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Evaluation of Spatial Processing in Virtual Reality Using Functional Magnetic Resonance Imaging (fMRI)

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Abstract

While the ecological validity of virtual reality (VR) applications is usually assessed by behavioral data or interrogation, an alternative approach on a neuronal level is offered by brain imaging methods. Because it is yet unclear if 3D space in virtual environments is processed analogically to the real world, we conducted a study investigating virtual spatial processing in the brain using functional magnetic resonance imaging (fMRI). Results show differences in VR spatial brain processing as compared to known brain activations in reality. Identifying differences and commonalities of brain processing in VR reveals limitations and holds important implications for VR therapy and training tools. When VR therapy aims at the rehabilitation of brain function and activity, differences in brain processing have to be taken into account for designing effective VR training tools. Furthermore, for an evaluation of possible restoration effects caused by VR training, it is necessary to integrate information about the brain activation networks elicited by the training. The present study provides an example for demonstrating the benefit of fMRI as an evaluation tool for the mental processes involved in virtual environments.

Introduction

IN THE DOMAINS of psychotherapy and rehabilitation, virtual environments (VEs) are applied to treat patients. Virtual reality (VR) enables the therapist to create real world scenarios which can be manipulated freely and quit immediately if required.

From a therapist's point of view, the quality of a VR training or therapy is determined by its achieved impact on everyday life. This is referred to as *ecological validity*. The ecological validity of a VR therapy is usually assessed by the transfer of progress obtained in VR to the real world. For instance, in case of acrophobia, VR training is considered to be ecologically valid if it enables the participant to climb real, not only virtual, heights.[1]

The quality of applications is described in terms of immersion and presence. These criteria are prerequisites for achieving ecological validity. While immersion refers to the technical performance of a VR application, presence describes the user's subjective psychological response to a VR system.[2] It is assumed that high levels of immersion cause an increased sense of presence and a more realistic experience.[3] Because presence is an individual and context-dependent user response, it is usually assessed by subjective interrogation.

It is presumed that ecological validity is limited by the fact that VR does not perfectly mimic the real world. The computer-generated VE does not perfectly simulate our sensory input and output. Heterogeneous results have been reported concerning the equivalence of perception and action in VR and the real world.[4–6]

A well-known difference when using stereoscopic displays is the contorted depth perception induced by presenting images on one surface. Focus cues such as accommodation and blur in the retinal image specify rather the depth of the display than the depth of the simulated objects.[7] Furthermore, there is a mismatch between accommodation and convergence on a virtual object. While eye convergence is the angle with which both eyes fixate an object, accommodation is the refraction of the lenses, which adapts to differential distances.

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In VEs, eyes converge to the object of interest, but accommodation is always adapted to the projection screen, not the object. This vergence-accommodation conflict was recently proven to cause visual fatigue and discomfort.[7] It is thus unclear if 3D objects in VR are processed analogically to the real world.

A method for the investigation of this question is functional magnetic resonance imaging (fMRI), which can serve as an evaluation method for the quality of VR applications. This relatively new evaluation method has been applied in VR applications in several clinical fields, such as woundcare,[8] simulated driving,[9] and smoking craving,[10] as well as in basic research regarding spatial memory[11] and fear conditioning.[12] Differences and commonalities of brain processes in VR and the real world can be identified. This sheds a light on human processing and helps identify crucial aspects of VR that are required to simulate real-world processing.

The investigation of human processing in a spatial VR task by using fMRI demonstrates that brain imaging methods can be used as indicators for the ecological validity and presence of VR applications. If the prerequisites for ecological validity are fulfilled, it enables the therapist to treat patients suffering from impaired spatial processing after brain damage. The VR task could then be used as a training tool for restoring activations in damaged areas of the brain.

Our initial aim was to create a VR therapy system for neglect patients who show a dissociation between near- and far-space processing.[13,14] It was necessary to first validate the VR system in terms of comparability with the real world. As a validation tool, we applied fMRI.

In the present study, we investigated the spatial brain processing of virtual objects in near and far space. Near space is space within arm's reach; far space is the space beyond arm's reach. Several studies carried out in the real world show dissociations between spatial processing in near and far space.[15,16] In the real world, differential brain activations were found for near and far space (i.e., near space was associated with the so-called dorsal visual stream and far space with the ventral stream). The ventral stream, which projects from the primary visual area to the inferotemporal cortex, is associated with the perceptual identification of objects; the dorsal stream projecting from visual areas to the posterior parietal region is linked to visually guided actions directed at such objects.[17] Because near- and far-space processing have been thoroughly investigated in the real world and associated brain areas have been identified, it offers a good foundation for a comparison with VR.

If VR successfully simulates the real world, it is hypothesized that brain processing in VR and the real world would be quite similar. Therefore, we expected brain activations elicited by our VR spatial processing paradigm to be comparable to those found in the real world.

Methods

Participants

Twelve healthy, right-handed male volunteers with a mean age of 25.8 years (20–29 years) participated in the study. Participants were recruited by means of posters and were paid a small allowance. All participants gave informed consent according to the declaration of Helsinki. The study was approved by the local ethics committee.

Spatial processing paradigm

As assessment tool, an equivalent of the line bisection task was chosen because it is a common assessment tool for spatial processing and has been validated in the real world. In the line bisection task, the participant is required to bisect horizontal lines by their perceived center. Impaired spatial processing results in a biased perceived center. To achieve higher ecological validity, everyday 3D objects were chosen instead of abstract 2D horizontal lines. Additionally, not only horizontal but also vertical processing of objects was assessed. For the horizontal task, a test tube on a wooden shelf was created; for the vertical task, a toilet paper roll in a vertically arranged metal holder was chosen (see Fig. 1). Before the testing, participants were informed about the object sizes. All objects corresponded to real-life size and were presented floating in the center of a box-shaped room (size 67.6×39.0×466.7 cm). The room was created as a tight box because the side walls of the room were required to be visible due to the small field of view (FOV) of 30 degrees to serve as spatial reference.

Participants were required to judge if the particular object was centered, shifted to the left, or shifted to the right by pressing an equivalent button. Both the horizontal and vertical objects were presented in near (60 cm) and far (150 cm) distance with 148 trials each. Trial duration was 2.7 seconds, which consisted of a maximum of 2 seconds for judgment followed by a mask of 0.7 seconds. There were three different degrees of shifting: slight shift (0.5 cm), medium shift (1.5 cm), and far shift (2.5 cm) to the left or right of the center, resulting in seven possible positions, including the center position. Relatively small distances were chosen to elicit stronger spatial processing. All positions were presented in randomized order with equal probability.

All stimuli were presented via a VisuaStim XGA head-mounted display (HMD) with a resolution of 1024×768 pixels (see Fig. 2 for task setup). For the presentation of the paradigm and recording of the participants' performance, the ReactorMan software[18] was applied. Synchronization was achieved by an active trigger signal sent by the MRI scanner before each scan started. A fiberoptic-connected button user-input device with three buttons (left, middle, right) was employed for decision interaction. A PC (Athlon XP, 2000 MHz, 2 GB) with a Matrox Millenium P750 graphics card functioned as host system. A more detailed description of the technical setup and challenges and possible solutions concerning the combination of VR and fMRI can be found in Beck et al.[19] General considerations regarding VR-fMRI studies can also be found in Astur et al.[20]

Image acquisition and analysis

Measurements were conducted using a Philips Gyroscan Intera 1.5 Tesla MRI system (Philips Medical Systems, Nederland B.V.) with a standard head coil. Plane functional images were acquired using a T2*-weighted echo planar imaging (EPI) sequence (imaging parameters: $TR = 2800$ ms, $TE = 50$ ms, $FA = 90^\circ$, slices = 30, thickness = 4 mm, gap = 0.4 mm, FOV = 240 mm). In total, 632 volumes (4×158) were collected. Head motion was minimized by using Velcro straps and foam padding.

Functional images were preprocessed and statistically analyzed using SPM2 (Wellcome Department of Imaging

FIG. 1. The horizontal and vertical tasks. **A:** Test tube on wooden shelf. **B:** Toilet paper roll in holder.

Neuroscience, London). Random effects statistical analysis was performed at an intensity threshold of $p = 0.01$ uncorrected with an extent threshold of $k = 13$ voxels. A Monte Carlo simulation with 10,000 iterations demonstrated that this cluster extent cutoff provided an equivalent to the Bonferroni correction with a threshold of $p = 0.05$ corrected for multiple comparisons.[21] All complex contrasts were inclusively masked by the minuend with $p = 0.05$ uncorrected. This was to exclude deactivations.

Results

Brain activations in near and far space were contrasted to discriminate structures that respond stronger to near or to far space respectively. The same procedure was done for both the horizontal and vertical tasks. The contrast images of the horizontal and vertical tasks show activations that are stronger for near space (in red) as well as brain areas that respond more strongly to far space (in green) (Fig. 3). Brain activations of the vertical and horizontal tasks show similar patterns in terms of the ventral and dorsal streams, which points to similar processing of near and far space regardless of the object orientation. Although an extended network was found, when contrasting the near- and far-space conditions in each task, differential extents of dorsal and ventral activations were found for near and far space. While in the far-space versus near-space condition (green color) of the horizontal as well as vertical tasks, more pronounced brain activations along the dorsal stream (postcentral gyrus, inferior and superior parietal lobe) were found, more pronounced activations along the ventral stream (lingual gyrus, middle temporal lobe) were observed in the near-space versus far-space condition (red color).

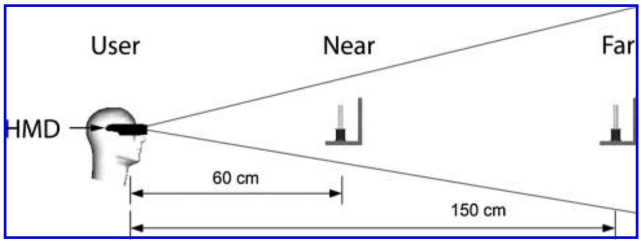

FIG. 2. Schematic view of the task setup including near and far distances.

Discussion

Regarding near and far space, our VR brain imaging results revealed that brain areas involved during spatial processing in VR differ from those involved in spatial processing in the real world. This is in line with the behavioral study mentioned previously in which it was found that virtual distances in VR were underestimated and showed differential performance for near and far space.[4] Our results are contrary to imaging studies carried out in the real world, where stronger activations for near space were found for areas along the dorsal stream and for far space alongside the ventral stream.[15,16]

The fact that VR far-space objects in our study elicited brain activations along the dorsal stream implies that far-space objects were processed spatially as 3D objects. In contrast, the VR near-space objects showed activations along the ventral stream, which points to object identification and recognition processes without spatial reference. It seems that objects in VR near space were processed as simple objects without spatial reference more comparable to 2D objects. Further research is needed to confirm the results.

Regarding the horizontal and vertical tasks, stronger activations can be observed for the vertical task, which indicates that more effort was needed. More effort is usually associated with more pronounced activations.[22] This could be because in everyday life we are more confronted with horizontally shifted objects than with vertically shifted ones. In almost every room, movable objects on horizontal shelves can be found, while movable objects on vertically arranged reference objects are rather sparse. The stronger familiarity of horizontally shiftable objects could have led to weaker brain activations and thus less necessary effort. Further brain imaging studies investigating the differences between horizontal and vertical spatial processing are required to confirm this result.

In summary, the present study showed differences in the spatial processing of VR environments as compared to the real world. Results imply that distances in VR seemingly are not equivalently processed as in the real world. This has an impact on VR training and therapy tools that try to elicit similar brain activity as compared to the real world.

However, there are some limitations of the present study. Because pure spatial processing in a static environment was to be assessed, the study design was kept as simple as

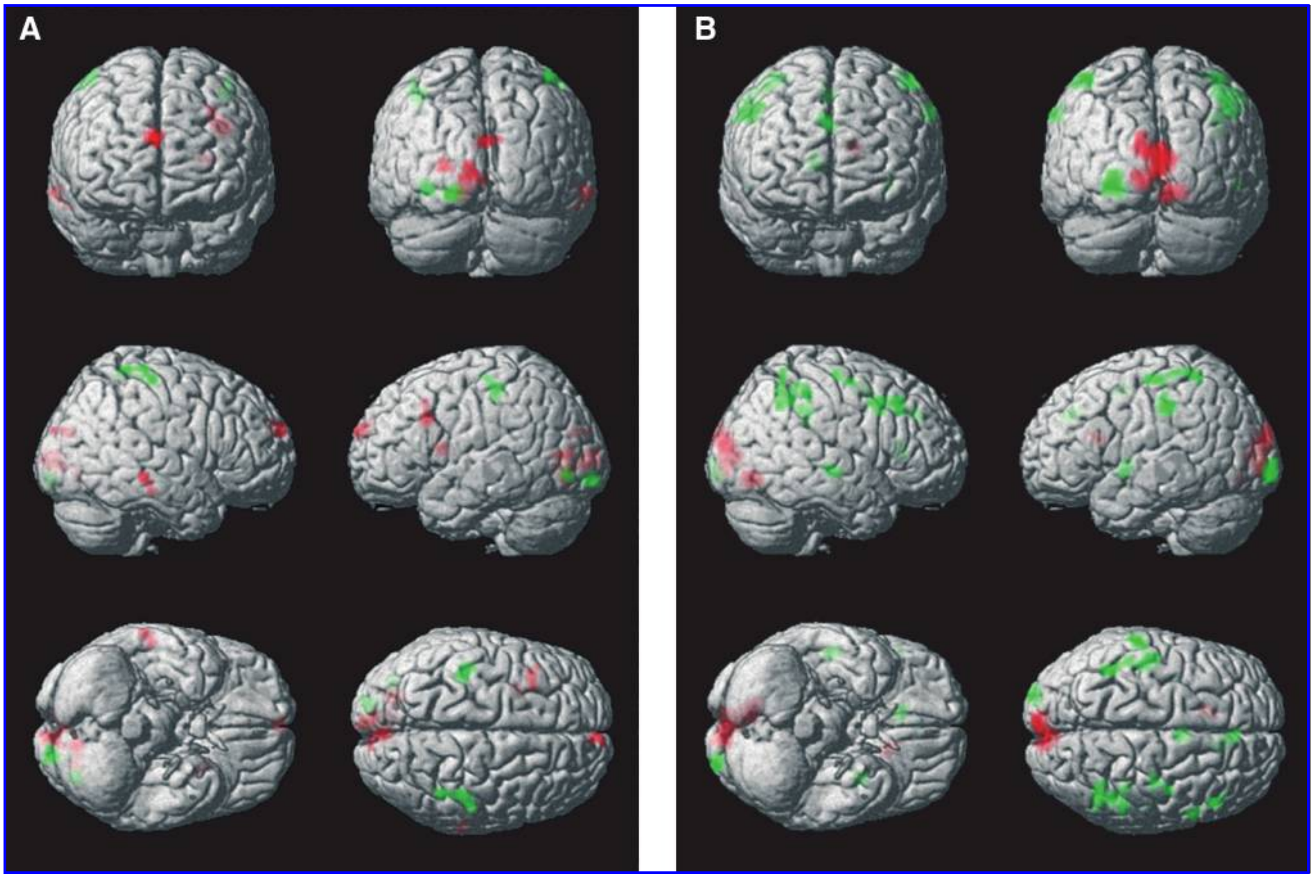

FIG. 3. Near-space activations versus far-space activations. **A:** Horizontal task. **B:** Vertical task. Activations in red indicate stronger activations for near space, activations in green indicate stronger activations for far space.

possible and context information was minimized. This could be a reason why VR objects in far space were processed similarly to real objects in near space. The only depth cues at hand were the eye convergence and the fact that the object size was known. Other deviations from the real world concerned missing depth cues such as additional reference objects or shadows. The differences described between real and virtual space raise the question whether 3D objects in VR can be processed equivalently to real objects in general.

Another limitation relates to hardware. Because specialized hardware was necessary for carrying out an fMRI study, only an HMD with limited resolution and a small field of view was available. The fact that near-space objects were probably processed as 2D rather than 3D objects could be due to near-space objects being less embedded in a spatial context than the far-space objects. Because the employed objects were life sized, the image of the objects in near space (60 cm) appeared to fill out almost the whole HMD, which left only little spatial information of the surrounding box-shaped room visible. As for the far-space condition, the objects appeared smaller and thus left much more of the surrounding room visible. Due to the limitations in equipment and constraints imposed by the configurability of the fMRI environment, it was not possible to carry out a direct comparison of the same paradigm in virtual as well as real space. Results of virtual space processing were rather compared to documented results in previous studies using different line bisection paradigms. For a direct comparison between virtual and real space processing, the same paradigm in virtual as well as real space with the same participants in the same scanner needs to be conducted.

Conclusion

Results of the present study showed differential brain processing of VR near and far space as compared to spatial processing in the real world. Regarding horizontal and vertical objects, results showed that both types of objects are processed similarly in 3D space but with a different degree of mental effort.

These results hold important implications for VR training and therapy tools. Results imply that the mimicking of the real world does not suffice to achieve ecological validity. When VR training and therapy tools aim at restoring brain function and activity, assessing brain activity elicited by these tools is advisable. Differences in brain processing between VR and the real world have to be taken into account when designing VR therapy tools as well as when evaluating possible restitution effects of the brain caused by VR therapy.

The well-known differences between perception in real and virtual space, the present limited technical feasibility, and the fact that VR spatial processing in our study was compared to slightly different paradigms in the real world constitute the constraints of the study.

Even if the presented results were distorted by technical limitations, this raises the question what quality is required to obtain valid results and how this quality can be ensured in applications using VR. The present study thus provides an example for evaluating the ecological validity of VR by investigating neuronal processing in VR as compared to reality.

Concerning VR spatial processing training, further research applying different setups, including context clues, smaller objects, manipulation of the accommodation-vergence conflict, and various spatial distances, are necessary to verify the results. With the employment of better hardware and the integration of technical advancements, the quality of VR applications can be improved in the future. For a validation of the differences in VR and the real world found in the present study, the same paradigms with the same participants in VR as well as in reality using fMRI methods is required.

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Disclosure Statement

No competing financial interests exist.

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