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A novel immersive virtual environment setup for behavioural experiments in humans, tested on spatial memory for environmental spaces

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Abstract. We present a summary of the development of a new virtual reality setup for behavioural experiments in the area of spatial cognition. Most previous virtual reality setups can either not provide accurate body motion cues when participants are moving in a virtual environment, or participants are hindered by cables while walking in virtual environments with a head-mounted display (HMD). Our new setup solves these issues by providing a large, fully trackable walking space, in which a participant with a HMD can walk freely, without being tethered by cables. Two experiments on spatial memory are described, which tested this setup. The results suggest that environmental spaces traversed during wayfinding are memorised in a view-dependent way, i.e., in the local orientation they were experienced, and not with respect to a global reference direction.

1 Introduction

Virtual reality technology enables us to study human behaviour in a closed perception-action loop within a natural environment. This provides a level of sensory realism and dynamic sensory feedback that corresponds closely to experiences in the real world, while at the same time, the experimenter is able to control stimulus aspects. This allows for both reproducible experimental conditions and the systematic variation of environmental features and context. Currently, in most virtual reality setups participants navigate through an environment that is visually displayed on a static screen. In doing so, they lack important ”body cues” indicating their movement, i.e., efference copies, vestibular and proprioceptive feedback. Without these cues orientation performance can drop dramatically (e.g., Klatzky, Loomis, Beall, Chance & Golledge, 1998 [1]). In order to provide these cues while ensuring high realism and at the same time keeping complete control, a new setup for free walking in virtual environments has been built at the new Cyberneum facilities of the MPI for Biological Cybernetics, called the *Tracking Lab*.

2 The Tracking Lab: A New Virtual Reality Setup for Navigation Experiments

In the Tracking Lab, participants are tracked by 16 high-speed motion capture cameras (*Vicon*® *MX 13*) while walking freely in a large hall of 15.3m x 11.7m x 8.4m (height) (Figure 1). The tracking system can capture the motions of persons by processing the images of configurations of multiple infra-red reflective markers in real-time at 120 Hz.

Tracking markers which are attached to the HMD provides accurate real time information about position and orientation of the participant's head in space to the room-mounted tracking system (see Figure 2). These coordinates are transmitted wirelessly (using WLAN) to a high-end notebook computer (*Dell XPS M170*) in the participant's backpack. This notebook is capable of rendering an egocentric view (and also auditory simulation) of a virtual environment in real-time using a *NVIDIA GO 6800 Ultra* graphics card (256 MB RAM). The participant views the scene in stereo by using the HMD. Currently a light-weight *Trivisio*® *3Scope*® stereoscopic HMD is used, which offers a geometric field of view of approximately 32x24 degrees at a resolution of 800x600 pixels for each eye. Figure 2 shows a participant wearing the VR tracking helmet, HMD and backpack. In the near future the Trivisio HMD will be replaced by a Rockwell Collins Proview SR80 HMD which provides both a larger field of view (53° (V) x 63°(H), 80° diagonal FOV) and a higher display resolution (1280x1024 full colour per eye with 100% overlap).

To suppress interference between the real environment and the simulated environment as good as possible, the laboratory can be completely darkened and acoustic panels around the walls are used to suppress acoustic reverberations. In addition, participants can be equipped with active noise-cancelling headphones (*BOSE*®

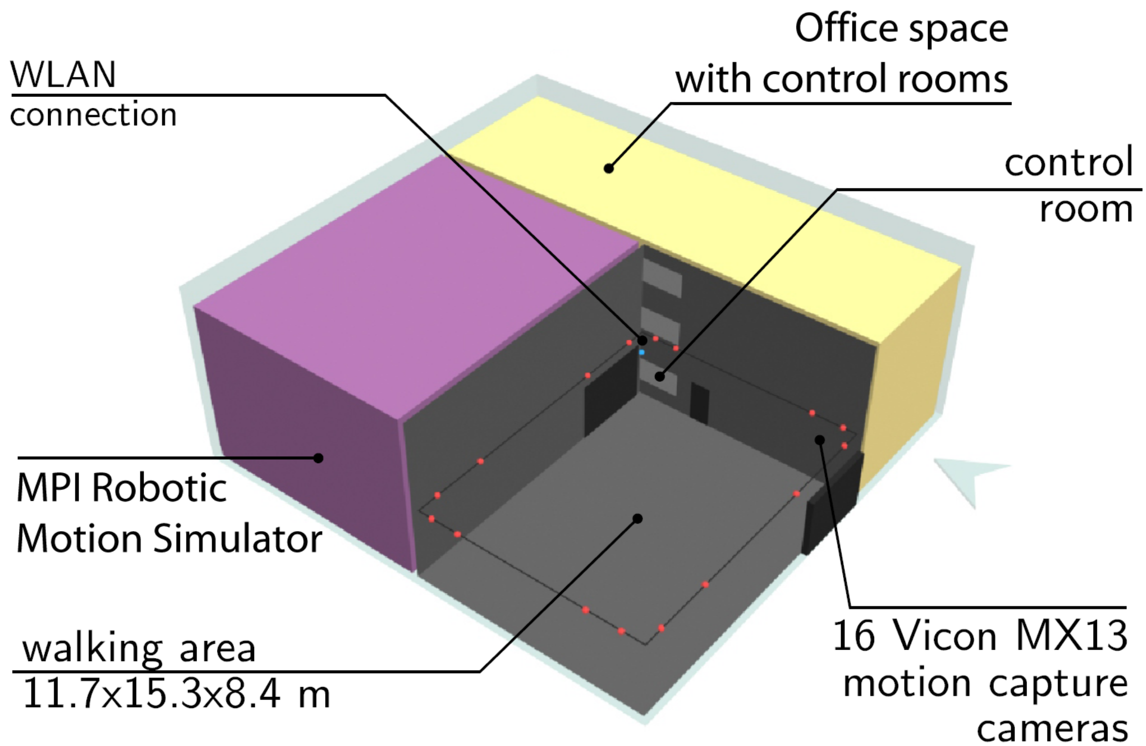

Figure 1: The tracking lab in the Cyberneum building of the MPI for Biological Cybernetics, showing dimensions and approximate location of the tracking cameras.

QuietComfort2®). A black curtain in front of the participant's face is used to reduce external peripheral visual influences that might otherwise disrupt immersion.

Programming of experiments in the Tracking Lab can be done by using the veLib (see http://velib.kyb.mpg.de/index.html), an in-house built C++ programming library for simple and powerful development of Virtual Reality experiments. The veLib provides a unified abstraction layer for communication with various input and output devices, and can load and render virtual environments in real-time by using OpenGL. The *VirTools*® system, which is a commercial programming environment for virtual reality applications, is also used.

3 Memory for environmental spaces – Experiment 1

The new virtual reality setup has proved of value as a flexible experimental setup. This was for example shown in experiments that investigated spatial memory.

3.1 Introduction

3.1.1 Theories about spatial memory

There is an abundance of different and partially conflicting theories about the nature of spatial memory in humans as well as other animals (e.g., Burgess, 2006 [2]; Mallot & Gillner, 2000 [3]; O'Keefe, 1991 [4]; Sholl, 2001 [5]; McNamara & Valiquette, 2004 [6]). These different theories can roughly be categorized with respect to their assumption of how people represent spatial information in long term memory. More specifically, these theories either assume that we store spatial information

1. in an *orientation independent* manner,
2. in an orientation dependent manner with respect to a *reference direction*, or
3. in an orientation dependent manner with respect to the different *experienced directions*

Figure 2: Participant in the Tracking Lab, equipped with tracking helmet, HMD, and notebook computer mounted on a backpack.

Our goal for the current study was to test these three types of theories by designing an experiment in which they produce different predictions that can be experimentally tested. These three theoretical positions are now explained in more detail.

1. Spatial memory is orientation independent. An orientation independent representation has mainly been argued for by Sholl and her colleagues (e.g., Easton & Sholl, 1995 [7]; Holmes & Sholl, 2005 [8]; Sholl, 2001 [5]; Sholl & Nolin, 1997 [9]). They propose an allocentric organisation of environmental knowledge (at least for well known environments). Essentially, this means that object-to-object relations are stored in memory (allocentric), as opposed to self-to-object relations (egocentric). The important implication of this theory is that the memory content can be accessed equally well, independently, of where we are in the environment and which direction we are facing. This implies that there should not be any performance measures that show systematically different results when participants are asked to imagine a previously-learned environment from different perspectives. This critical feature of this theoretical position is why it is referred to as ”orientation independent”. In this orientation-independent approach additional egocentric reference systems are assumed where space is represented not in object-to-object relations but in self-to-object relations. Orientation independence is thought to only occur in well learned environments.

2. Spatial memory is orientation dependent with respect to a reference direction. Reference direction theory also assumes an allocentric, i.e., object-to-object memory for space. The objects, however, are encoded with respect to one or two reference directions, e.g., ”north” (e.g., Mou, McNarama, Valiquette & Rump, 2004 [10]; Rump & McNamara, in press [11]; McNamara & Valiquette 2004 [6]). The axes of coordinate systems which define spatial locations might also be interpreted in that way (e.g., O’Keefe, 1991 [4]). According to this theory, retrieving information from memory (e.g., when being asked to imagine a certain position and orientation in a previously-learned scene) should be easiest, when the to-be-imagined orientation is along one of the reference directions, which should be reflected in better performance (e.g., reduced response times). The memory is consequently said to be ”orientation-dependent” with respect to one or more reference directions. Such a reference direction is proposed to originate either from the initial exposure to an environment (e.g., the first view of a room), or from the

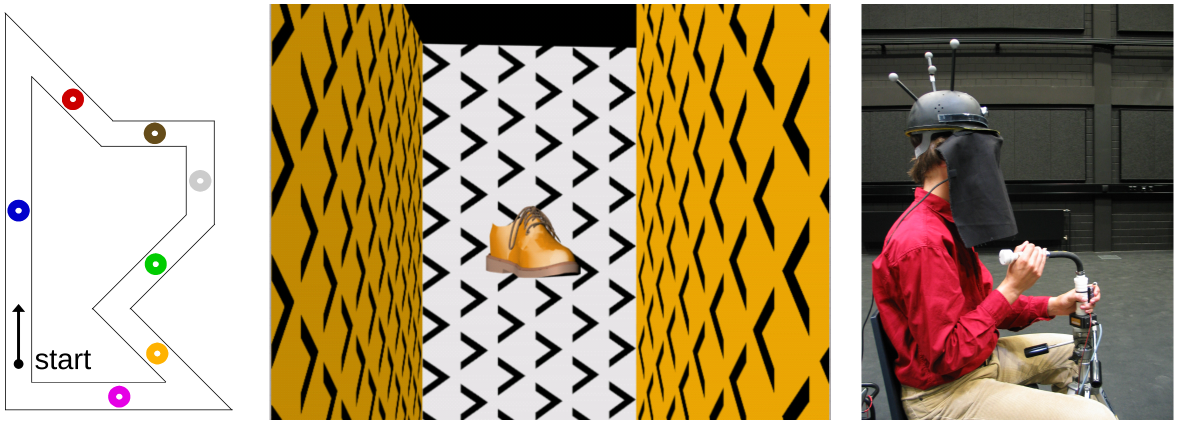

Figure 3: A map of the virtual environment with circles representing objects (left). A perspective screenshot of the environment (middle) and the setup for measuring self-localisation and pointing performance (right).

main orientation or intrinsic axis of an environment. For example, in a rectangular room the reference axis would most likely be aligned with the longer walls of the room.

3. Spatial memory is orientation dependent with respect to experienced views. The third theory is typically referred to as ”view dependent” and assumes the environment to be stored in the local orientation in which it was experienced (e.g., Christou & Bülthoff, 1999 [12]; Mallot & Gillner, 2000 [3]; Wang & Spelke, 2002 [13]). The main implication of view-dependent theory is that performance (e.g., when being asked to imagine a certain position and orientation in a previously-learned scene and point to an object from that imagined perspective) should be best when the to-be-imagined orientation is aligned with the experienced local orientation and decreased for non-matching orientations. This view-dependent memory content is not changed or updated while moving around. According to the definition of Klatzky (1998) [14], such a representation is classified as allocentric, as it is not dependent on the current position and orientation of the navigator. It is stored with respect to the point of view from which it was experienced. This point of view is not changed when moving around. As with the two other theories location-to-location information or allocentric representations are used. Alternatively, view-dependent theory can also be conceptualized as egocentric representations (e.g., Burgess, 2006 [2]; Rump & McNamara, in press [11]; Wang & Spelke, 2002 [13]).

3.1.2 Memory for environmental spaces

All three theoretic positions have found support in various experiments. The supporting evidence, however, depends critically on the kind of space in which they were tested. One basic distinction of spaces is the one between vista and environmental spaces (Montello, 1993 [15]): *”Vista spaces”* are defined as spaces that are bigger than humans and that are visible from a single point of view. Typical examples for vista spaces include most rooms, open squares or even small valleys. Contrary to that, *”environmental spaces”* are defined as spaces where one has to move around and integrate different views to experience all parts. Examples include buildings or towns.

Theories assuming orientation independent memory or orientation dependency with respect to the experienced view have been tested in vista spaces as well as in environmental spaces. A number of experiments that use vista spaces demonstrate orientation dependency with respect to a reference direction (Mou & McNamara, 2002 [16]; Mou, et al., 2004 [10]; McNamara, Rump & Werner, 2003 [17]; Shelton & McNamara, 2001 [18])[1]. It remains an open question whether such a reference direction also underlies memory for environmental spaces. So far no study explicitly tests the three theories in environmental space. Therefore, the goal of the current experiment is to conduct experiments testing the three theories.

[1] In the experiment of McNamara, Rump and Werner (2003) [17] participants pointed to locations on a large open field with a rectangular temple in the middle defining a frame of reference. As many locations could be seen from all other locations this environment can be understood as a vista space rather than an environmental space, despite it being quite large.

3.2 Methods

Eighteen participants (9 women, 9 men; age: M = 25 years, SD = 3.7 years) walked through a virtual environment consisting of seven objects in differently coloured corridors (see Figure 3). Objects were a brush, a telephone, a shoe, a watch, scissors, a banana and a book. Similar objects were used in studies related to the reference direction theory (e.g., Mou et al., 2004 [10]). The participants always walked through the circular environment in one direction, therefore, experiencing views of a corridor from only one direction. The structure of the environment and its initial exposure was arranged to establish a reference axis as predicted by the reference direction theory (see up in the map of Figure 3). A test for recalling objects while walking through empty corridors ensured comparable knowledge levels for all participants. Participants who did not name all objects correctly could walk two extra rounds through the corridors before being asked again. In the following test phase, the participants found themselves at a location where an object had been situated during the learning phase. At this location they faced the experienced direction, i.e., along the corridor, or they faced the reference direction as predicted by the reference direction theory, i.e., upwards in the map of Figure 3, or they faced any of six other possible headings. This resulted in eight possible orientations dividing the whole circle in eight steps by $45°$ which were all tested once. The participants were asked to signal when they had localised themselves in the environment, i.e., press a button when they knew in which corridor in which orientation they were located. We measured the time they took for this self-localisation. Immediately afterwards they were presented with a goal, i.e., a text representing a learned object, in the direction to which they should point as fast as possible with a pointing device (see Figure 3 right side).

The pointing device consists of a pointing handle which is connected to a fixed base by a buckling resistant flexible hose. This allows participants to indicate any direction by moving the pointing handle in that direction. A two-axis acceleration sensor in the pointing handle records static and dynamic accelerations (including gravitational acceleration), from which the pointing direction can be reconstructed with an accuracy of about $1°$. We measured pointing accuracy and pointing time, i.e., the time between presenting the goal object and the end of the pointing motion). The goal objects participants had to point to were chosen randomly as was the order of trials.

3.3 Hypotheses

The experiment was designed such that the three above-mentioned theories about spatial memory would predict different patterns of performance:

1. According to the orientation independent theory, participants should perform equally well for the different directions they are facing in the test phase.

2. The reference direction theory predicts better performance when the current view of the scene is aligned with the reference direction. According to the theory this reference direction correspondes to the ”upward” direction in the map of Figure 3. Furthermore, participants' performance would be expected to vary depending on their orientation with respect to the global reference direction.

3. The view-dependent theory predict best performance when participants are aligned with the viewing direction in which they experienced the environment. This orientation is locally defined by the orientation of the corridor. According to this theory, participants' performance should vary depending on their orientation with respect to the experienced orientation.

3.4 Results & Discussion

The pointing accuracy was quantified as the mean absolute pointing error. It differed significantly from the chance level of 90° ($t(19) = 8.10$, $p < .001$). That is, participants did indeed acquire knowledge of the layout.

No differences in participants' performance due to the global orientation could be found (time for self-localisation, time for pointing and pointing accuracy all $F < 1$). That is, the current data provide no support for the reference direction theory, at least for the stimuli used in this experiment (see Figure 4).

Participants' pointing accuracy varied as a function of local (experienced) orientation (see Figure 5; ANOVA within subjects). As predicted by view-dependent theory participants identified their location and heading faster ($F(7, 119) = 7.0$, $p < .001$, $\eta^2 = .29$) and they pointed more accurately ($F(7, 119) = 2.58$, $p = .017$, $\eta^2 = .13$) when oriented in the direction in which they had experienced the environment, i.e., when aligned with a corridor (see Figure 5). An alternative explanation of a speed-accuracy trade-off could be ruled out (i.e., differences in

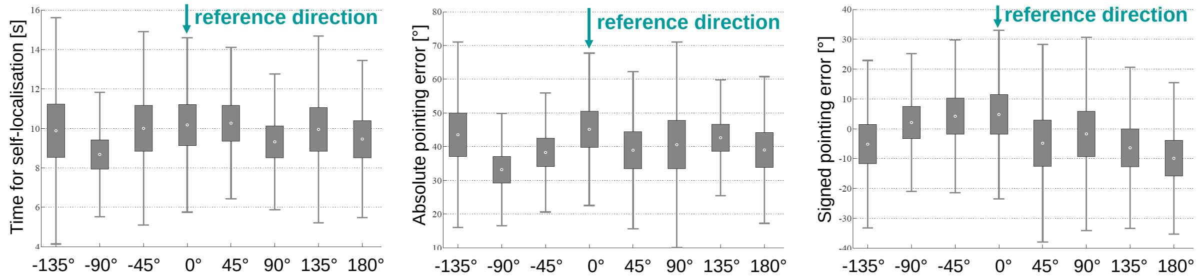

Figure 4: Mean performance, quantified in terms of the time for self localisation (left), absolute pointing error (middle) and signed pointing error (right) as a function of global orientation, i.e., heading relative to the global orientation or reference direction (0°). Means, standard errors (boxes) and standard deviations (whiskers) are displayed.

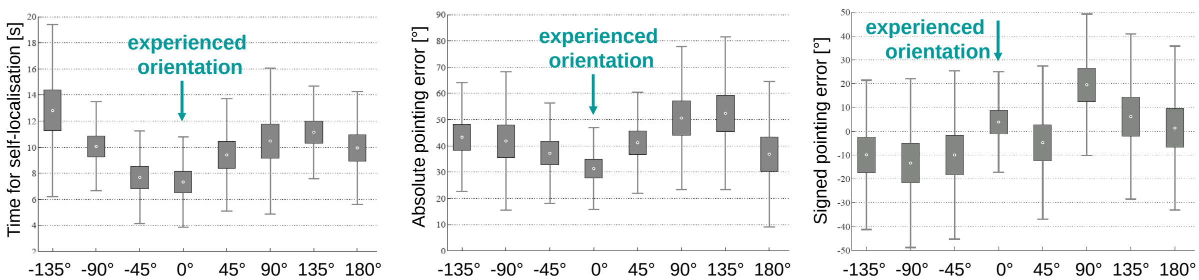

Figure 5: Performance plotted as in Figure 4, but as a function of local orientation, i.e., heading relative to the experienced orientation (0°).

pointing accuracy were due to opposite differences in pointing time), since there was no effect in time for pointing ($F(7, 119) = 2.05$, $p = .054$, $\eta^2 = .11$).

We also directly compared the reference direction theory and the view dependent theory. Participants pointed more accurately ($t(17) = 2.51$, $p = .023$, $d = 0.59$; time for pointing: $t(17) = 1.89$, $p = .075$, $d = 0.45$) and localised themselves more quickly ($t(17) = 5.23$, $p < .001$, $d = 1.25$) when facing the experienced direction than when facing the reference direction (see Figure 6).

Orientation-independent theory would predict equal performance for all facing directions. Our data shows, however, clear orientation dependency with respect to the experienced view. This is inconsistent with orientation-independent theory of mental representations for environmental spaces. The time of exposure to the environment might, however, not have been sufficiently long to form a perspective-free memory of the environment. Using much longer learning times might eventually have lead to different results.

4 Memory for environmental spaces – Experiment 2

4.1 Introduction and Methods

A closer look at the data from Experiment 1 shows that pointing performance for orientations contrary to the experienced local orientations (180° conditions in Figure 5, where participants saw a view of the corridor that was in the opposite direction as the walking direction) was also quite good. This suggests an advantage of being aligned with the corridor, even when facing the direction opposite of the initial walking direction. One potential underlying reason could be that looking along the corridor provided more useful visual cues than when facing the wall of the corridor. For example, the exact facing direction might have been more easily perceivable and a look along the corridor provided a view of the next turn and the texture and color of the next corridor.

For self-localisation performance, however, participants still perform better when looking in the experienced direction (0°) as compared to the opposite direction (180°). Furthermore, during the self localisation phase participants turned their head more often towards the experienced direction than they turn it towards the opposite direction (in average 12 gazes more often per participant $t(13) = 3.43$, $p = .004$, $d = 0.92$). Nevertheless, due to the experimental procedures of the first experiment the initial viewing direction was confounded with the direction that potentially provided more useful visual information.

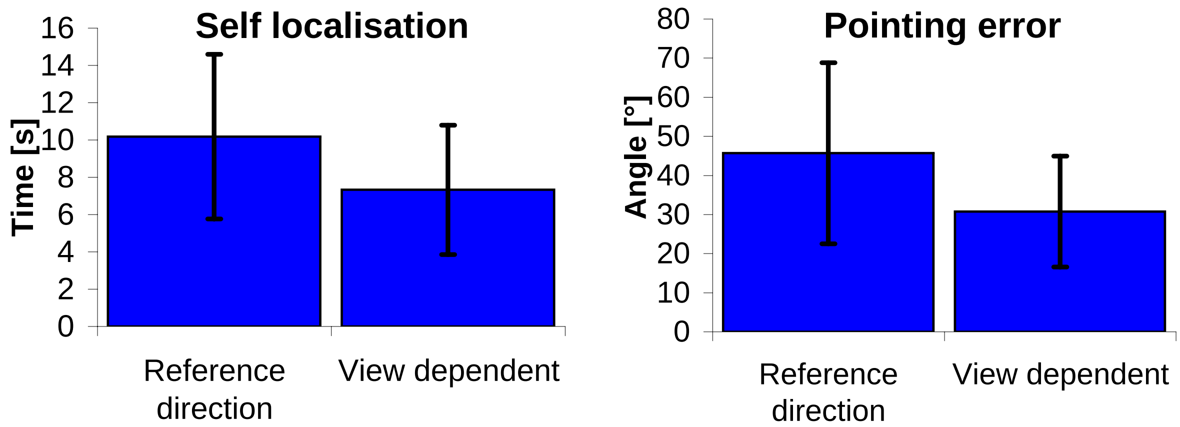

Figure 6: Direct comparison between the orientations participants should perform best as predicted by the reference direction theory (left bars) and by the view-dependent approach (right bars). Means and standard deviations are shown.

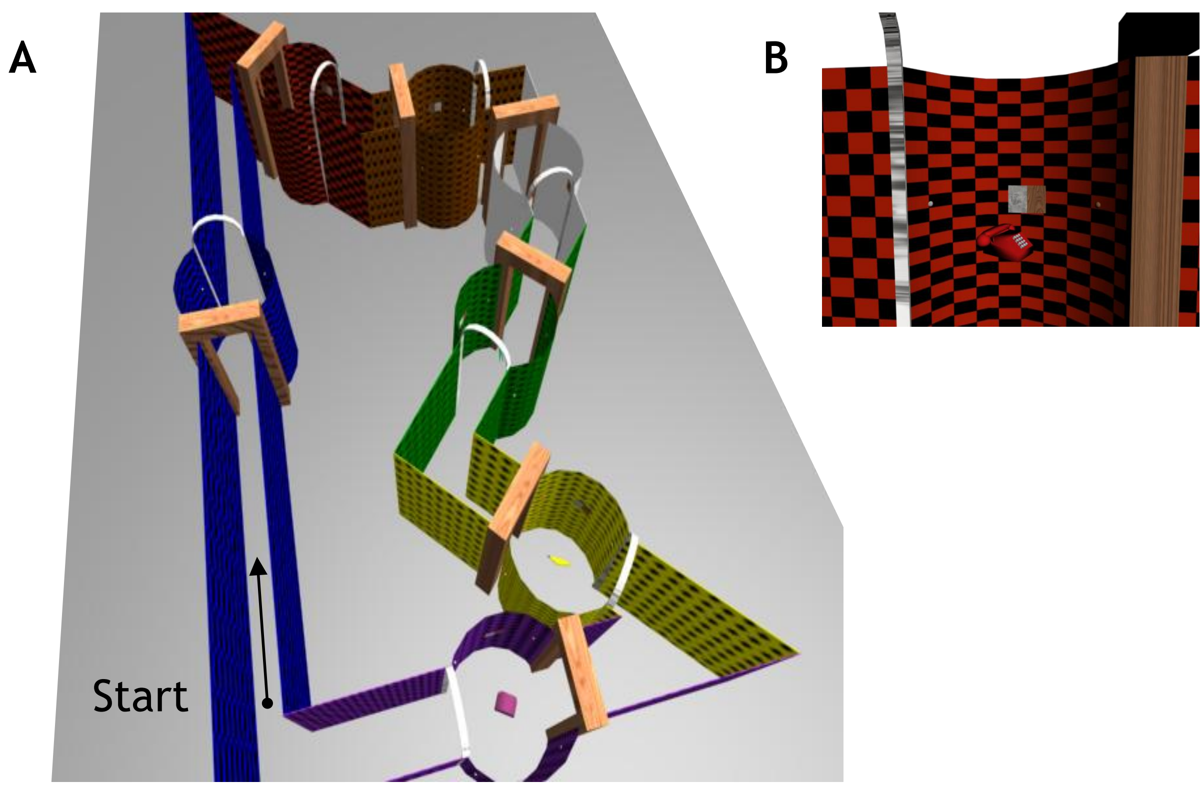

Figure 7: Perspective view of the virtual environment (A) and of the inside of one room (B). Participants always walked around the environment clockwise, starting with the blue corridor. For the test phase, the doors were closed and the objects removed. From inside a room the participants had to, first, identify their location and heading and, second, point to the location of another object.

In order to rule out this influence completely we conducted a second experiment with 20 different, naïve participants (gender-balanced) in which we equalised the visible area by constructing circular rooms around each of the target objects and by closing the entrance and exit doors of the rooms during self-localisation and pointing (see Figure 7). Additionally, participants in Experiment 2 were instructed not to turn their heads during pointing. If they did so during pointing nevertheless, the display turned black. They could, therefore, not adjust for the orientation

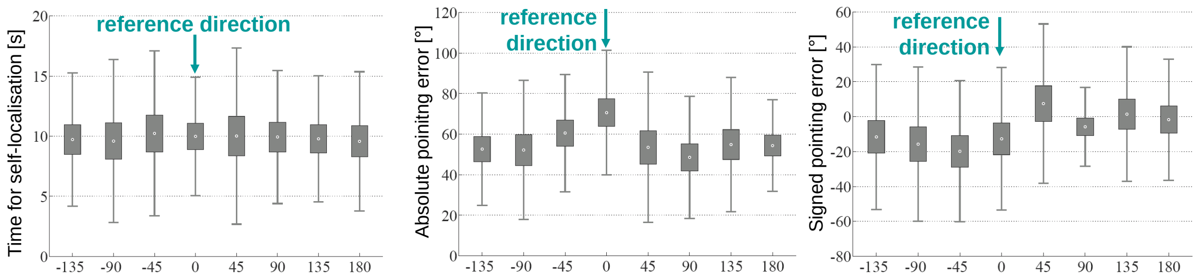

Figure 8: Performance in Experiment 2, quantified in terms of the time for self localisation (left), absolute pointing error (middle) and signed pointing error (right) as a function of global orientation, i.e., heading relative to the global orientation or reference direction (0°). Means, standard errors (boxes) and standard deviations (whiskers) are displayed.

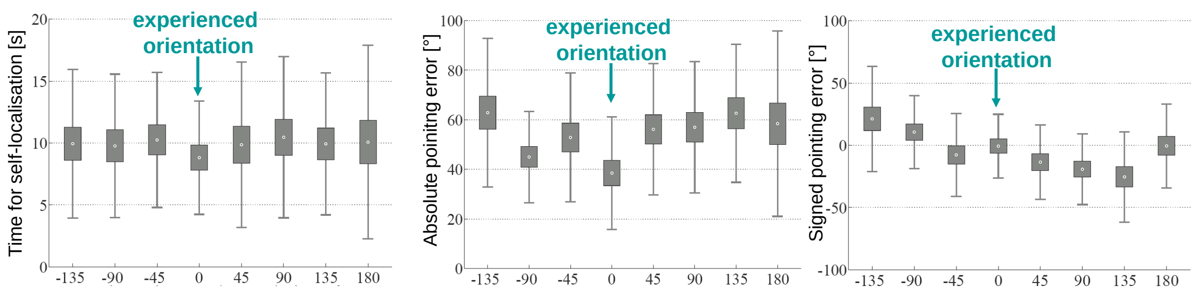

Figure 9: Performance plotted as in Figure 8, but as a function of local orientation, i.e., heading relative to the experienced orientation (0°).

of their body. To ensure that participants had sufficient visual information to be able to determine their current location and heading even without having to turn their heads, the entrance doors had a wooden texture and the exit door on the opposite side had a metallic texture. Additional small objects (e.g., small rectangular plates that had a wooded and metallic texture on the side facing the wooden and metallic door, respectively) positioned in every circular room at $\pm 45°$, $\pm 90°$ and $\pm 135°$ indicated the other directions. We also changed the criteria for finishing the learning phase: At the end of the eighth passage, participants were shown the wall texture of a corridor and were then asked to name the object that is in the corridor of that texture. Participants who did not name all objects correctly could walk two extra rounds through the corridors before being asked again. We also changed the wall textures for this. Apart from these differences, the experimental procedures were identical to the first experiment.

4.2 Results and Discussion

The results of Experiment 2 confirm and extend the results of Experiment 1. No dependency of the participants' performance on the global orientation was found, neither in terms of the absolute pointing error ($F(7, 133) = 1.43$, $p = .199$, $\eta^2 = .07$) nor for the pointing time ($F(7, 133) = 1.01$, $p = .430$, $\eta^2 = .05$), or for the time for self-localisation ($F(7, 133) = 0.23$, $p = .980$, $\eta^2 = .01$, see Figure 8). The reference direction theory was, therefore, not supported by the current data.

Participants pointed more accurately when oriented in the direction in which they had experienced the environment (see Figure 9, left side; $F(7, 133) = 3.11$, $p = .005$, $\eta^2 = .14$). Note that this was found despite the fact that participants could not see the corridor any more, as the doors were closed during the test phase. Note also that the advantage of the 180° condition that was observed for Experiment 1 disappeared for Experiment 2. The pointing error was smaller when oriented along the experienced orientation than when oriented 180° to that ($t(19) = 2.17$, $p = .043$, $d = 0.48$). This might, of course, be related to the corridor itself not being visible any more during the test phase of Experiment 2. An alternative explanation of the results by a speed-accuracy trade-off, i.e., that the differences in pointing accuracy where only due to differences in pointing time, could be ruled out. There was no effect in pointing time ($F(7, 133) = 1.02$, $p = .419$, $\eta^2 = .05$). Effects in the signed pointing error, i.e., considering whether the participants pointed to the right or left, indicate that aligning the current orientation during pointing with the experienced orientation stored in memory might be part of the effect (see Figure 9 right side;

$F(7, 133) = 4.39$, $p < .001$, $\eta^2 = .19$). In the first experiment, participants could (and most did) align themselves during the test phase by turning their head in the direction of the corridor (i.e., thus facing $0°$). Due to head turning no increase in the signed pointing error could be observed when the current orientation (of the body) differed from the experienced orientation (see Figure 5 right side).

In Experiment 2, however, the corridor as well as the adjacent turn and parts of the neighbouring corridor were occluded by the doors. This might have contributed to the result in Experiment 2 that the self localisation time was independent of the participants orientation with respect to the experienced orientation ($F(7, 133) = 0.71$, $p = .664$, $\eta^2 = .04$). This indicates that visual and/or geometric features might be necessary for self localisation, but not for pointing (see Valiquette & McNamara, in press [19]).

As in Experiment 1 we directly compared the reference direction theory and the view dependent theory by comparing pointing performance for the conditions that are predicted to be best by the two theories: Participants pointed more accurately ($t(19) = 4.38$, $p < .001$, $d = 0.98$) when facing the experienced direction than when facing the reference direction. However, no significant differences were found in time for pointing ($t(19) = 0.29$, $p = .773$, $d = 0.07$) or time for self-localisation ($t(19) = 1.78$, $p = .093$, $d = 0.40$).

Note that the explanation of encoding the environment in view-dependent manner does not necessarily encompass an egocentric representation in the sense that only object-to-body relations of the environment are stored. We think that long-term-storage of environmental information as in the case of our experiments always encompasses object-to-object information, or more generally, location-to-location information. This information is not updated while the participant moves around, and is in the sense of Klatzky (1998 [1]), therefore, an allocentric and not an egocentric representation. This is a mere terminological difference to other positions in order to distinguish updating form long-term memory (see Burgess, 2006 [2]; Rump & McNamara, in press [11]; Wang & Spelke, 2002 [13]). Memory for the environmental space of this experiment would hence be classified as allocentric, because it is stored in long-term memory. Nevertheless, our results clearly show that it is view-dependent

The orientation-independent theory would predict equal performance for all facing directions. The current data showed, however, clear orientation dependency for both Experiment 1 and 2, which is inconsistent with the orientation-independent theory of mental representations for environmental spaces. As in the first experiment, however, the exposure to the environment (participants walked on average 8.1 times through the environment) might not have been sufficiently long to form a perspective-free memory of the environment, and using much longer learning times might eventually have lead to different results. Our results cannot, of course, exclude an orientation independent representation which exists in addition to an orientation dependent one.

In summary, the current results suggest that spatial memory for environmental spaces can be encoded with respect to the local orientation in which it was experienced. Conversely, we could not find support for a global reference direction underlying the spatial memory of all participants, even though the environment used was designed to provide a strong global reference direction. Individual participants might have used individual reference directions which are, however, not always identical to the direction predicted by the reference direction theory. This experiment used environmental spaces, which is a crucial difference to previous experiments which used vista spaces rather than environmental spaces (e.g., Mou & McNamara, 2002 [16]; Mou, et al., 2004 [10]; McNamara, Rump & Werner, 2003 [17]; Shelton & McNamara, 2001 [18]). For memory of vista spaces like the individual corridors in our experiments, our findings do not contradict the predictions of the reference direction theory. Both the reference direction theory and the view dependent theory predict the same performance advantage.

5 Conclusion

The new virtual reality setup has proved valuable as a flexible experimental setup. We conducted two experiments in order to show this. Through these experiments we demonstrated that memory for newly learned environmental spaces, like buildings or cities, is orientation dependent. This dependency can be explained by the view-dependent theory, but not by the reference direction theory or by assuming an orientation independent memory. These results are an important step toward deepening our understanding of spatial memory of environmental spaces and distinguishing between the large variety of existing theories on the nature of human spatial memory.

The new free walking space setup combines the advantages of virtual reality, namely control and variability of environmental features, with the availability of bodily cues like proprioception, vestibular cues and efference copy which have been shown to be important for wayfinding. Our new setup solves these issues by providing a large, fully trackable walking space, in which a participant with a HMD can walk freely, without being tethered by cables. These issues make it an excellent setup for conducting experiments in many fields of research such as spatial cognition, multisensory integration, or wayfinding.

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