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Walking with and Without Walking: Perception of Distance in Large-Scale Urban Areas in Reality and in Virtual Reality

Abstract

The perception of distance when walking through an urban area depends on several factors. In addition to knowledge of the physical length of a route based on known parameters such as the walking speed and the time or number of steps, this paper also discusses external factors such as the visual appearance and details of the route and internal factors such as the physiological effort or emotional states during the walk. It is not clear which of the latter factors are stored in memory and are used to estimate a perceived distance. The hypothesis of distance estimation on the basis of perceived and remembered effort is held by several researchers. The reported experiments tried to clarify that question with research in actual reality and virtual reality. In doing so, we were able to separate the component of real walking from other sources that possibly affect distance estimation. In addition, this work demonstrates the power of experiments in VR compared with equivalent experiments in reality.

1 Introduction

The way people orientate and navigate in unknown urban areas remains a fascinating problem. People are not able to remember a new route with all the turns, the number of steps, and all the objects they have seen like pictures in a movie. One interesting question is which details people remember and why they remember these in particular (Lynch, 1960). From many investigations, it is believed that spatial knowledge develops from location (Schölkopf & Mallot, 1995) to route (Schweizer & Janzen, 1996) to survey (Siegel & White, 1975, Tolman, 1948). The ability to remember walked distances and landmarks correctly is necessary in route and survey knowledge. To perform navigation tasks successfully, distance knowledge is essential. Investigating spatial knowledge is possible in environments in reality as well as in the laboratory, and both methods have their advantages and problems. Today's realizable computer-generated virtual environments offer the chance to combine the richness of the real world with the reliability of experiments in the lab. Therefore, another question of this work is to what extent do people behave similarly in navigational tasks in immersive virtual realities as they do in reality. Do experiments with distance estimations after walking through real environments and distance estimations after moving through virtual environments (without real walking) produce identical results?

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2 Distance Perception and Estimation

The distance between two points or the space between them could be expressed and measured (Schweizer, Hermann, Katz, Jansen, & Trendler, 1999) as a Euclidean distance, defined as the length of a straight line between these two points and often called "the line as the crow flies," or as a route distance, which is the physical length of an existing path between these two points. In this paper, we use the term *distance* only in the latter sense.

Distance estimation is possible on the basis of explicit or implicit knowledge. Sources of explicit knowledge are data such as counts of steps, walking time, and information from maps or other navigation aids. People are also able to calculate a given distance if the structure of an urban area is very regular and the length of a city block is known, or if a route has additional aids to count or calculate the walked distance, such as street posts with known spacing or signs with distance information. Sources of implicit knowledge could be heuristics, which concerns the time or physiological effort needed (Jansen-Osmann, 1999). This is in accordance with Briggs (1973), who described five possibilities or sources of information to estimate distances:

- *Motor reaction:* the amount of energy that is consumed to travel from one location to another
- *Time and speed:* knowledge of the relationship between time, speed, and distance
- *Perception:* the addition of all perceived single distances between locations (or landmarks) on the route between A and B
- *The use of structural patterns in the surroundings:* counting of city blocks or traffic signs
- *Symbolic representations:* the use of paper maps, road signs, and other aids

Following the information-storing model of Milgram (1973), the estimation of the diameters of an area depends on the information of that area that is stored in memory. This is in accordance with the findings of Jansen-Osmann (1999) that distance estimations depend on the information about the special properties of the route. Thorndyke (1981) called this the "feature effect." Additionally, the distance estimation of a route depends on the segmentation of that route (Allen, 1981, 1988; Allen & Kirasic, 1985). The same is true for routes with many changes of direction (Sadalla & Magel, 1980). Finally, distance estimation depends on whether the exploration of the area is managed actively with a free choice of route and speed, o passively, watching a movie or traveling by train or in a ca (Sholl, 1987; Gale, Colledge, Pellegrino, & Doherty, 1990). Radvansky, Carlson-Radvansky, and Irwin (1995) identified from this three classes of factors that influence distance perception:

- amount of information about the route
- number of segmentations of the route
- exploration active or passive

In his literature review, Montello (1997) analyzed a number of empirical and theoretical research studies, looking for factors that influence distance estimations and identifying three different classes of factors:

- number of environmental features
- travel time
- travel effort or expended energy

Subjective estimations of distance sometimes differ from the objective, measured distances and from distance calculations based on explicit knowledge such as the factors just mentioned. People estimate the distanc of a way to a destination differently than the distance the way back (Jansen-Osmann, 1999). Even different emotional and/or physiological states result in differences between distance estimations of identical routes (Downs & Stea, 1982). Subjective estimations of distance also differ depending on the effort to reach a go "Perception of spatial layout relates optical informatio specifying distal layout to the physiological effort required to act on that layout. Perception changes with changes in distal layout, and changes in physiological potential." (Proffitt, Banton, Steve, & Epstein, 2000) "Space is perceived in terms of effort," (George Berkeley, 1709); and "in spatial layout is perceived in terms our potential for actions, affordances" (Gibson, 1979)

Additional sources of differences between estimatio of distances are memory effects. New spatial informati interacts with stored knowledge about space and form spatial experiences (Haseloff & Jorwieck, 1971). This supported from the assertion in literature that distance estimations from memory are shorter than the same estimations from an immediate distance perception.

The quality of distance estimations also varies with experience. People who know an area well estimate distances within that area much more precisely than people who are new in the area (Downs & Stea, 1982).

3 Walking in Reality and Moving in VR

The term *virtual reality* for these new experimental environments was initially coined by J. Lanier in 1989. The term is used today in a variety of ways and often in a confusing and misleading manner. In this paper, the term refers to immersive virtual reality in which the user becomes fully immersed in an artificial, visual, three-dimensional world that is completely generated by a computer.

Experiments performed in the real world suffer from a lack of reliability between experimental sessions. Former laboratory methods increased reliability but suffered from a lack of cues that could be presented to the subjects. Experimental subjects are very good in using all aids that are available in a specific situation to perform well, regardless of whether they use them normally. Steck and Mallot (1999) showed that, when people are in a VR with local as well as global landmarks and have the instruction to use only local landmarks, they have no problem switching to the use of global landmarks whenever the local landmarks are not visible. This means that it could be misleading to transfer results from laboratory research with a restricted number of cues concerning spatial knowledge or abilities to the behavior of humans in real environments. Increasing computer power, new software tools and projecting technologies offer the chance to combine the richness of the real world with the reliability of experiments in the lab. One question of this work is to what extent people behave in navigational tasks in such an immersive virtual reality as in reality.

Proffitt et al. (2000) performed an experiment with the goal of measuring the influence of the potential for action on distance estimations. His experimental subjects estimated different short distances (4–14 m) of a red cone from their position, wearing and not wearing a heavy backpack and without walking. Only when wearing no backpack—the potential to walk with less effort—did the subjects underestimate the real distances significantly. These findings seem to support the hypotheses of the influence of physical effort on distance estimations. The results from the Proffitt experiment seem to support the idea of a correspondence between experiments in VR and real environments. His experimental subjects did not walk, but they estimated the distances as if they had walked towards the goal with and without wearing a backpack. These findings are in contradiction to that of Allen, Siegel, and Rosinsky (1997). In their experiment, subjects estimated distances moving through a VR using a head-mounted display (HMD). Some of the subjects (low condition) were seated and moved through the VR without being able to look around. Another group (high condition) walked on a treadmill while moving through the VR and were able to look around. Both experimental groups underestimated the distances in the VR. In the high condition, subjects estimated the distances to be much shorter than in the low condition.

In both experiments, distances were underestimated in general. In the Proffitt experiment, people estimated distances to be shorter when they had to exert less effort. In the Allen et al. (1997) experiment, just the opposite happened. Both findings do not answer the question of whether experiments with distance estimations after walking through real environments and distance estimations after moving through virtual environments (without real walking) produce identical results.

4 Information Content of Routes

The aforementioned explanations of distance estimation differences and their experimental evidence are extremely nonuniform. Among them all, the number of environmental features encountered while traveling has received the most empirical and theoretical support (Montello, 1997). However, from the literature previously cited, it is difficult to define exactly under which circumstances an entity of the world has the characteristic of being a (salient) "environmental feature" that has an effect on distance perception and estimation (Montello, 1997). If one is interested in only two extremes of different numbers of environmental features present in an experiment (low number of features vs. high number of features), a simple heuristic to measure information content could be to count significant changes in the environment on the left and right of a route. Changes are visually conspicuous differences such as different-looking buildings, intersections, noticeable changes in direction, and gaps in uniform sequences of fences or trees. We consider a route with many of those changes to have high information content and vice versa.

5 Motivation and Assumptions

The main goal of the experiments we have reported is the comparison of two experimental procedures. Do experiments performed in reality produce similar results compared with experiments performed in an immersive virtual reality, assuming that the visual image of both reality and VR are identical to a great extent? Given this, the question is to what extent the experience of walking through the world differs from moving through an identical VR without real walking. A second question is to what extent the number of environmental features on the route—the information content of the route—makes a difference in the experience of the route. Additionally, we are interested in the influence of differences between subjects such as familiarity with the experimental terrain.

We are looking for the factors that have a significant effect on the perceived distance that is measured with subjective distance estimations. Our questions are as follows.

- *Real walking vs. moving without walking:* What is the influence of the physical effort and sensory-stimulation component of walking or not walking on distance estimations?
- *Information content of routes:* What is the influence of the high or low richness of the surrounding visual world on a route, its information content?
- *Differences between subjects:* Do subjects who are familiar with the experimental terrain behave differently than subjects who have no prior knowledge of it?

We have several assumptions about the answers to these questions.

- We expect that distance estimations in an immersive virtual reality without walking do not differ systematically from distance estimations in a real environment with walking, given a sufficient visual correspondence between the two environments.
- We expect differences in the distance estimations o learned routes in environments with a high and lo information content. The distance estimations of routes in environments with a high information content should be greater.
- We expect differences in the distance estimations o subjects who are familiar with the terrain prior to the experiment compared with subjects who have not had any experience with the terrain until the experiment.

6 Methods

6.1 Experimental Terrain

The large-scale urban area of our experiments is the campus of our university in Neubiberg near Munic (see Figure 1). The area is a square of approximately 500 m on a side. Within that area are more than 50 buildings of similar and different sizes and shapes, nestled among thousands of trees and bushes. The paths and roads between them are small and have no rectangular intersections. Only two of the roads and paths have names. All buildings have numbers, but the numbering scheme is chaotic and follows no known system Only people who live there know the area because it is surrounded by dense vegetation.

6.2 VR System

We constructed the virtual reality 'NeuViberg' on SGI Onyx2 Reality Engine with two raster managers. Th software was written in Performer V2.2, a GUI in C++ based on the SGI graphics language, OpenGL. NeuVibe consists of all buildings, relevant objects, vegetation surroundings, sky, atmospheric effects, and so on. The tex-

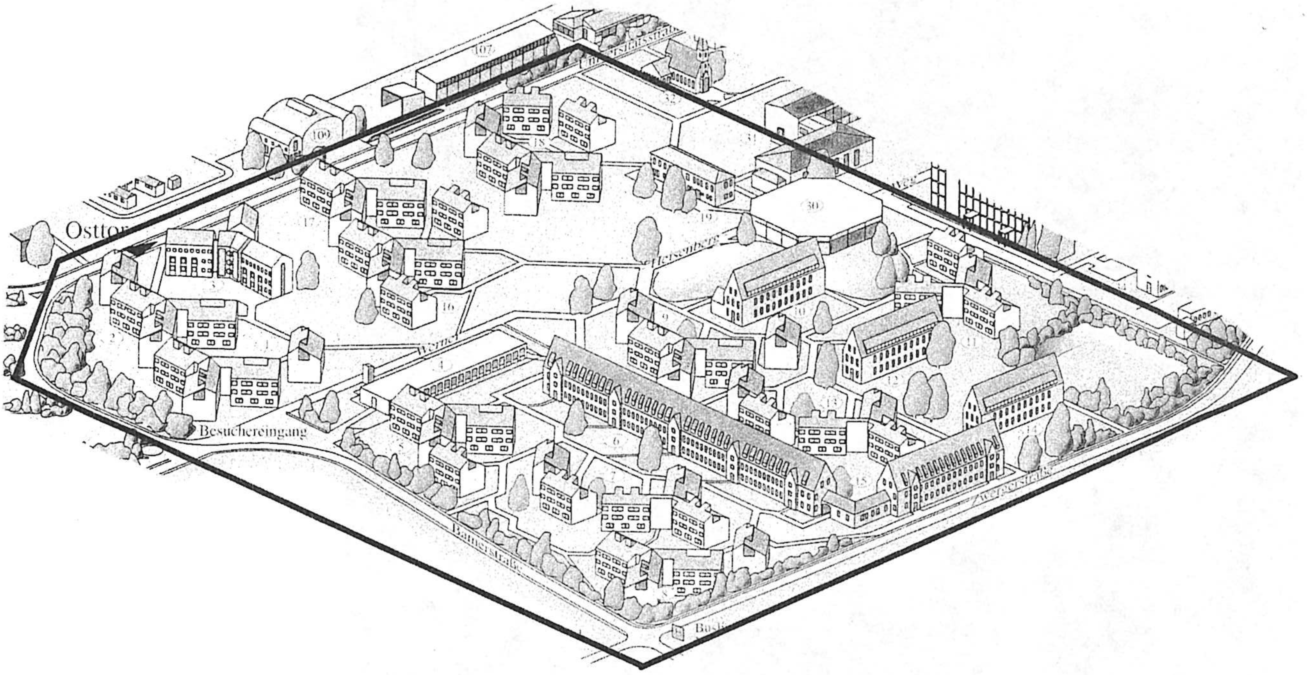

Figure 1. *Experimental terrain 'NeuViberg.'*

tures of buildings, vegetation, and other objects are digital pictures from the originals, processed and corrected as needed. The whole scene was projected in the 5 m version of the Vision Dome from ELUMENS Corp. (see Figure 2). Our experimental subjects were positioned in the middle of the Vision Dome and had a visual image and flow field of the virtual reality in 180° in all directions. They moved through the VR using a computer mouse to control the direction and speed of movement of the visual image within the limits of pedestrian movement speed.

6.3 Experimental Paradigms

The prior questions and expectations were investigated in two experiments with a "learning and test" paradigm using the production method for distance estimation. The production method means that our subjects were not asked to estimate the experienced length of the experimental routes in meters or any other abstract methods (map drawing, comparison with known distances, or others). Our method is to put the experimental subjects on a test range after walking (moving) on a learning route and ask them to walk (move) the same distance they had experienced before.

We performed two experiments that are briefly described as follows (see Table 1).

1. Twenty male subjects familiar for years with the terrain walked routes with a high or low information content first and were asked to walk the same distances on a neutral test range afterwards.
2. Fifty-six male and female subjects who were totally unfamiliar with the terrain walked a route with a high information content first and were asked to walk the same distances on test ranges with a high and low information content afterwards.

Both experiments were performed in reality and in VR.

6.4 Distance Measurements

The physical distances walked in reality were measured with the aid of a calibrated wheel. The corre-

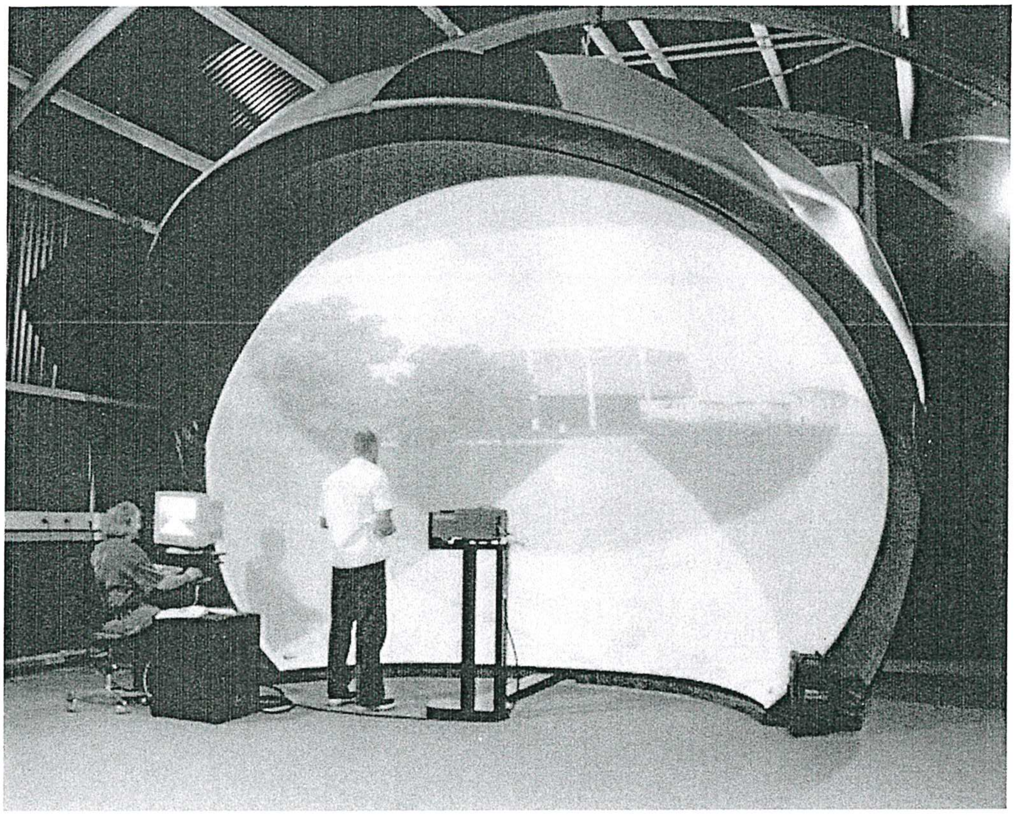

Figure 2. *VR projection system with 180° field of view.*

Table 1. *General design of both experiments*

	experiment 1 information content		experiment 2 information content	
learning	low	high		high
test	low		low	high

sponding distances in VR were recorded from the position of the projection eye point of the simulation program.

7 Experiments

7.1 Experiment 1

Subjects familiar with the campus of Neubiberg walked (moved) a guided tour of approximately 500 m with a high or low information content. Immediately after the learning experience, they were asked to walk (move) the same distance on a neutral test range (see Figures 3–8). Half of the subjects performed in reality, the other half in an immersive VR.

7.1.1 Subjects. Twenty male subjects participatec They were students at our university, had lived on the campus for several years, and knew the area well. Their ag range was 22–26 ($\bar{x}_{age} = 24$), and they had received training in orientation and navigation as part of their military service. Before and during the experiments, all subjects ha no information about the intentions or hypotheses of the experiments. Afterwards, they received a full explanation. Their personal data were recorded in an anonymous form

7.1.2 A1 * (B1 * V1) Design. To control undesired learning effects, we used a mixed experimental design. The independent variable A (reality vs. VR) was

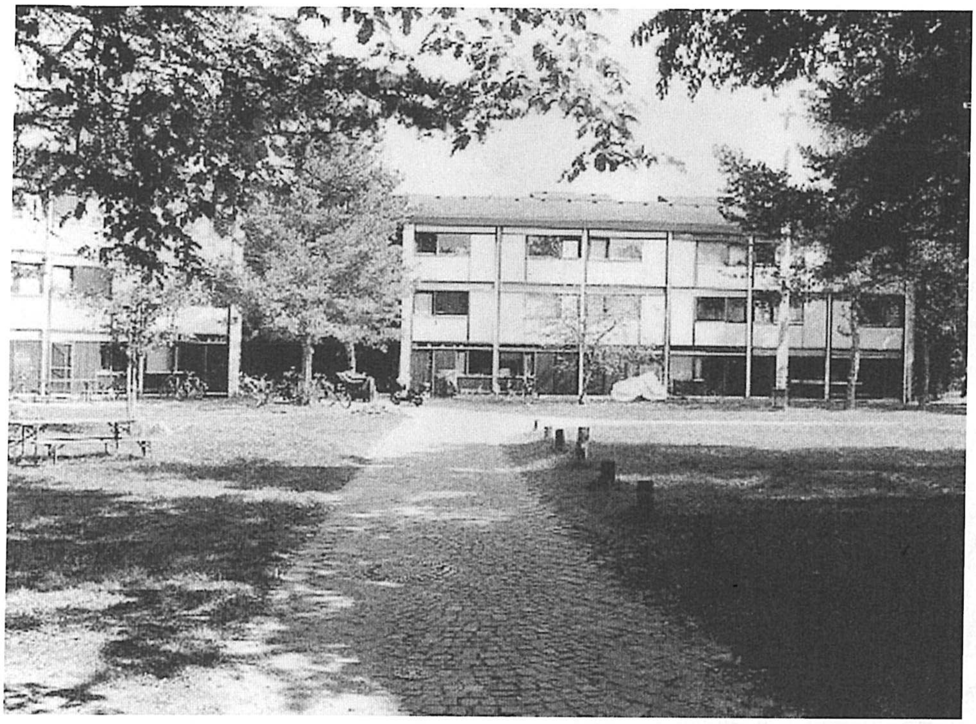

Figure 3. *View of a route with high information content in reality.*

investigated between subjects. Independent variable B (low vs. high visual information of the route) was investigated within (see Table 2).

7.1.3 Procedure. The twenty subjects were divided into four subgroups. Groups 1 and 2 started in the low and continued with the high information content environment. Groups 3 and 4 started in the high information content environment and continued in the low one. Groups 1 and 3 performed the tasks in reality; Groups 2 and 4 performed them in virtual reality. After the second test, the subjects were asked to describe the perceived difficulty of the tasks. Additionally, their perceptional stylus was measured with the "embedded figures test" (Witkin, Oltman, Raskin, & Karp, 1971).

The whole experiment, with all tests and measurements, lasted 90 min for each subject, from the beginning with the first learning experience to the end of the paper-and-pencil test after the second test.

7.2 Experiment 2

Subjects totally unfamiliar with the campus of Neubiberg walked (moved) a route of approximately 500 m with a high information content (see Figures 3 and 6). Immediately after the learning part, half of them were asked to walk (move) the same distance on a different test route with a low information content (see Figures 4 and 7) and the other half on another test route with a high information content (see Figures 3 and 6). Half of the subjects performed in reality, the other half performed in our VR.

7.2.1 Subjects. Fifty-six subjects (28 male and 28 female) participated, having been invited to participate via newspaper advertisements. They had no experience with the terrain and had never visited the campus before. Their age range was 30–50 ($\bar{x}_{age} = 42$). Before and during the experiments, all subjects had no information about the intentions or hypotheses of the experiments. Afterward,

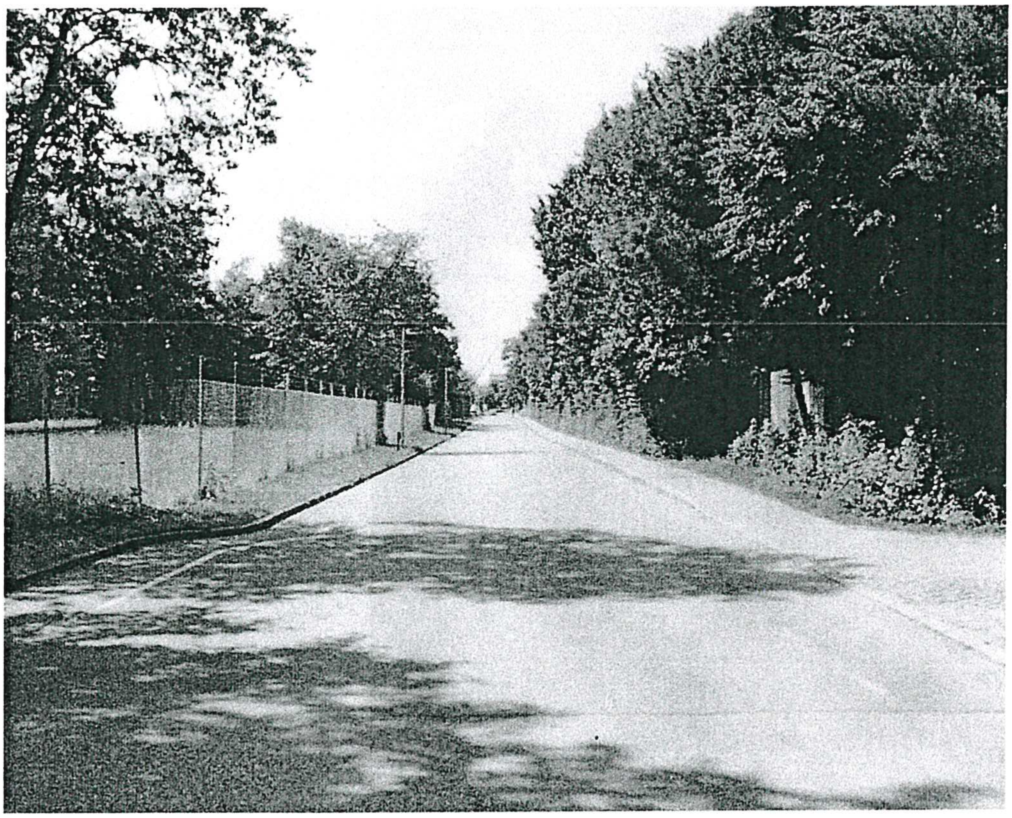

Figure 4. *View of a route with low information content in reality.*

they received a full explanation. Their personal data are recorded in an anonymous form.

7.2.2 A2 * B2 * (V2) Design. To control undesired learning effects, we used a mixed experimental design. The independent variables A (reality vs. VR) and B (low vs. high visual information of the test route) were investigated between subjects (see Table 3).

7.2.3 Procedure. The 56 subjects were divided into four subgroups. All groups learned a route in an environment with a high information content. After that, Groups 1 and 3 were tested in a low information content environment, and Groups 2 and 4 were tested in a high information content environment. Groups 1 and 2 performed the tasks in reality; Groups 3 and 4 performed them in VR.

The whole experiment, with all tests and measurements, lasted 60 min for each subject, from the beginning with the learning experience to the end after the test.

8 Results

8.1 Results of Experiment 1

8.1.1 Reality - VR (A1). All together, the subjects of Experiment 1 significantly overestimated in their reproductions the learned distances (one samp *t*-test, paired, two-sided, $p = .014$). The male subjects, trained in outdoor navigation and orientation and familiar with the experimental environment, pe formed well in reality. There was a small difference between the walked distances of the learned routes and the reproductions on the test range whenever subjects walked in reality, but this difference was no significant. The reproduction performance of subjec who moved in VR was worse. This was the main

Figure 5. *View of neutral test range in reality.*

source of the differences observed in the previously described comparison over all conditions. It showed a significant overestimation of the length of the learned route in the reproduction on the test range (one sample *t*-test, paired, two-sided, $p = .022$). However, the differences between the distance reproductions in reality and VR were not significant.

These results are in contradiction with the findings of Proffitt et al. (2000) and Allen et al. (1978). Both found an underestimation of distance estimation in an experimental situation without walking.

8.1.2 Low-High Information Content of the Route (B1). The information content of the route had no effect on the results. The mean values of the distance reproductions in the high information condition are slightly higher but failed to reach significance in a two-sided *t*-test with independent samples. It seems that our experimental realization of low and high information content of the learning routes had no effect on the distance perception of the subjects.

8.2 Results of Experiment 2

8.2.1 Reality—VR (A2). The subjects, not trained in outdoor navigation and orientation and totally unfamiliar with the experimental environment, performed well in reality. As in Experiment 1, the group of subjects who walked in reality slightly overestimated the learned distance in their reproductions on the test ranges. This difference was not significant. The performance of those who moved in VR was worse and showed in their reproduction a significant underestimation of the length of the learned route (independent samples, *t*-test, two-sided, $p = .00000$) for both test routes (low and high information content of the test

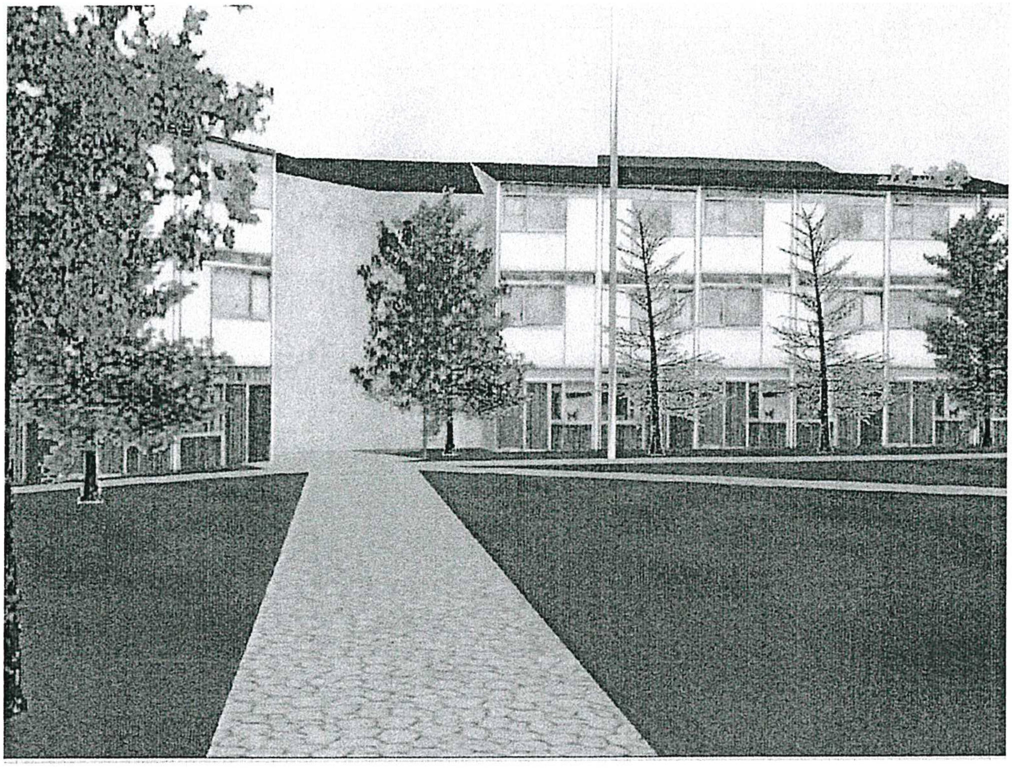

Figure 6. *VR view of the route shown in Figure 3.*

ranges). The differences in distance reproductions between the reality and VR condition are significant, too (independent samples *t*-test, two-sided, $p = .0002$ for the reproduction on the test range with high information content and $p = .00007$ on the test range with low information content).

In Experiment 2, we found a correspondence between the reported experimental results from Proffitt et al. (2000) and Allen et al. (1978). (See above.) The distance was underestimated in an experimental situation without walking.

8.2.2 Low-High Information Content of the Route (B2). As in Experiment 1, the information content of the routes had no effect on the results. The mean values of the distance reproductions on the test range with high information content (high condition) are slightly lower compared with the corresponding low condition, but they failed to reach significance in a two-sided *t*-test independent samples. Again, it seems that our experimental realization of low and high information content of the test routes had no effect on the distance reproduction of the subjects.

8.2.3 Gender Differences (V2). Experiment 2 was performed with groups of male and female subjects. Our results show several differences between them, but significant only in the reality condition. Only this condition reflected differences between male and female subjec (independent samples *t*-test, two-sided, $p = .027$). In this condition, male subjects underestimated the learned distance, and female subjects overestimated it. In the VR condition, both genders clearly underestimated the learned distance. The differences between the reality and the VR condition for male subjects were significant (independent samples *t*-test, two-sided, $p = .0001$). The differences between the reality and the VR condition for female subject were significant, too (independent samples *t*-test, two-sided, $p = .00003$). Differences between male and female subjects in the low and high information content condi-

Figure 7. *VR view of the route shown in Figure 4.*

tion of the test routes failed to reach the significance borders in two-sided tests.

8.3 Conclusions

In the two experiments, several questions were to be answered by investigating spatial distance perception, memory of spatial entities and details, and distance reproduction (estimation).

8.3.1 Question 1. The first question is methodological and asks whether experiments in sufficiently immersive, visual, virtual environments with the advantages of highly reliable experiments could replace experiments outdoors in reality. It is reduced to the simple question whether or not the act of walking is an essential part of our perception of distance.

In the first experiment, performed with 20 male subjects who knew the terrain well, the mean differences between learned route length and the reproduction in reality and in VR show a slight, significant overestimation of the length of the learned route but no difference between the reality and the VR condition. This result is in contradiction to the findings of Proffitt et al. (2000) and Allen et al. (1978). Both found an underestimation of distance estimation in an experimental situation without walking. From that result alone, one could conclude that distance reproductions performed in reality are identical to those performed in a sufficient, visually corresponding VR. The fact that this difference results mainly from differences in estimating distances in VR clearly shows that further work is needed to clarify Question 1.

In the second experiment, performed with 56 male and female subjects not trained in outdoor navigation and orientation and totally unfamiliar with the experimental terrain, all subjects performed well in reality. As in Experiment 1, the group of subjects who walked in reality overestimated the learned distance slightly but not significantly in their distance reproductions. The

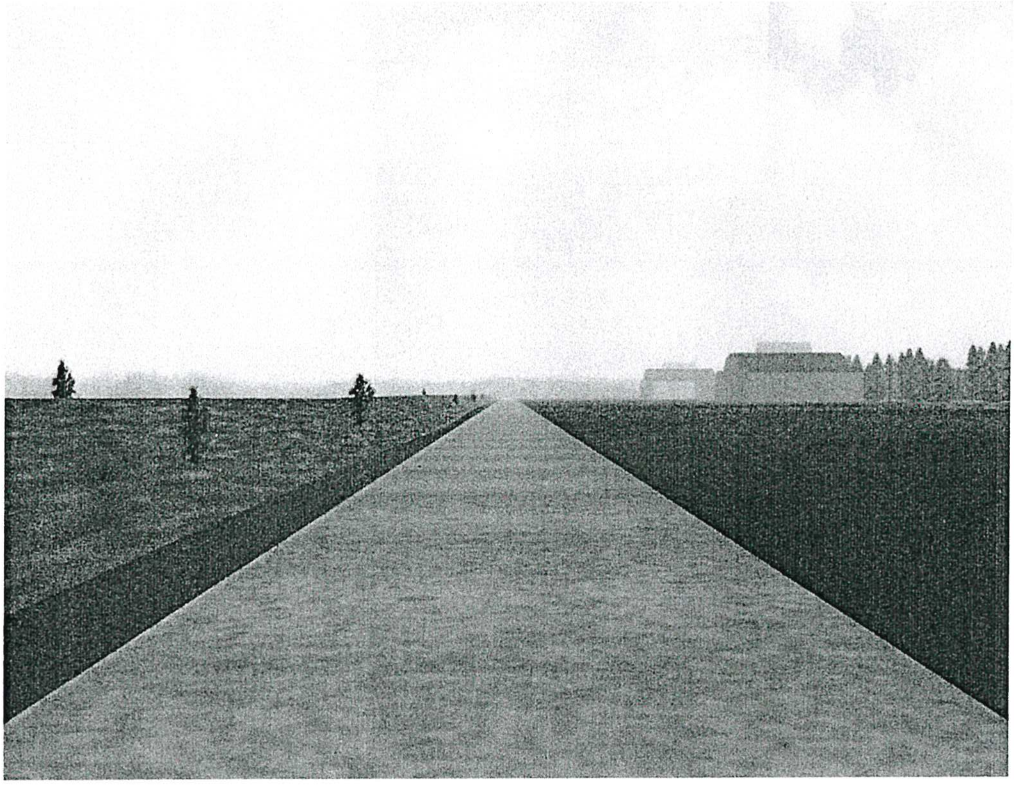

Figure 8. *VR view of the route shown in Figure 5.*

Table 2. *Design of Experiment 1*

	Group			
	1 5 subjects	2 5 subjects	3 5 subjects	4 5 subjects
route task	low-test-high	low-test-high	low-test-high	low-test-high
1st learning	reality	VR	reality	VR
1st test	reality	VR	reality	VR
2nd learning	reality	VR	reality	VR
2nd test	reality	VR	reality	VR

performance of those who moved in VR was worse and showed a significant underestimation of the length of the learned route for both test routes (high and low information content). The differences in distance reproductions between the reality and VR condition are significant, too. In Experiment 2, we found a correspondence between the reported experimental results of Proffitt et al. (2000) and Allen et al. (1978). The learned distance in an experimental situation without walking while doing the distance reproduction was clearly underestimated.

8.3.2 Question 2. The second question asks about the effects of environmental differences on spac

Table 3. *Design of Experiment 2*

	Group			
	1 14 subjects 7 male 7 female	2 14 subjects 7 male 7 female	3 14 subjects 7 male 7 female	4 14 subjects 7 male 7 female
route task	low-high-high	low-high-high	low-high-high	low-high-high
learning	reality	reality	VR	VR
test	reality	reality	VR	VR

and distance perception and memory. The number of environmental features encountered while traveling has received the most empirical and theoretical support (Montello, 1997). We reduce this to only two numbers of natural environmental features and ask which effects they have on distance estimations.

In the first experiment with 20 subjects, the information content of the route had no effect on the results. The mean values of the distance reproductions in the high condition are slightly higher, but they failed to reach significance in a two-sided *t*-test. It seems that our experimental realization of low and high information content of the learning routes had no effect on the distance perception of the subjects. As with Question 1, it seems necessary to increase the number of subjects to clarify the situation.

However, in the second experiment with 56 subjects, the information content of the test routes had no effect on the results either. The mean values of the distance reproductions in the high condition are slightly lower but failed to reach significance. Again, it seems that our experimental realization of low and high information content of the test routes had no effect on the distance estimation of the subjects.

8.3.3 Question 3. The third question asks about the effects of differences between subjects. It is obvious that greater familiarity and experience with a terrain improves spatial abilities within that terrain. However, is this true for isolated acts such as distance estimations?

In the first experiment, only male subjects estimated distances. In the second experiment, both genders participated. One main difference between the results of both experiments is the general overestimation of distances in the first experiment and the partial underestimation of the distances in the second experiment. However, both experiments differ in the environmental experience as well. Looking only at the differences in the real condition in both experiences, no significant difference could be detected. Subjects with or without knowledge of the terrain behaved nearly identically in reality. In the VR condition, the data shows another result. In this condition, the distance estimations differ drastically between subjects of the first experiment and the second.

The results of the gender comparison in the second experiment could explain this difference. Female subjects showed higher variances in their reproduction results. They showed the greatest differences between the reality and the VR condition, but male subjects reproduced the learned distances in the second experiment in the VR condition lower, too. Therefore, the factor that is responsible for under- or overestimation of distances is not only the familiarity with the terrain. We suppose that the subjects of the second experiment with a mean age of 42 could be unfamiliar with computer handling and computer-generated VR images to a greater extent. Male subjects with the mean age of 24 in the first experiment could be more familiar with the use of computer images and mouse steering within a VR environment.

- We conclude that, for subjects untrained in and unfamiliar with using computers, walking in reality seems to behave differently than moving with a

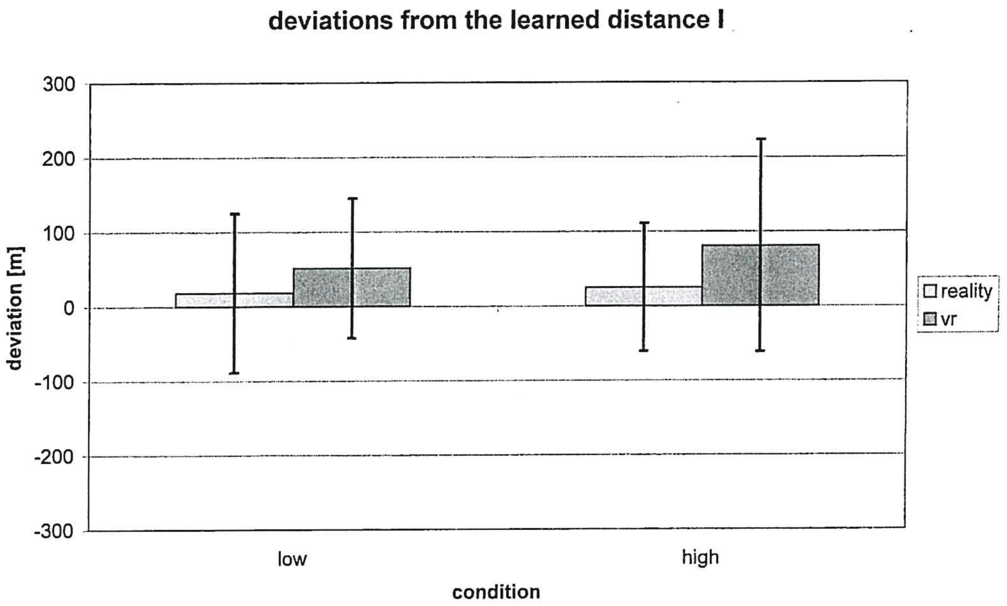

Figure 9. *Experiment 1. Deviations of the distance reproductions from the learned distance for the conditions reality-VR environment (A1) a low-high information content of the learning route (B1).*

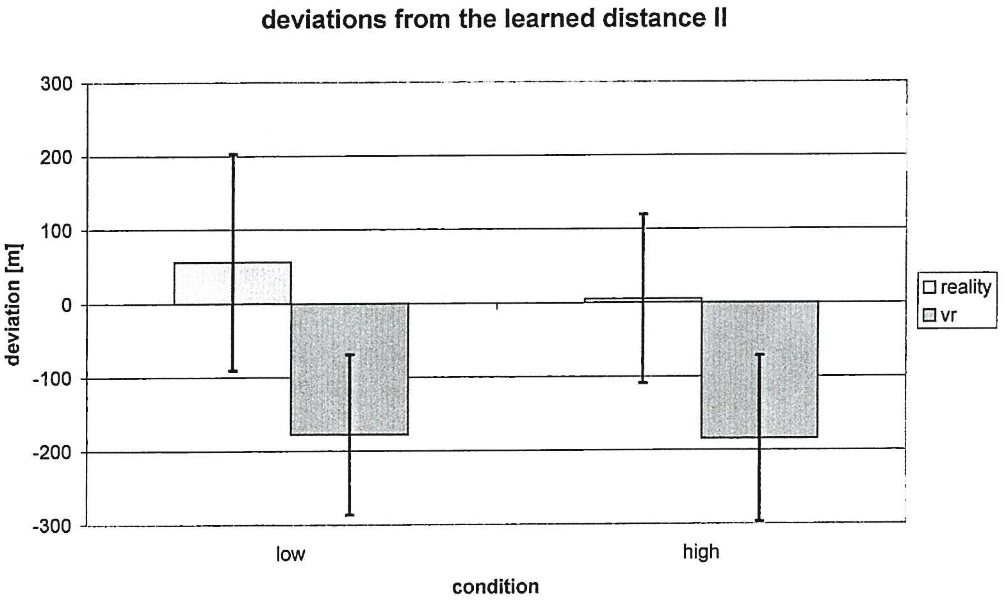

Figure 10. *Experiment 2. Deviations of the distance reproductions from the learned distance for the conditions reality-VR environment (A2) and low-high information content of the learning route (B2).*

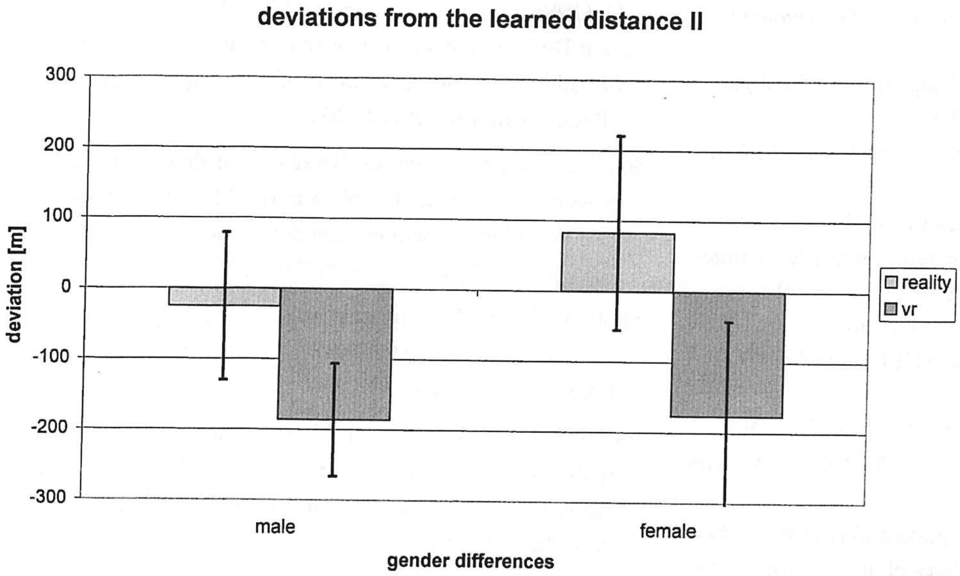

Figure 11. *Experiment 2, gender differences in distance reproductions for the experimental conditions reality-VR (A2) and low-high information content of the test route (B2).*

computer mouse through a VR. Trained subjects or people who are familiar with computer-generated environments behave similarly in reality and in VR.

- Differences in natural or natural-looking environmental features do not have a comparably strong effect on the performance in distance perception and estimation. Even in situations with only one perception of a route, people are able to extract the relevant information from different routes to estimate their distance on different test ranges well.
- The question of the relevance of real walking for being really immersed in a VR seems to be unanswered. Further research comparing real walking in reality with treadmill walking in VR is needed.

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