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Relearning of metric relations in a familiar environment

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Abstract. The ability of spatial memory to adapt to changes in an environment was investigated in an experiment, where participants navigated in a virtual reality reconstruction of a city they were familiar with. In the learning phase, participants used a special bike to pedal through a reconstruction of the inner city of Tübingen, Germany. Their task was to memorize the locations of the buildings in the city. In the experimental conditions, the city was scaled nonuniformly compared to the actual city, that is the north-south axis was streched or compressed relative to the east-west axis. In the control condition, the proportions of the virtual city were not distorted. In the test phase participants were asked to judge distances between buildings from memory by both, verbal magnitude estimation and navigation. They had to estimate all possible distances between 8 pairs of houses. Distance estimates differed between scaling conditions, but they reflected the scaling of the virtual environment only in one condition. Therefore, it could be shown, that modifications of a familiar environment on a purely metrical level affect spatial representations, but there is only weak evidence that distance estimates mirror the distortions of the virtual environments.

1 Introduction

In spatial cognition research, there is a long tradition of theorizing and experimenting on the subject of how spatial environments are represented, and considerable effort has been put into this line of research. On the other hand, little attention has been given to the fact that the environment we live in changes continually. From time to time, new streets and house are built, and other houses, which may have served as landmarks in our cognitive maps, cease to exist. Trees grow, new shops replace the ones we are used to, and sometimes, even a whole district changes its face as a result of a new urban development plan. In all these cases, our spatial representations have to change accordingly, if we still want to be able to navigate and plan routes successfully.

The question of how spatial memory adapts to these changes is largely unresolved. One notable exception is the topic of how place cells in the hippocampus of rats adapt to changes in an environment. Muller & Kubie (1987) found that expansion of a circular area enlarged some place fields but their shape and orientation remained constant. On the other hand, altering the shape of the environment caused a complete change of the firing patterns of the place cells. O'Keefe and Burgess (1996) found that changing a rectangular environment in one dimension led to corresponding changes in the hippocampal place fields' shape and locus.

Other results of animal psychology provide evidence that changes in an environment do not lead to the formation of new spatial representations, but existing representations adapt to the changes. For example, already Tolman (1948) showed in a labyrinth experiment with rats that when a familiar path to the location of food was blocked, but new paths were provided instead, rats tended to select the path which led in a straight line to the goal. This shows that rats are able to use their previous spatial knowledge for navigation even when the enivronment has changed.

In our study, we were interested in how spatial knowledge changes as a result of modifications in a familiar environment on a purely metric level. People who knew the inner city of Tübingen for at least one year relearned the spatial relations in the city in a virtual reconstruction, which was distorted compared to the original. The distortions were introduced by unisotropic scaling of the actual coordinates, that is the virtual city was strechted along one axis.

Moreover, it has been argued, that metric relations are not learned at all (McNamara, 1991). If this is true, then modifications of an environment on a purely metrical level should have no effect on distance estimates from memory.

A third point of interest was the question, whether spatial knowledge gained by real world experience can be modified by training in a virtual environment. While virtual environments offer some interesting possiblities to study human behavior (see Bülthoff, Foese-Mallot, & Mallot, 1997, Bülthoff & van Veen 2001), the experience of navigating through virtual environments differs from real world experience in many ways. Spatial knowledge acquired by walking around in a city is not the result of a purely visual input, but other modalities, that is vestibular, proprioceptive, auditive, and olfactory inputs, contribute to this experience as well. Virtual environments, however, usually focus primarily on the visual modality. Information stemming from other modalities is usually either missing or only roughly simulated. Experiments in our laboratory have shown, that not only route based knowledge but also configurational knowledge can be acquired in virtual environments (Gillner & Mallot, 1998; Mallot, Gillner, Van Veen, & Bülthoff, 1998), and that spatial knowledge stemming from real environments can be transfered to virtual environments (Sellen, Van Veen, & Bülthoff, 1998). However, it is still an open question, whether training in virtual environmens can modify real world experience.

A fourth point of interest was the question, whether different methods of estimating distances would lead to different results. Virtual environments provide some intriguing possibilities for estimating spatial relations from memory. Apart from the standard procedure of verbal magnitude estimation, distances in virtual environments can be judged by interactive naviation. Because it is easy to remove any visual cues for the position of a goal, people can be told to estimate spatial relations by actually navigating to a goal which is not visible anymore. While it might be argued that this is a more natural method of obtaining distance estimates, it is unclear, whether navigation based distance estimation leads to comparable and maybe even more reliable results than verbal distance estimation.

2 Method

The experiment was conducted in the Virtual Environments laboratory at the Max-Planck-Institute for Biological Cybernetics, Tübingen. The experimental sessions lasted about 1.5 hours.

2.1 Participants

45 people, most of them students at the University of Tübingen, participated in the experiment. All of the participants lived in Tübingen or in the surroundings, and were familiar with the inner city of Tübingen for at least one year. They were paid 15 DM per hour.

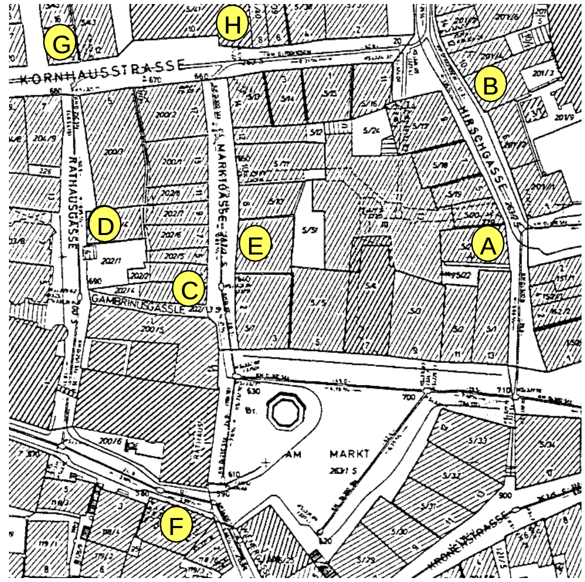

Figure 1: Map of Tübingen's historic inner city (with the market place south to the center) that shows the area used in the experiment. The letters mark the locations of the houses used in the learning check and distance estimation phase of the experiment.

2.2 Material

The spatial setup used for the experiment was a virtual reconstruction of a part of Tübingen's inner city (see Figure 1). This model ist part of *Virtual Tübingen*, an ongoing effort to reconstruct the inner city of Tübingen for behavioral experiments. It consists of a highly realistic model of the streets, places, and houses in this part of the city. In order to prevent participants from navigating outside the experimental area, all streets leading out of this area were blocked by walls. The positions of the houses were realistic with respect to their coordinates on the east-west and north-south axis, but not with respect to their elevation differences. In the model used in the experiment, all houses were put on a flat surface, because a more detailed model with elevation differences was still under construction at the time the experiment was conducted.

The model was displayed on a large curved projection screen in form of a half-cylinder with a diameter of 7 m and a height of 3.15 m. The model was rendered in real time by a Silicon Graphics Inc. ONYX Infinite-Reality supercomputer and projected on the screen by 3 video projectors providing a total resolution of 3200×1000 pixels (see Figure 2).

Participants could navigate through this model with a *VRbike*, a bicycle simulator which was placed in the center of the projection screen (see Figure 2). The *VRbike* is a modified exercise bicycle which allowes to steer and pedal actively through the city. Pedal resistance is computer controlled using a physical model of the inertial forces. On each of the bike's steering handles there are three buttons which can be freely programmed. In the present experiment, one button on the right hand side was used as brake, and one button on the left hand side was used to switch between the phases and trials of the experiment. A more detailled description of the experimental setup is given in Van Veen, Distler, Braun, and Bülthoff (1998).

2.3 Design

The scaling of the virtual city was variied between subjects. Participants in the "Unscaled" condition explored a version of the city where the proportions were correct with respect to the real city. In condition "NS-Larger" the north-south axis was scaled bigger than the east-west axis by a factor of 1.5. In condition "EW-Larger" the north-south axis was scaled smaller than the east-west axis by a factor of 2/3. With respect to the unscaled environment, scalings were $\sqrt{3/2}$ and $\sqrt{2/3}$, leaving the area unchanged. The other main experimental factor, "objects", i.e. the spatial relations to be judged in the distance estimation task, was variied within subjects. Each subject had to judge all distances between 8 different locations, resulting in a total of 28 estimation trials. The order of distance estimation trials was determined randomly for every subject. All of these distances were judged twice, once by navigation, and secondly by verbal magnitude estimation.

2.4 Procedure

The experimental procedure consisted of three phases, exploration phase, learning check, and distance estimation. For each of these phases, instructions were given on paper. During the whole experiment, the experimenter was sitting behind the participant.

Exploration phase. Participants were instructed to explore the virtual city by driving along the streets with the *VRbike*. Their task was to remember the locations of the houses. They were told they had to judge distances from memory in a later stage of the experiment. Participants were free to choose any route to explore the city and they could stay in the exploration phase as long as they wanted, with a minimum of 10 minutes. They were instructed to press a button on the bike, when they felt familiar with the city and were ready for the learning check. Upon pressing the button, participants were prompted to read the instruction for the learning check.

Learning check. In each trial of the learning check, a 512×400 pixels picture of one of the critical houses' front facades (see Figure 3) was displayed in the top right corner of the projection screen's center part. Participants had the task to cycle to the location of the house displayed in the picture from their current location on the shortest possible route. The target pictures were visible for the whole duration of the trial. If participants did not remember the location of a house, they had to search for it. When they reached the front of the displayed house, they could press a button on the bike to proceed to the next trial. Pressing the button initiated the next trial only when participants were at maximum 7 meters away from the center of the facade. The starting position of the first trial was near location C (see Figure 1) looking southwards facing the market place. On each subsequent trial the starting position of the trial was at the goal of the trial before, i.e., in the learning check, participants travelled along a single route without any interrupts. The house pictures displayed in the learning check consisted of the critical locations of the subsequent distance estimation task. Each of the critical locations was presented twice, in random order. Presentation order was also randomized between subjects, with the restriction that no house was presented for the second time until all of the houses had been presented once. After reaching the location of the 16th house and pressing the button, participants were asked to read the instruction for the distance estimation phase.

Distance estimation. In each trial of the distance estimation phase, participants were placed on a flat surface with a ground texture identical to the ground texture in Virtual Tübingen. They were facing the center of the front facade of a single house which was placed 8 meters ahead of them. Now other houses were visible in this phase of the experiment. The visible house served as reference locations for the distance estimations. Target locations were displayed as pictures in the same way as in the learning check. Participants' task was to drive to the place where the target location would have been, relative to the reference location. They could go there on any route they wanted, and they were allowed to turn around and look at the reference location in order to judge, whether they had arrived at the correct spot. When they felt they were at the correct position, they were asked to press a button on the bicycle. If, by accident, they pressed the button too early, they were allowed to repeat the trial from the starting position. After each trial, the screen was blanked, and the instruction appeared that they had to press the left button on the bike to proceed to the next trial. Before starting the subsequent trial, participants were asked to judge the straight line distance between the houses verbally in meters. Verbal distance judgments were recorded by the experimenter.

Figure 2: Experimental setup. On the curved projection screen, a part of *Virtual Tübingen* is displayed. In the center of the projection screen, the *VRbike* is visible. On the ceiling, the three video projectors can be seen.

Figure 3: Target stimuli displayed in the learning check. The order of these pictures corresponds to the alphabetical order of the location markers in Figure 1 (top row: locations A-D, bottom row: locations E-H).

After 28 trials the experiment ended. At the end of the experiment, participants were questioned informally, whether they had noticed any differences in the virtual city compared to real Tübingen.

3 Results

The interview at the end of the experimental session revealed that most participants noticed the missing elevation differences in the model, but none of the participants noticed the nonuniform scaling, even though they were asked specifically about distortions.

In order to examine, whether distance estimates were affected by the scaling of the city, an 3 x 28 anova was computed with “scaling” as a between subjects factor and “objects” as a within subject factor. For navigation estimates the main effect of objects was significant, $F(27, 1053) = 57.41, p < .001$, while the main effect of scaling was not significant, $F(2, 39) = 1.81, p < .18$. The interaction of objects and scaling was marginally significant, $F(54, 1053) = 1.31, p < .07$.

For verbal estimates there was a significant main effect of objects, $F(27, 1053) = 20.83, p < .001$, but no significant main effect of scaling, $F(2, 39) = 0.35, p < .71$. The interaction between those factors was significant, $F(54, 1053) = 1.34, p < .052$.

While the analyses of variance can only show, whether distances are estimated differently depending on scaling condition, much more precise predictions can be made, if one assumes, that distance estimates in a distorted environment differ only from the estimates in the undistorted environment by a constant ratio, which is dependent only on the overall scaling ratio and the orientation of the path to be judged. In this case the ratio should be maximal if the distance to be judged goes along the axis which is scaled bigger, and it should be minimal, if the distance goes along the axis, which is scaled smaller. More precisely, the theoretical ratio between distance estimates in an undistorted environment and distance estimates in a distorted environment as a function of orientation should be sinusoidial, as shown by the curves in Figures 4 and 5.

Figure 4 shows the empirical ratios for the navigation estimates. For a statistical test of the correspondence between the empirical data and the predicted sinusoidial curves, differences between predicted ratios in condition “NS-Larger” versus condition “EW-Larger” were correlated with the corresponding differences between the empirically obtained distance ratios. In other words, the signed distances between all pairs of empirical measurement points in the plot were correlated with the signed distances between the corresponding points on the theoretical curves in order to measure the overall goodness-of-fit of the empirical data to the predicted values. The correlation coefficient was 0.77, $t(26) = 6.21, p < .001$.

To test the fit of the data seperately for each scaling condition, empirical distance ratios were correlated with predicted distance ratios for each scaling condition. These correlations were $r = 0.82, t(26) = 7.43, p < .001$, for condition “EW-Larger” and $r = -.08, t(26) = -0.42, p = 0.68$, for condition “NS-Larger”.

Ratios for verbal estimates are shown in Figure 5. The correlation of differences between predicted ratios and empirical ratios was 0.51, $t(26) = 3.06, p = .005$. Individual correlations were $r = 0.75, t(26) = 5.85, p < .001$, for condition “EW-Larger” and $r = -.54, t(26) = 4.26, p < .001$, for condition “NS-Larger”.

In order to examine, how subjective space was influenced by the scaling of the virtual environments, the distance estimates were subjected to metric multidimensional scaling using Young’s (1997) stress formula 1 as a goodness-of-fit measure. A Euclidean metric was used to derive subjective coordinates in two-dimensional space for both, verbal and navigation based distance estimates of every individual subject. Since stress is invariant against translations, rotations, and (uniform) scaling, the coordinates can be brought into correspondence to the stimulus configuration by a Procrustes transformation (see Borg & Groenen, 1997) without altering the result in a meaningful way. Figure 6 shows the resulting configurations for multidimensional scalings based on mean estimates in the three scaling conditions. Unfilled circles show the subjective locations whereas points indicate the actual locations in the unscaled stimulus configuration.

To examine the effects of scaling in the learning phase, the individual scaling solutions were transformed back to the unscaled stimulus coordinates using one additional free parameter: Nonuniform scaling was achieved in the remapping procedure by allowing different scaling parameters for the x-axis and the y-axis. Remapping of subjective coordinates was done by a parameter estimation algorithm which minimized the sum of squared distances between stimulus coordinates and corresponding coordinates in the MDS plots. If the scaling of the virtual environments affected distance estimates, the ratio of the scaling factors for the N-S axis und E-W axis should reflect this scaling.

As can be seen in Figure 7, the scaling ratios for the verbal judgments reflect the scaling of the virtual environments. The scaling ratio for the unscaled environment is close to 1 while the scaling ratio for the “NS-Larger” condition is bigger than 1, and the scaling ratio for the “EW-Larger” condition is smaller than 1. However, the effect of scaling on ratios for verbal estimates was not significant, $F(2, 38) = 2.00, p < .15$.

For navigation based estimates the scaling ratios did not reflect the scaling of the virtual environments and the difference was also not significant, $F(2, 38) = 0.34, p = .71$. A combined ANOVA yielded no main effect of scaling, $F(2, 38) = 1.20, p = .30$, no main effect of type of judgment (verbal vs. navigation based), $F(1, 38) = 0.75, p = .39$, and no interaction between these factors, $F(2, 38) = 1.37, p = .27$.

4 Discussion

Distance estimates were analyzed using three different methods. First, analyses of variance were employed to test, whether scaling had any effect on the distance

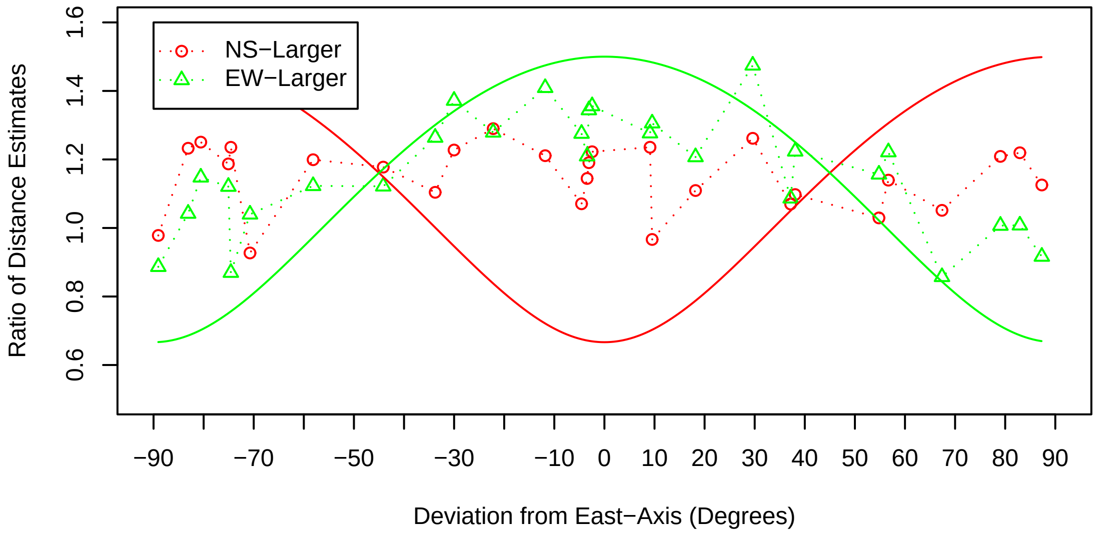

Figure 4: Ratios of distance estimates obtained by navigation in the undistorted city to estimates in the distorted conditions as a function of orientation of the path to be judged. The sinusoidial curves are predicted values for condition “NS-Larger” (minimum at 0), and “EW-Larger” (maximum at 0).

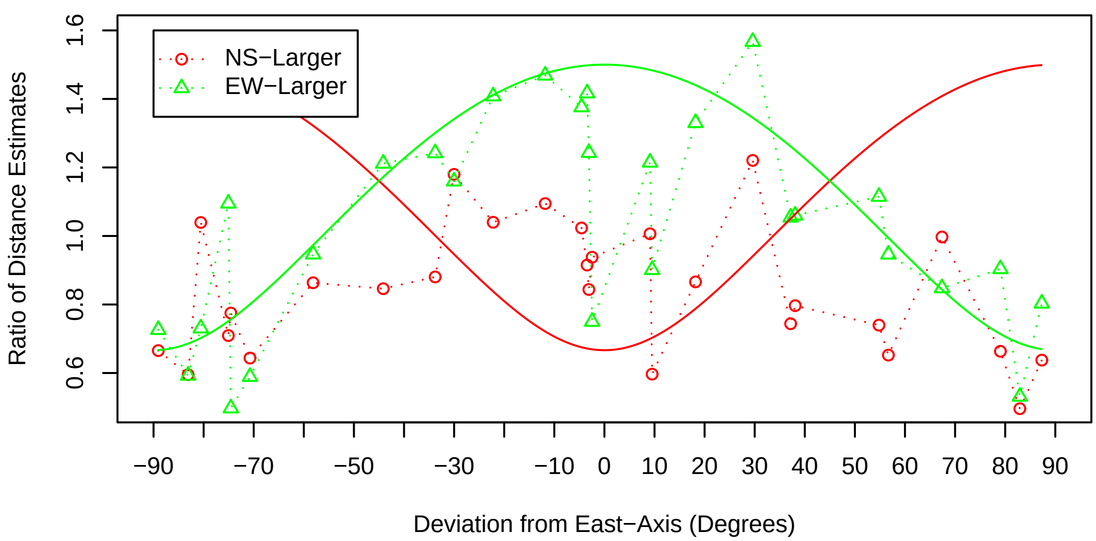

Figure 5: Ratios of verbal distance estimates obtained in the undistorted city to estimates in the distorted conditions as a function of orientation of the path to be judged. The sinusoidial curves are predicted values for condition “NS-Larger” (minimum at 0), and “EW-Larger” (maximum at 0).

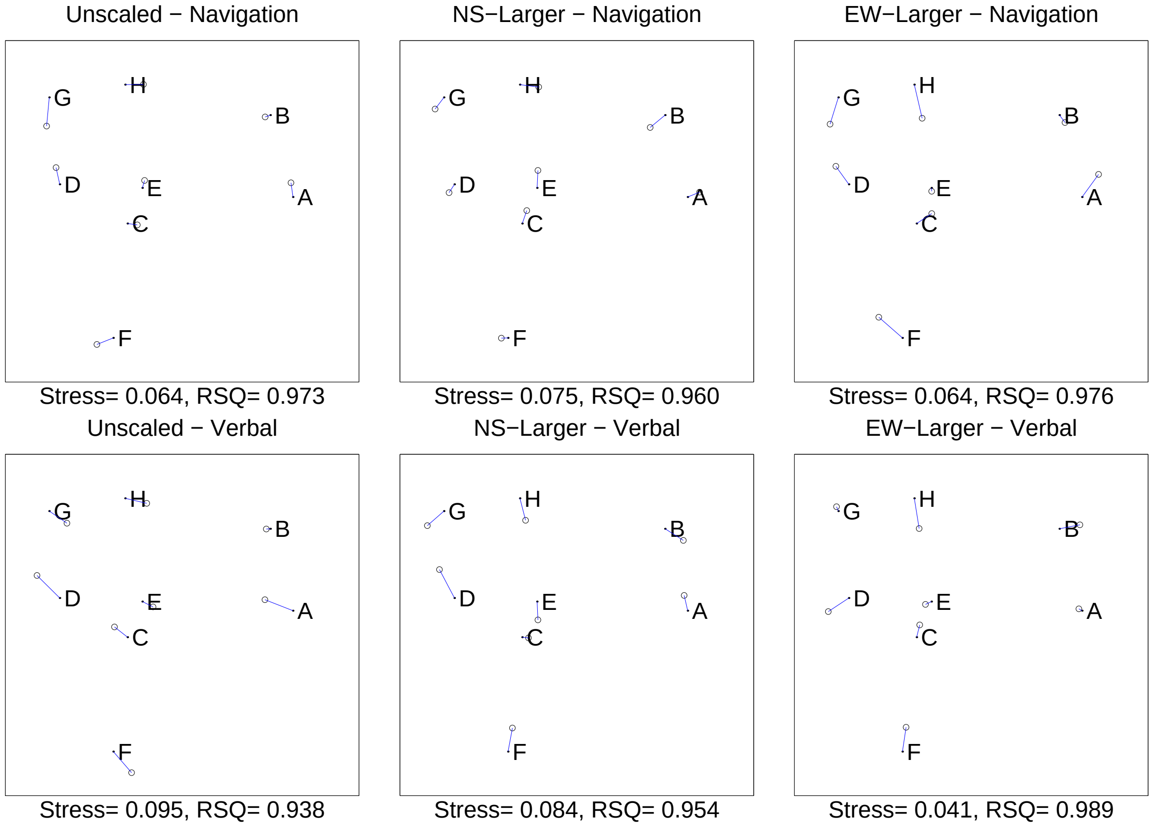

Figure 6: Scaling solutions for multidimensional scalings of distance estimates based on navigation (top row) and verbal judgments (bottom row). The scaling solutions (open circles) were brought into maximum correspondence to the actual locations (points) via a Procrustes transformation. At the bottom of each configuration, Young's Stress formula 1 and the residual sum of squares (RSQ) are given as a goodness-of-fit measure.

estimates at all. These anova's yielded an interaction between object pairs to be judged and scaling condition, which was significant for verbal estimates and marginally significant for navigation estimates. This supports the notion that distance judgments follow the scaling of the virtual environment, since in this case, distances between objects would be judged differently, depending on the scaling condition and the angle between the path to be estimated and the axis of scaling. However, it does not test any specific predictions. Therefore two more analyses were conducted.

To analyze, whether distance estimates reflect the scaling of the virtual environments, ratios between distance estimates in the distorted environments and estimates in the undistorted environment were plotted against the angle of the path to be judged, and compared to the corresponding ratio of distances in the virtual environments. There was a significant linear correlation between the differences of the observed distance ratios in the scaling conditions and the corresponding differences in the predicted ratios for both types of estimates. This result supports the notion that distance estimates were distorted in a way resembling the distortions of the virtual city, and leads to the conclusion that the purely metric manipulations introduced in the scaling conditions had corresponding effects on the distance estimates.

However, inspection of Figures 4 and 5 reveals, that this effect can only be observed for one of the two scaling conditions. While in condition “EW-Larger” there is some resemblance to the predicted curve, for the “NS-Larger” condition no such tendency is apparent. Seperate correlations of distance ratios in conditions “NS-Larger’ and “EW-Larger” confirm this impression. Significant, positive, linear relationships between empirical and theoretical distance ratios exist for condition “EW-Larger” but not for condition “NS-Larger”. Therefore, there is partial evidence that distance estimates were scaled according to the scaling of the virtual environments, but it remains unclear, why stretching the virtual city along the east-west axis reveals this pattern while streching it along the north-south axis does not.

Multidimensional scaling of distance estimates was

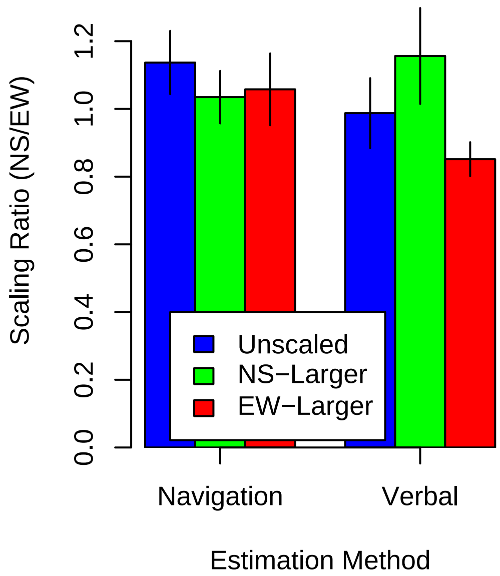

Figure 7: Ratios of horizontal to vertical scaling coefficients, obained by remapping the MDS configurations to the undistorted stimulus configuration. Error bars indicate standard errors.

used to reconstruct the subjective spaces from the distance estimates. If the distance estimates were distorted according to the distortions in the virtual environment, a generalized Procrustes procedure, which allows for axes specific scaling coefficients, should reveal a bigger ratio between the NS-axis and the EW-axis, in condition “NS-Larger”, and a smaller ratio in condition “EW-Larger”, with the “Unscaled” condition lying in between. On a descriptive level, verbal distance estimates followed this pattern, while navigation estimates did not. But none of the analyses of variance produced significant results.

In summary, the results indicate that distance estimates were affected by the scaling of the virtual environment, but there is only partial support for the hypothesis, that the effects reflect the actual distortions. Coming back to the questions raised in the introduction, we could show that changes in an environment on a purely metric level affect the cognitive maps. However, it could not be shown that distance judgments were simply scaled according to the scaling of the environment.

With regard to the question of whether spatial representations formed by real world experience can be changed by virtual environments, the results only indicate that some changes occur, but a more detailed analysis would require a pretest of the participants’ preexperimental knowledge before the exposition to the virtual city. In this way, one would be able to answer the question of how preexperimental knowledge is affected.

Comparing the results of verbal and navigation based distance estimates, the ANOVAs reveal that verbal judgments had a higher effect-noise ratio than navigation based estimates. A possible explanation is, that the reduced virtual environment we used in the distance estimation task (consisting of one house and the ground texture) did not provide enough distance cues to form reliable estimates.

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