conflicting body information. So in the case of conflict, humans identify locations visually rather than use on body based information. However, body cues do contribute in addition to visual information as well. Ruddle et al. (2011) compared walking through a large scale space on an omnidirectional treadmill with navigating the same space only visually. Participant's direction and distance estimates to remote locations profited from physical walking distances within the environment, but not from physical rotations alone as compared to navigating only visually. Although humans do rely mainly on visual information, body-based cues especially traversing distances contribute to our memory as well.

If vision is important, which features of the visual information are used by navigators? Steck & Mallot (2000) displayed local and global landmarks (i.e., houses and mountains) on a screen covering 180° of the horizontal field of view. Participants memorized both types of landmarks using them to retrace a route when the one or other type was absent. When putting local and global landmarks into conflict (by displacing the global ones) participants showed quite individual preferences. Stankievicz & Kalia (2007) had participants navigate through a virtual maze with certain objects and intersections appearing rarely or more often. Subjects relied more strongly on landmarks which were more salient or specific. Structural landmarks such as walls were valued higher than object landmarks. Humans seem flexible with respect to which visual information to use. In general, they focus on informative landmarks and on the surrounding geometry. Gillner et al. (2008) used virtual reality to generate an environment where smooth color distributions provided the sole cue to position while features and objects that could have provided landmark information were absent. Still, subjects were able to home and recognize places, indicating that a simple, 'snapshot-matching' mechanism of place recognition is available to humans.

<Figure 3 near here>

Virtual Reality can not only be used to examine newly learned spaces. Frankenstein et al. (2012) asked inhabitants of Tübingen to point to locations within a photorealistic model of their hometown (Virtual Tübingen; Figure 2 and 3). Participants performed the more accurately the more closely they were facing North within Virtual Tübingen and their pointing performance did not differ at all for close-by and far away pointing targets. This indicates that spatial memory within their hometown was acquired from maps and combined with a different source of information, namely navigation-based information in order to point from within an environment.

Virtual Reality is also highly suited to examining the neural basis of location memory and navigation. This is, for example, done by measuring brain activity during moving through a virtual environment. In an early study, Maguire et al. (1998) showed that visual navigation as compared to simply following an indicated path is associated with activity in parietal areas and the hippocampus. The more directly navigators approached a familiar route the higher was hippocampal activation. Wolbers & Büchel (2005) showed that the integration of locally experienced views within a virtual environment is paralleled by increased hippocampal activity. Hippocampus is involved in relating multiple views; other regions are involved in different aspects of navigation. Janzen & Weststeijn (2007) showed that the relevance of landmarks (i.e., whether they were located at decision points or at non-decision points) is processed in the parahippocampus, whereas the processing of route order is related to various other structures, for example, parietal areas.

<Figure 4 near here>

Virtual reality is not limited to humans. Dombeck et al. (2010) as well as Hölscher et al. (2005) had rats walking a movable sphere while displaying their progression visually (Figure 4). During that they measured electric currents in implanted electrodes within the hippocampus and identified so called place cells - cells which code for a certain location within the space (O'Keefe & Dostrovsky, 1971). This shows that even animals react towards a Virtual Reality in a way they behave within real environments.

The examples show how Virtual Reality can be fruitfully used within spatial cognition research. Despite some disadvantages such as the occurrence of simulator sickness, Virtual Reality allows for highly realistic stimulation while at the same time keeping full experimental control. With the technology further improving and especially becoming cheaper and more easy to use Virtual Realities will also become more widespread not just within spatial cognition research.

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Illustrations, Tables and Multimedia:

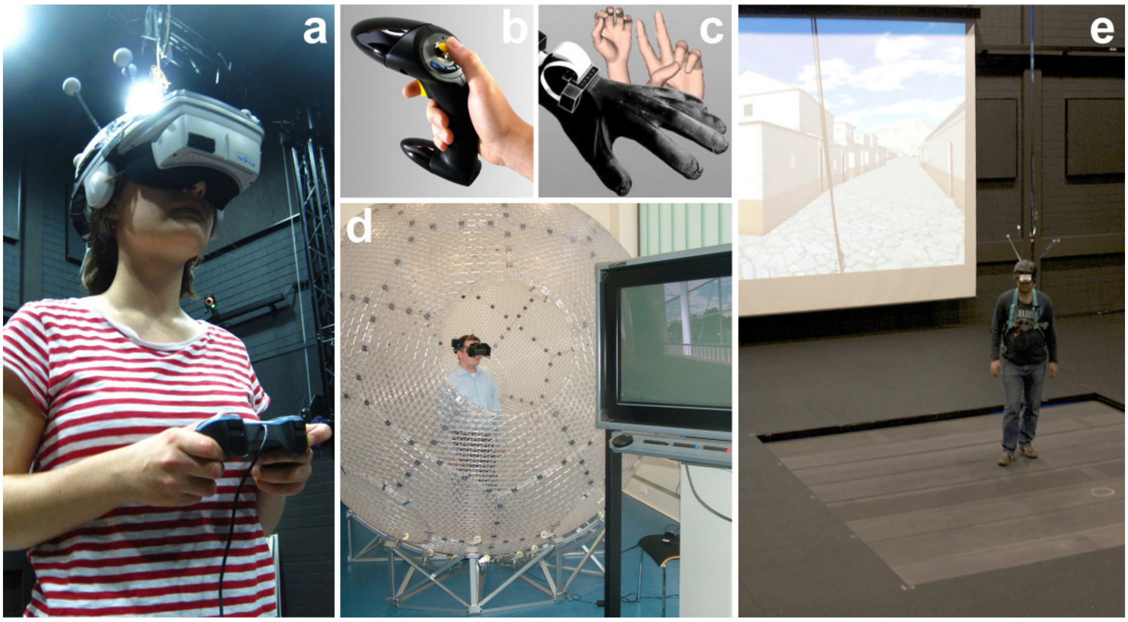

Figure 1: Devices for interacting with and presenting of virtual environments. a) Subject is using a gamepad to interact within a virtual environment presented via head mounted display (from Max-Planck-Institute for Biological Cybernetics, Tübingen). b) Flystick to

interact in all possible degrees of freedom. c) Data glove to control the movement of a virtual hand. d) Subject is walking in the VirtuSphere (from Cognitive Neuroinformatics, University of Bremen). e) Subject walking on the omnidirectional ‘Cyberwalk’ treadmill (from Max-Planck-Institute for Biological Cybernetics, Tübingen; http://www.cyberwalk-project.org/).

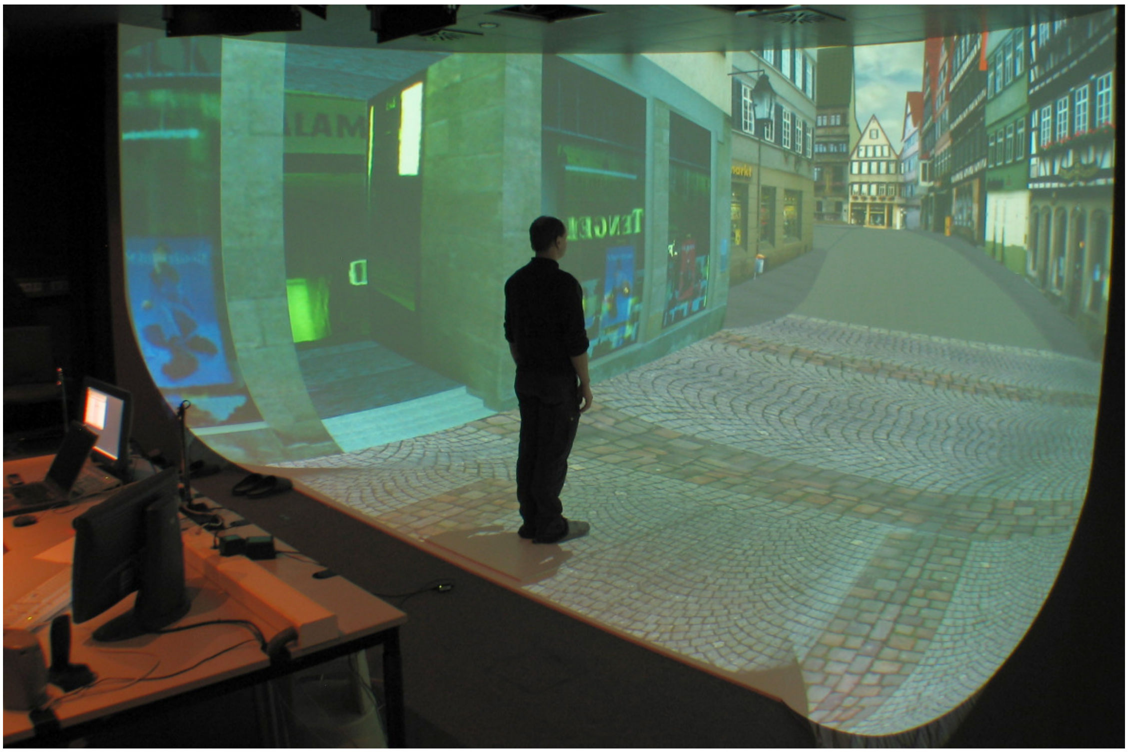

Figure 2: Virtual Tübingen displayed in the PanoLab, a wide-area high realistic projection system for interactive presentations of virtual environments (http://virtual.tuebingen.mpg.de/PanoLab.html)

Figure 3: Virtual Tübingen. View on the city hall from the virtual model of Tübingen, Germany (http://virtual.tuebingen.mpg.de/). Virtual Tübingen was used in Frankenstein et al. (2012).

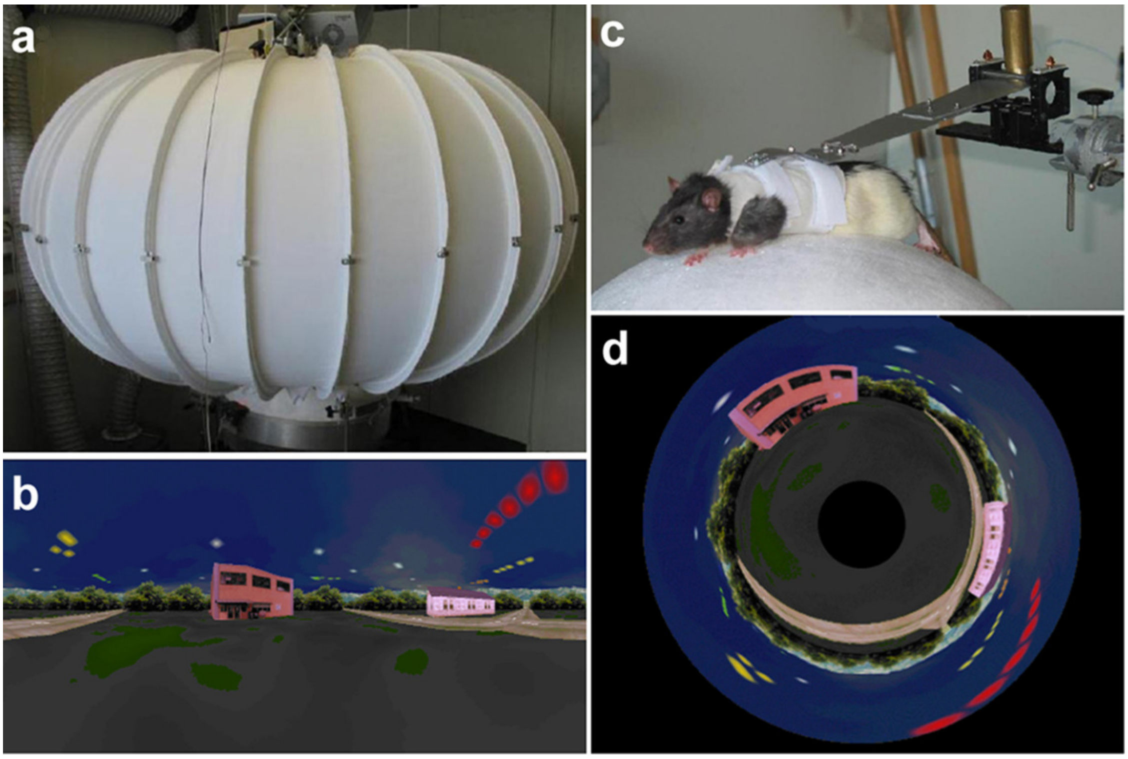

Figure 4: Virtual Reality projection setup for rats running on top of an air-cushioned polystyrene sphere as used in Hölscher et al. (2005). a) 360° projection screen. b) Image generated by the world cameras with a 360° field of view in horizontal direction. c) Rat

fixed on top of the sphere is located inside of the screen. d) Distorted image projected via one video projector onto the 360° projection screen.

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Cross References: