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Geographical slant facilitates navigation and orientation in virtual environments†

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Abstract. Theoretical considerations and earlier experimental findings indicate that traveling over slanted terrain can lead to an enrichment of the perceived spatial cues relevant for navigation. We investigated the proposed facilitation of a uniformly slanted environment on navigation and orientation performance with a virtual environment presented on a large 180° screen, using as material a virtual town with eight places and twenty-four landmarks. In the control condition, this town was placed on a flat surface; in the two experimental conditions, the town was placed on a slope with a uniform angle of 4°. Pedaling on a bicycle simulator, participants first explored the environment, then solved navigation tasks, pointed from various positions to distant landmarks, judged the relative elevation of pairs of distant landmarks from memory, and finally drew a sketch map of the environment. In comparison to the control condition, the number of navigation errors was significantly lower in the slanted conditions, and the deviations in the pointings to distant landmarks were massively reduced. Participants from the slant conditions also showed good knowledge of the relative elevations of pairs of distant locations. However, no differences in map-drawing quality were found. The results lend additional support to the proposition that our spatial knowledge, which is used in navigation and orientation, contains vertical information.

1 Introduction

Besides vegetation and climate, slant is one of the most conspicuous features of landscapes: plains, hills, valleys, or mountains are each very distinguished kinds of scenery. Furthermore, slant has several practical influences, both positive and negative, on navigation: a hilly territory often leads to warped city ground plans and street progressions, making navigation more complicated. On the other hand, being on top of a hill might give you a good overview of the surroundings; or, if you are looking for a creek or river, going down is the right and readily perceivable direction. Recently, the human ability to perceive the slant of terrain has received increasing experimental interest (eg Creem and Proffitt 1998; Proffitt et al 1995). Basically, the outcomes demonstrate that humans can perceive relative differences in the slant of terrain (both in natural and virtual environments) very well, even if they tend to systematically overestimate the absolute amount of slant.

The perception of a terrain as being slanted leads (in comparison to flat terrain) to some kind of additional spatial information. We explore here a practical implication: the hypothesis that this additional spatial information will facilitate navigation. We discuss possible reasons why this effect can be expected, and we report an experiment which directly tested the prediction of an improved navigation performance in a slanted virtual-environment setting.

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1.1 *Relevant spatial information for navigation*

In navigation research, the acquisition of spatial knowledge in large-scale environments is typically accredited to simultaneously acquired landmark knowledge and knowledge of the routes which lead from one landmark to another. The ongoing experience and integration of new routes in an environment leads to configurational knowledge (Siegel and White 1975; for an overview, see Montello 1998). Such integrated route knowledge can be depicted in graph-like structures (Kuipers 2000; Schölkopf and Mallot 1995; Werner et al 2000). Landmarks are typically perceived visually, although hearing and haptic perception can also lead to landmark discrimination, as shown by blind persons. On the other hand, the basic perception of the routes between landmarks is believed to be of predominantly sensorimotor nature (Siegel and White 1975, page 24) mainly based on the experience of the own-body movements during navigation. We will explore these different kinds of cues and then discuss the possible ways of experiencing slant in their respective terms.

1.1.1 *The encoding of navigational actions in body coordinates.* All navigational actions are accompanied by active or passive body movements, which are encoded by muscle receptors, the vestibular system, and (in active movements) in prior motor plans of the movements. These perceptible body movements inherently contain spatial information about directions and direction changes, for example turns towards a goal, and distances like the length of a grasping arm movement or the accumulated length of several steps toward a goal. We will use the term 'kinesthetic' for all these kinds of perceptions containing information about body posture and body movements.(1) The kinesthetically perceived spatial-information content of the body turns and translations that accompany the coverage of a route can directly encode the spatial form of this route, as a kind of graph representation in body coordinates (Restat 1999). Also, the turns and translations can be summed up as a vector containing the actual straight-line distance and direction towards a known point in space like the starting point of the route. This process is referred to as 'path integration' and is used by many animals (eg Müller and Wehner 1988) including humans (eg Loomis et al 2001), and robots (eg Röfer 1999). For example, in the "triangle completion paradigm" (Loomis et al 1993), blindfolded participants were led along a straight line with distances between 10 and 30 m, around a corner with variable angle, and along another straight line. From that point, they had to walk back to the starting point, relying only on their internal representation of direction and distance towards the point based on their experienced body movements along the path. Similarly, in the "walking-without-vision paradigm", participants had to fixate a goal up to 22 m away, they were then blindfolded, and had to walk the distance to the goal solely relying on the path integration of the kinesthetic perception of walking (eg Elliot 1987; Rieser et al 1990; Steenhuis and Goodale 1988; Thomson 1983). The outcomes of both paradigms demonstrated that participants are well able to use body information for navigation. However, they also showed that the range of purely kinesthetic-based navigation is too restricted for larger environments. Reliable perception of the spatial extension of walked ways seems to be limited to distances around 20 – 30 m; and the path integration of turns is always error-prone, since the internal representation of turns is not very exact and, furthermore, biased towards 90° angles (May et al 1997). Therefore, additional information to control and correct the spatial progression towards the goal is necessary. This requires the perception and use of landmarks and related external spatial-orientation cues.

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(1) In addition, visually perceived optic flow normally accompanies body movements and alone can lead to strong apparent perceptions of bodily self-motion, for example in virtual-reality setups. These apparent self-motions can be considered as kind of 'simulated' kinesthetic perception, which is extracted from the visual-flow field. For example, Gibson (1958, 1979) termed this visually based body perception as 'visual' kinesthetis in demarcation to the 'classical' muscular and vestibular kinesthesis.

1.1.2 *Landmarks and related external orientation cues.* Three kinds of external orientation cues can be distinguished. The first kind are local landmarks ('local position information', 'orientation marks'), recognisable locations on the intended way which signify a point of terrain. Typically, such local landmarks consist of visually perceptible objects like peculiar houses or trees. However, the possibility to signify a location is not exclusively bound to visually perceptible cues; for example, Jansen-Osmann (1998; see also Loomis et al 2001) demonstrated that participants can utilise pure acoustical landmarks (sounds associated with certain locations) for navigation.

The second kind of orientation cues consists of geometrical peculiarities such as the angle under which two streets meet, which can signify the intersection (cf Gouteux and Spelke 2001), or the geometric outline of rooms (Cheng 1986). Another piece of relevant information can be the geometrical progression of elongated way segments which promote (eg streets), influence (eg curved streets), or block (eg fences, rivers) the direct access to the goal. For example, we might recognise a peculiar street section because of its special curvature. Especially in the absence of salient landmarks, the geometrical progression of ways and the required body turns while walking these ways seems to be an important and commonly used navigational feature in human way-finding (Heft 1979).

A third possible source for orientation is geocentric direction information, a stable direction which can be accessed over a larger area. Examples are widely observable 'global landmarks' like towers or hills, but also cues like the azimuth of the Sun (in connection with the time of day), or technical devices like compasses. A natural counterpart for the use of compasses is found in insects which utilise the polarisation pattern of the sky light (eg Rossel 1993) as directional information for flight navigation. Such geocentric compass information is known to improve notably path integration (Mallot 2000, pages 228 – 235; Maurer and Séguinot 1995).

1.2 *Relevant spatial information from slant*

How does slant fit into these various kinds of informational resources? In principle, slant can add distinctive cues to all kinds of orientation sources mentioned above. First, slant can be perceived kinesthetically: moving upright over a slanted surface requires a different body balance, which can be felt, for example, in the changed angle of the feet joints. Additionally, the enhanced strain of moving upwards (or steeply downwards) can be felt kinesthetically. Second, the overall and varying slant of a way between two locations is one of the important visually (and kinesthetically) perceivable characteristics of the geometrical way progression, basically its orientation in vertical direction. Two otherwise identical streets might be distinguished by their different vertical progression. Third, the relative elevation of a place in an environment in comparison to other places can instantiate a visually perceivable local position information which might help in certain conditions to distinguish between otherwise identical places (eg places with identical houses which are situated on a hill or in the valley). Finally, given that larger areas of an environment are uniformly tilted, slant can even provide a compass-like geocentric directional cue with one salient axis (up and down) and one indifferent orthogonal axis (sideways), which can be readily perceived at any place or route segment of the slope.

1.2.1 *Empirical findings.* Taken together, there are promising theoretical reasons for the proposed usefulness of slant in human navigation. There are, in addition, some empirical findings which can be related to this notion. In particular, there are findings which indicate that the relative height of landmarks is encoded as part of the spatial knowledge of a vertically differentiated environment. Foley and Cohen (1984) demonstrated that participants take into account height differences when asked to judge the straight-line distances between locations on different floors of large buildings. Gärling et al (1990) demonstrated that participants were able to judge from memory which one of pairs of familiar places in their hometown had a higher elevation. Since the locations were several hundred metres apart, their relative height difference could not be perceived directly through seeing 'up' or 'down' from one to the other. This indicates that the accessed spatial knowledge of the elevation of places stems from the experience of navigating the slanted streets of the city. A second finding of this study was that the necessary amount of time to reach a decision about the relative elevation of two places was not correlated with the overall spatial distance between the places. In contrast, a small difference in the relative elevation between places was highly significantly correlated with longer decision times, indicating an influence of discrimination insecurity. Gärling et al concluded that the elevation knowledge of the participants was not retrieved indirectly by some kind of mental travel (in terms of Kosslyn et al 1978) between the pairs of places, but was directly accessible as information which was readily associated with the places.

Experimentally, the usefulness of slant as a navigation cue has been demonstrated in animals: Moghaddam et al (1996) showed that rats, when searching in darkness for a food source on top of an elevated cone, were able to navigate a more direct path than when searching on a flat surface.

Given these theoretical considerations and prior findings, we expect that an environment with a conspicuous slant would increase participants' navigational accuracy and performance in comparison with a flat, but otherwise identical, environment. To address this hypothesis in an experimental setup (at least for large-scale environments several hundred metres in diameter), it is highly expedient to use a virtual environment. In the present experiment, three versions of a virtual town with eight locations, each with three landmarks (eg houses) were used. One version was placed on flat terrain. The other two were placed on identically slanted terrain, but differed in the orientation of their maximum extension with respect to the gradient direction. The participants had to solve fifteen navigational tasks in the unknown environment; their accuracy provided the navigation-performance measurement. Afterwards, their acquired spatial representation was assessed by measuring the preciseness of pointing tasks and sketch-map drawings. It was expected that participants in the slant conditions would perform better and show more precise spatial knowledge than participants in the flat condition. Furthermore, to control if the experienced slant was encoded in the spatial representation, participants in the slant condition had to judge the relative elevation of pairs of landmarks.

2 Method

2.1 *Virtual environment*

2.1.1 *Scenery.* In this experiment, three similar virtual environments varying only in geographical slant were used. The basic environmental setup, an artificial town called "Hexatown" (see figure 1), had been used already for several experiments concerning landmark configuration (cf Gillner and Mallot 1998; Mallot and Gillner 2000; Steck and Mallot 2000).

The eight junctions were uniformly constructed from a circle which was divided into six 60° sectors. Every second sector contained a street with a uniform distance of 100 m, leading to the next junction. The three streets formed an intersection with 120° corners in the middle of the junction. In the 60° sectors, between the streets, an object (building, gas station, etc) was placed. With a given field of view of 180°, participants could see either two objects at the sides and a street in the middle, or two streets at the sides and an object straight ahead. Around the junctions, identical circular hedges with openings for the three streets were placed. Through these openings, the particular object in line of view at the next junction was visible. All other distant junctions and their objects were occluded by the hedges. At the peripheral junctions of Hexatown,

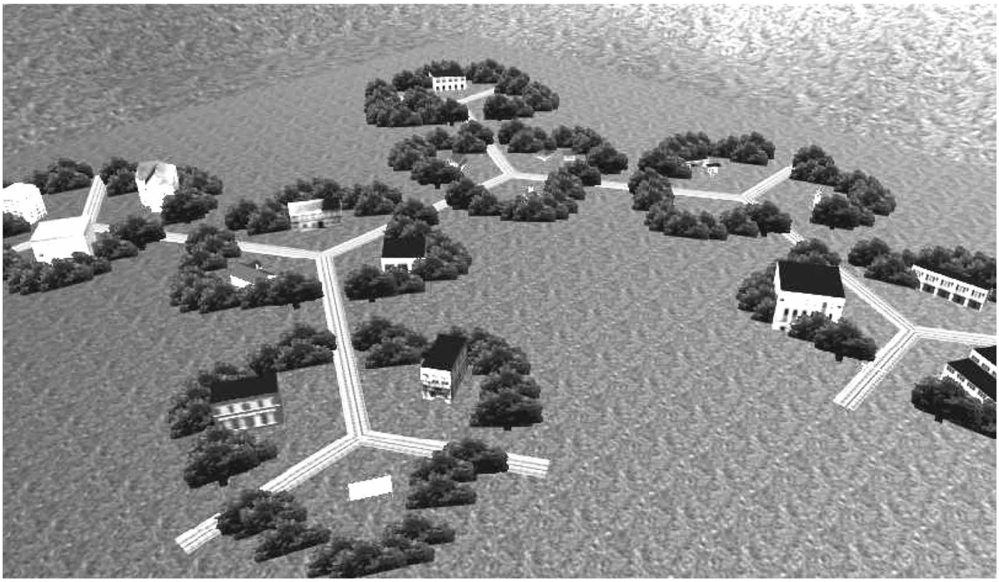


Figure 1. An aerial view of Hexatown. Such aerial views were not shown to participants.

the two outgoing streets were visibly blocked dead-ends and could not be entered by the participants. The octagonal ground plane of the town was surrounded by a vertical background showing a repeating mountain range and blue sky. Since the lengths of the streets as well as the basic plan of the junctions were symmetrical and identical, there was no usable information in the geometric angle or progression of the streets which allowed the identification of the momentary direction or approached place. Also, the mountain range could not be used to infer global directions. With regard to the three kinds of external orientation cues proposed in the introduction, participants in the flat-Hexatown condition were restricted to local landmarks for orientation and navigation.

2.1.2 *Apparatus.* The experiment was performed on a high-end graphics computer (Silicon Graphics, ONYX2 3-pipe Infinite Reality), running a Performer application that we designed and programmed. The simulation was displayed nonstereoscopically, with an update rate of 36 Hz, on a half-cylindrical projection screen (7 m diameter and 3.15 m height). The computer rendered three 1280×1024 pixel colour images projected side by side with a small overlap. Images were corrected for the curved surface by the projectors to form a 3500×1000 pixel display. Participants were seated on a virtual-reality bicycle (a modified version of a training bicycle from CyberGear™) which was equipped with 'force feedback', ie the possibility to modulate the force required to move the pedals (see figure 2). Changes in pedaling rate or force feedback were updated constantly and took effect in the next generated frame (frame rate: 72 Hz). The bicycle was mounted stationary in the setup in such a way that the seated participant's head was in the centre of the projection-screen cylinder (eye height 1.25 m). The display covered a field of view of 180° horizontally × 50° vertically. The setup is depicted in figure 2; for a detailed description, see van Veen et al (1998). MultiGen 3-D modeling software was used to generate the virtual environment; Medit 3-D modeling software was used to construct the buildings.

2.1.3 *Virtual-slant implementation.* The slanted versions of Hexatown were generated by realising three different slant aspects. First, the ground plate of the 3-D Hexatown model was implemented as tilted. Accordingly, in the presentation, this led to a higher horizon upwards, a lower horizon downwards, and a tilted horizon sideways.

Figure 2. The virtual environment apparatus used in the experiment. The participants were placed on the training bike in front of the half-cylindrical screen.

Also, the geometrical cues like texture density, the perspective gradient, and the texture-compression gradient (Blake et al 1993) changed accordingly between the upview, downview, and sideways view. Second, prototypically upright-oriented objects like houses, trucks, and trees were implemented upright and could therefore be used as reference objects. Third, when moving in the slanted environment, the force-feedback feature of the bicycle was used to increase the necessary effort for pedaling according to actual slant, thus causing the kinesthetic perception of effort when moving on slanted surfaces. Since the available setup did not encompass the technical possibility to change the tilt of the bicycle according to slant, the slant perception on the basis of body posture in comparison with the vestibular gravitational down vector could not be simulated. However, preliminary tests (Mochnatzki 1999) with the described setup showed that participants could detect even small virtual slants (0.4°) reliably. Even without the changes in body posture, the implemented slant cues led to a well-perceivable slant impression.

Another finding from these tests was that the additional force feedback did not lead to a measurable increase in slant discrimination in comparison with a pure visually implemented condition. Therefore, we assume that in our setup the slant perception is mostly due to the visual-slant cues. We think that a pure kinesthetic condition (eg a flat environment with a steady 'wind' from one direction which could be felt in pedaling) would be much more complicated to use successfully in navigation. However, we included the force feedback to enhance the immersion of the virtual slant.

2.1.4 *Slant conditions.* In the control condition, the Hexatown environment was on a flat plane. This condition will be referred to as FLAT. In the other two conditions, the ground plate of Hexatown was tilted with a slant angle of 4° (equivalent to an inclination of 7%, see figure 3). This is ten times larger than the reliably perceivable slant of 0.4° from the preliminary tests. The two slanted environments differed in the orientation of the slant with respect to the minimal (object 15 or 19 to object 2) and maximal spatial extension (object 5 to object 21) of Hexatown (see figure 4).

In the first slant condition, the minimal extension axis of Hexatown was aligned with the salient up–down axis; the maximal extension axis was aligned with the indifferent sideways axis. This setup resulted in the minimal sum of elevation differences between the junctions, ca 156 m. Therefore, this condition is referred to as small elevation variance (SEV).

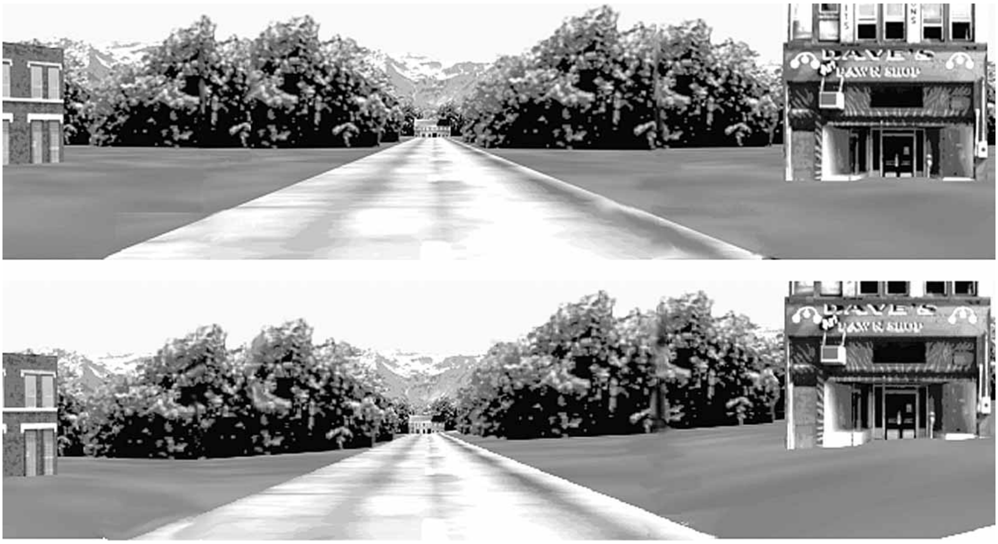
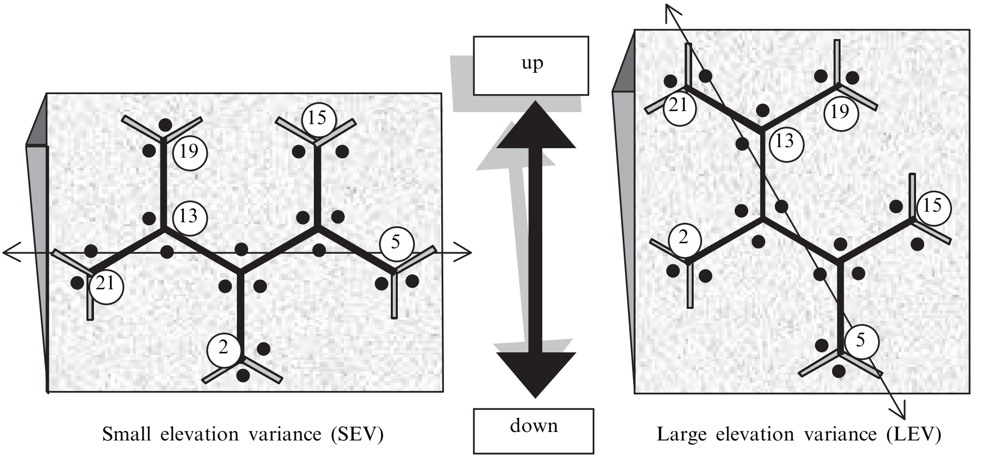


Figure 3. An example for scenery in the flat (above) and the slanted environment. Buildings, trees, and streets remained upward.



Small elevation variance (SEV)

Large elevation variance (LEV)

Figure 4. The layout of the landmarks and streets in the two slant conditions. The thin arrow indicates the maximal extension axis of Hexatown.

In the second slant condition, the maximal extension axis was turned 60° into the gradient direction, leading to an increased sum of location elevation differences of ca 216 m. This condition is referred to as large elevation variance (LEV). The 60° reorientation in comparison to the SEV condition was chosen, because this variation keeps the slant of the eight streets in SEV and LEV relatively similar: in SEV, three streets are oriented directly in up–down direction; four streets are oriented with 33% slant up or down the slope. In LEV, two streets are heading directly upwards and five streets are oriented with 33% slope.

Both conditions have in common that the uniform slant can be used as geocentric direction information and that the single streets are comparably tilted, but in the LEV condition the larger sum of location elevation differences between the junctions (216.5 m versus 156 m in SEV) could lead to a more pronounced encoding of location heights and therefore to a higher distinctiveness of landmarks. A comparison between the two slant conditions can clarify if these differences lead to higher performance in the LEV condition.

2.2 *Procedure*

The three experimental conditions (FLAT, SEV, LEV) were tested in a between-subjects design with sixteen participants per condition. The experiment had four different parts: the navigation tasks, the orientation tasks, the elevation judgments, and a map-drawing task. Participants were instructed separately for each part and did not know the upcoming tasks in advance. On average, participants needed 90 min for the whole experiment.

2.2.1 *Navigation tasks.* In the first part, the participants had to perform fifteen search tasks in the unknown environment. With the first five exploratory tasks, the participants were trained to find the task-relevant places and junctions. The ten following tasks tested their achieved navigational knowledge. Before each trial, a full 180° semi-panoramic view of the goal location was shown. After a button press, the goal presentation was exchanged with the full view of the current starting position.

Through turns and translations, the participants had to move to the indicated goal locations. Participants navigated through Hexatown using the virtual-reality bicycle. At the junctions, 60° turns could be performed by pressing one of two buttons (left or right) fixed to the bicycle. Since the bicycle standpoint in reference to the 180° screen was fixed and unmovable, turns of the participant to another direction were simulated through turning the virtual environment on the screen around the participant. The simulated turn movement was 'ballistic', with the following predefined velocity profile: turns took 4 s, with a maximum speed of $30^\circ\ \mathrm{s}^{-1}$ and symmetric acceleration and deceleration. The smooth profiles for rotation were chosen to minimise simulator sickness. The simulated translations on the streets were initiated by pressing an additional button. Translations were not ballistic: translation velocity was controlled by the pedal revolutions of the participants, with a mechanical-motion model that changed the tightness of movability of the pedals according to the current inclination of the street along the geographical slant. But participants were not able to change the direction of the movement, which led them in the middle of the street to the next junction and stopped there automatically.

Each turn and each translation was counted as one motion decision. When the participants had reached their goal, a message was displayed, indicating whether they had used the path with the least possible number of motion decisions ('fastest' path), or not. If not, they had to repeat the task until they completed it without unnecessary turns and translations. As a reminder, the participants always had the possibility to expose a small picture of the current goal object in the bottom left corner of the middle screen by pressing an assigned button on the bicycle handles.

2.2.2 *Training tasks.* The first five tasks were administered to train the participants in the virtual environment. The starting point of these tasks was landmark 15 (home). The five goal locations were increasingly farther away from landmark 15, starting with landmark 5 (two junctions), continuing with landmarks 2 and 13 (three junctions), and finally with landmarks 19 and 21 (four junctions). The earlier Hexatown studies had shown that the initial orienting in Hexatown is complicated for a lot of participants; therefore this sequence with increasing complexity was administered uniformly. After the five exploration tasks, participants had covered all junctions in Hexatown.

All goal locations in the next navigation tasks were restricted to the five goals and the starting point of the exploration phase, the other landmarks were 'fillers' which could be used for navigation or ignored. Since the success in finding a new location in an unknown environment cannot be attributed to the presence or absence of slant, the outcomes of these five tasks were not used in the further analysis.

2.2.3 *Return path and novel path tasks.* The next ten search tasks consisted of either return paths from the previously learned goal locations to the location at landmark 15, or novel paths between the five goal locations from the exploration phase. Since the routes from landmark 15, through Hexatown, to the different goal locations had been traveled five times successfully, it was expected that the pure return to landmark 15 would be easier for the participants than the novel paths which required the planning and execution of a new route through Hexatown. Return-path and novel-path tasks were carried out in alternation. As dependent variable, the number of moves (turns and translations) leading away from the goal were counted as errors. Moves on a wrong path which were leading back in the direction of the goal were interpreted as successful reorienting of the participant and therefore not added to the number of errors.

The repeating of tasks until error-free performances were achieved had the consequence that, with increasing navigation difficulties due to variations in the experimental design or the personal navigation abilities, participants were exposed more often to the environment and had therefore more training runs than participants with less navigation difficulties. This procedure should ensure that all participants were able to orient themselves and to navigate successfully prior to the subsequent pointing judgments.

Note that one street unit between two junctions had a length of 100 m and was simulated 1 : 1 in the basic variables (velocity of optic flow, displayed size of objects, etc). The fifteen navigation tasks had a length of two up to four junctions; even for an immediate correct solution, participants had to cover between 200 and 400 m distance. For the fifteen tasks, participants had to cycle between 6 and 10 simulated kilometres.(2) This part of the experiment took about 50 to 60 min.

2.2.4 *Pointing tasks.* After the navigation phase, pointing tasks were carried out to evaluate participants' ability to assess the geocentric directions (independent of connecting streets) towards distant junctions. Still sitting on the bike, the participants were shown a full view of one of the locations from the previous navigation tasks as starting place. Then, a picture of the landmark at the goal location was presented at the bottom of the screen. By pressing the left-turn or right-turn button, the simulated environment on the 180° screen started to turn in that direction around the participants until the button was released. The task of the participants was to turn the environment for such an angle that the estimated direction to the position of the goal from the given reference location was straight ahead. A stationary vertical line in the middle of the main screen was superimposed on the turning image to mark the correct forward direction. The basic idea behind this pointing procedure was the simulation of the optic flow which the participants would experience when they themselves would turn towards an unseen goal in a real environment.

This procedure is not without problems. Klatzky et al (1998) as well as Bakker et al (1999) reported that participants produced larger turning errors in virtual environments when using only optic flow in comparison to conditions in which the participants turned also their head and body. However, the effectiveness of optic flow seems to be dependent on the screen size and the display device. Klatzky et al and Bakker et al used head-mounted displays, which have a small field of view and lead to larger turning errors than optic flow on projection screens (Riecke et al 2002; Schulte-Pelkum et al 2002).

(2) After all, the VR-bike was originally a training bike. To avoid exhaustion of the participants, the overall bicycling effort was pronouncedly lower than in reality.

In contrast to the findings cited above, prior psychophysical experiments with the apparative setup used in our experiment have shown that participants provided with visual optic-flow feedback from the large 180° screen are able to execute reasonably accurate self-inferred turns (Riecke et al 2002).

For locations and goals, the five landmarks which were the goal locations in the exploration tasks and novel path tasks were used, resulting in five reference locations with four different goals each. Owing to the chosen ground plan of Hexatown, one of the goals was directly visible from one of the reference points, leading to perfect performance. This pointing task was therefore excluded from further analysis. Altogether, nineteen pointing judgments per participant were collected. The absolute differences in angle between the pointing judgments and the correct directions were recorded and averaged per participant, leading to the dependent variable 'averaged pointing deviation' (APD). This part of the experiment took about 12 – 15 min.

2.2.5 *Elevation judgments.* To test if participants had successfully encoded elevation information during the navigation phase, elevation judgments were collected in the SEV and LEV conditions after the pointing tasks. Pairs of landmark pictures from the six goal locations with different elevations were presented without further environmental background. The participants had to decide which location had appeared at a higher elevation in the virtual environment. For each of the two slant conditions, ten pairs of goals were selected and tested. Beside the decision itself, the decision time was recorded. This task took about 5 min.

2.2.6 *Map drawing.* Finally, participants were asked to draw, using pen and paper, a map of the test environment in as much detail as possible. There was no time limit for the participants. Most participants finished their map drawings in about 10 min.

2.3 *Participants*

A total of fifty-three persons, aged 17 to 41 years ($M = 28$ years), participated as paid volunteers in the experiment. One participant could not finish the experiment because of simulator sickness. As could be expected from earlier experiments with this setup, a few participants experienced huge problems in orienting themselves in the virtual environment, which led to irregularly high error rates. As a common criterion for exclusion from further analysis, a mean APD larger than 50° was chosen. With this criterion, the data of four participants (two under LEV conditions, one each under SEV and FLAT conditions) were excluded. The remaining forty-eight participants consisted of twenty-four women and twenty-four men. Gender was balanced in the three conditions.

2.4 *Statistical design*

The main hypothesis was the prediction that participants in the two slant conditions would perform better in the spatial tasks than participants in the flat condition. To test this hypothesis, the experimental outcomes of the flat condition are compared with the pooled outcomes of the two slant conditions. The second hypothesis was that participants in condition LEV would perform better than participants in the SEV condition, because of the higher elevation variance. This hypothesis is tested with direct comparisons between the two slant conditions (SLANT; refers to the pooled outcomes of SEV and LEV conditions). The other single pairings (FLAT – SEV and FLAT – LEV) are reported supplementarily.

3 Results

3.1 *Errors in the navigation phase*

Overall, about two-thirds of the participants could deal well or even perfectly with the navigation tasks. The global mean number of errors for the five return-path tasks was 1.98 ($\mathrm{SD} = 2.12$, $\max = 8$), and for the five novel-path tasks it was 3.25

(SD = 3.74, max = 14). An inspection of the participants' error rates in the return-path and novel-path tasks showed a marked difference between the experimental conditions (see table 1 for return-path errors, and table 2 for novel-path errors): while participants' errors in the FLAT condition were relatively evenly distributed, the distribution of participants' errors in the SLANT condition was highly skewed to the left, which can be seen in the difference between the mean and the median. Especially in the LEV condition, about half of the subjects (return path: 8; novel path: 7) made no navigation error at all [see tables 1 and 2, column '*n* (zero errors)']. On the other hand, in the SLANT condition and both navigation tasks, the maximum number of observed errors was higher than in the FLAT condition (see tables 1 and 2, column 'max'). Because of the skewed distributions in the slant conditions, the nonparametric, rank-based Mann–Whitney U-test was used for the hypothesis testing. The mean ranks of the navigation performances in the different conditions are depicted in figure 5.

Table 1. Results for return-path errors. The slant condition contains the pooled outcomes of SEV and LEV conditions. Ranks are shown for paired comparisons of experimental conditions. Statistical results (Mann–Whitney U-test) for the paired ranks are shown at the bottom.

Condition	Measures for the experimental condition					Ranks			
	mean	SD	median	max	*n* (zero errors)	(a)	(b)	(c)	(d)
FLAT	2.44	1.59	2	6	2	29.84		18.78	19.56
SLANT	1.75	2.33	1	8	14	21.83			
SEV	1.88	2.36	1	8	6		17.22	14.22	
LEV	1.63	2.36	0.5	8	8		15.78		13.44
Statistical results									
U						170.5	116.5	91.5	79.0
p						0.028*	0.325	0.081	0.034*

Table 2. Results for novel-path errors. The SLANT condition contains the pooled outcomes of SEV and LEV conditions. Ranks are shown for paired comparisons of experimental conditions. Statistical results (Mann–Whitney U-test) for the paired ranks are shown at the bottom.

Condition	Measures for the experimental condition					Ranks			
	mean	SD	median	max	*n* (zero errors)	(a)	(b)	(c)	(d)
FLAT	4.44	3.81	3	11	3	29.81		18.38	19.94
SLANT	2.66	3.62	1	14	13	21.84			
SEV	3.12	3.52	2	12	6		17.91	14.63	
LEV	2.19	3.78	1	14	7		15.09		13.06
Statistical results									
U						171.0	105.5	98.0	73.0
p						0.029*	0.189	0.125	0.017*

The comparison of errors between the FLAT and the SLANT condition showed a difference in the predicted direction in both path tasks: the participants in the SLANT condition produced fewer navigation errors and received a significantly better mean rank [see tables 1 and 2, column 'rank a'. The statistical values for the comparisons are at the bottom of the columns].

Concerning the second hypothesis of the increased performance due to the higher elevation variance in the LEV condition, the results showed only a small and insignificant benefit in comparison to the SEV condition (see tables 1 and 2, column 'rank b').

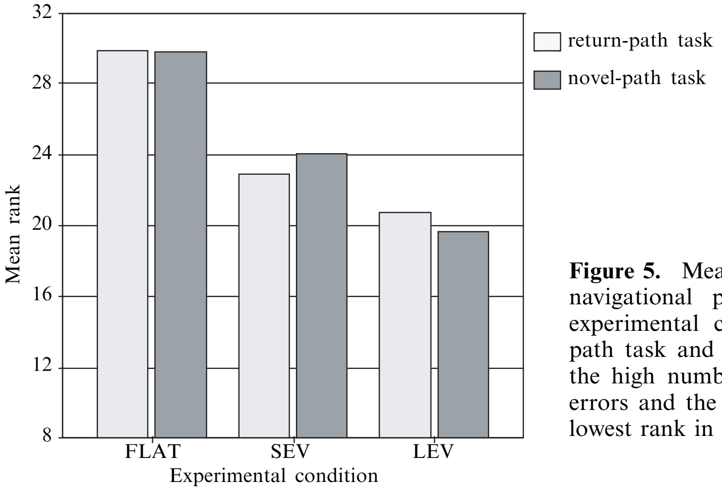


Figure 5. Mean ranks of participants' navigational performance in the three experimental conditions, for the return-path task and novel-path task. Owing to the high number of participants with no errors and the resulting ties in ranks, the lowest rank in both tasks was 8.5.

Additional comparisons between the FLAT condition and the SLANT condition showed, for both kinds of path tasks, a significantly lower amount of errors in the LEV condition (tables 1 and 2, column 'rank c'), but only an insignificant trend towards a lower amount of errors in the SEV condition (tables 1 and 2, column 'rank d'). While the relative differences between the three experimental conditions were approximately equal in return-path and novel-path tasks, an overall comparison of the two path tasks with a nonparametric Wilcoxon signed-rank test showed that novel-path tasks led to a significantly higher amount of errors ($Z = -2.489$, $p = 0.013$).

3.2 *Pointing judgments*

The averaged pointing deviations (APDs) varied highly between participants. The lowest obtained APD was 6.7°, meaning that this participant pointed on the average across the nineteen pointing tasks only 6.7° to the left or right of the correct direction to the distant goal. In contrast, the highest APD in the present statistical analysis was 46.7°, and the APDs of the four excluded subjects were 51.0°, 58.3°, 59.5°, and 63.5°.

As predicted, the participants in the FLAT condition had a higher APD (35.28°, SD = 10.48) than the participants in the SLANT condition (20.66°, SD = 11.79). This difference was highly significant ($t_{46} = 4.196$, $p < 0.001$).

In contrast, the expectation of a superior performance of the subjects in the LEV condition compared with the SEV condition was not supported. The APD in the LEV condition (19.26°, SD = 10.69) was only marginally lower than the APD in the SEV condition (22.01°, SD = 12.99; $t_{30} = 0.665$, $p = 0.256$). As in the navigation tasks, the higher elevation difference in the LEV condition did not lead to a significantly better performance in the pointing judgments (see figure 6).

Additional comparisons showed that with pointing judgments, both slant conditions showed a significantly lower APD than the FLAT condition (FLAT – SEV: $t_{30} = 3.167$, $p = 0.002$; FLAT – LEV: $t_{30} = 4.280$, $p < 0.001$).

The profound difference between the FLAT condition and the SLANT condition can be illustrated by the finding that nineteen participants (59.4%) from the SLANT condition had lower APDs than the best performing participant in the FLAT condition with an APD of 16.67°. The distributions of the respective pointing deviations in the three conditions are depicted in figure 7. The reduced amount of deviation is present over the whole distribution range, but is more pronounced in the range of larger deviations.

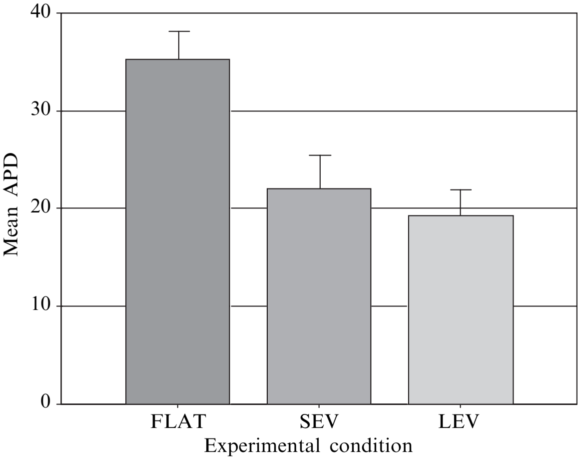


Figure 6. The mean APDs of the FLAT condition were significantly higher than the means of the two slant conditions, which were not significantly different from each other. Bars indicate ±1 standard error.

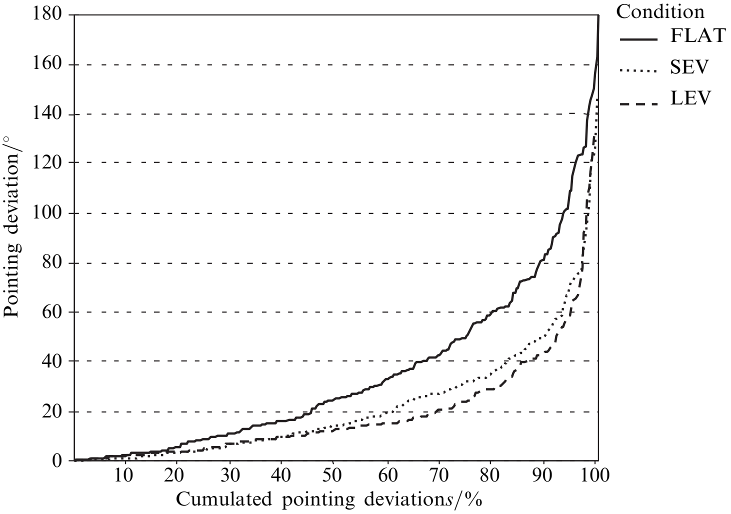


Figure 7. A comparison of the error distribution of the pointing measurements shows the reduction of deviation in the LEV and SEV conditions. The difference is present over the whole range, but more marked in the amount of large pointing deviations in the FLAT condition. Pointing measurements deviate less than 20° from the correct direction for about 70%, 60%, and 45% in conditions LEV, SEV, and FLAT, respectively.

3.2.1 *Analysis of the single pointing deviations.* To gather further insights into the mechanisms of the facilitating influence of perceived slant, the single pointing deviations of the three conditions in the nineteen tasks were compared, in search for tasks which were complicated for one group but not for others. One consideration was that pointing directions along the slant gradient might show lower deviations than perpendicular pointing directions. However, no systematic influence of slant gradient and pointing direction on the pointing deviations could be found. Furthermore, no obvious differences between the LEV and SEV conditions could be observed; the SEV condition tended to be just a little bit more imprecise in most tasks.

Taking random variance into account, the differences in the mean pointing deviations in the nineteen tasks were relatively moderate in the two slant conditions, ranging from 11.0° to 32.5° in the LEV condition and 9.4° to 41.2° in the SEV condition. In comparison, much higher task-specific differences in the mean pointing deviations were found in the flat condition, ranging from 14.9° to 89.9° (see figure 8).

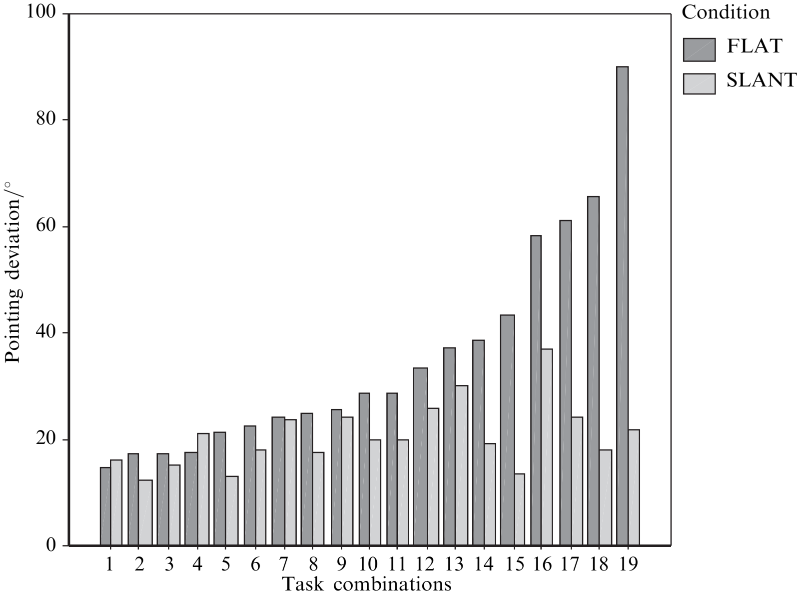


Figure 8. Mean pointing deviations in the nineteen task combinations, ordered ascending for the FLAT condition. The mean pointing deviations per task were markedly more spread in the FLAT condition than in the SLANT condition.

An inspection of the singular participant deviations in the four tasks with the highest deviations in the FLAT condition (right bars in figure 8) showed markedly increased numbers of totally wrong pointings, indicating that in these location – target combinations, a lot of participants in the FLAT condition were severely disoriented. Interestingly, this pattern was not reflected in the SLANT condition, leading to extreme differences in the pointing deviations which are alone responsible for a good part of the high significance of the statistical comparisons. However, the SLANT condition also elicited lower pointing deviations in most other location – target combinations, although these differences were not so spectacular. A recalculation under exclusion of the four tasks with the highest deviations in the FLAT condition still yielded a significant difference ($t_{46} = 2.531$, $p = 0.012$) between the mean APD in the FLAT condition (26.36°, SD = 7.35) and the SLANT condition (19.44°, SD = 10.52).

The unexpectedly strong influences of configuration on direction knowledge are currently investigated in a new research project. In a pilot study, we could reproduce strong location – target specific differences in different place configurations. The results indicate that the main factors for an enhanced probability of high pointing errors are (a) a location encircled by other places (as landmark 13) and/or (b) a direction to the target which is eccentric from the main orientation at the location and afar from other targets. We think that these factors will be at least in part responsible for the very high deviations in the FLAT condition. Two of the four most disorienting-prone tasks (as well as the fifth) had as location the encircled landmark 13 (see figure 4); the two others consisted of the most eccentric targets for the respective location (21→2; 19→5).

3.3 *Elevation judgments*

With the ten elevation-judgment tasks, where pairs of landmarks had to be judged on their relative elevation, participants in the SEV and LEV conditions were tested for their representation of the relative elevations of landmarks in Hexatown. Their performance was very good: the participants from the SEV condition produced a mean of

8.25 correct answers (SD = 1.43); the participants from the LEV condition produced a mean of 9.13 correct answers (SD = 1.26; see figure 9). The number of correct answers per participant was compared with the chance level number of five correct answers in a one-sample *t* test. Results from both conditions are significantly above chance level ($t_{15}^{\mathrm{SEV}} = 9.04$, $p < 0.001$**, $t_{15}^{\mathrm{LEV}} = 13.11$, $p < 0.001$**). Therefore, along with the navigation through the slanted virtual environment, the participants had been able to acquire knowledge about the elevation of places whose relative vertical position could not be perceived directly. In accordance with the second hypothesis, a comparison between the two slant conditions revealed in this task a significantly higher amount of correct answers in the LEV condition than in the SEV condition ($t_{30} = 1.832$, $p = 0.039$*). The higher elevation variance in the LEV condition had led to better knowledge about the relative elevations of places.

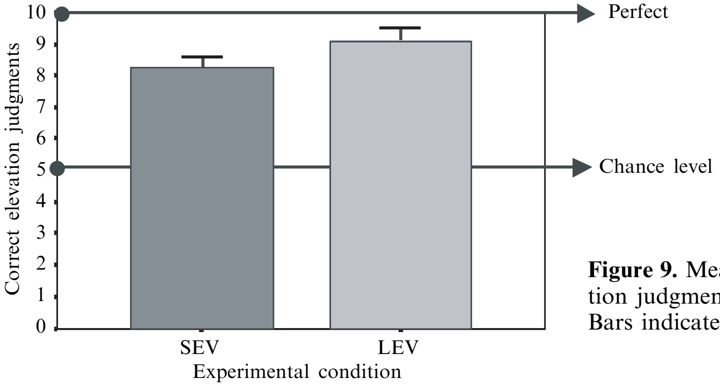


Figure 9. Mean number of correct elevation judgments in the two slant groups. Bars indicate ±1 standard error.

3.3.1 *Decision times.* For the analysis of the decision times (DTs), the times from the first elevation tasks were excluded, because these were highly increased, owing to the participants' need to accommodate the new task. The average DT in the SEV condition was 5.1 s, and in the LEV condition 4.1 s. This difference was not significant ($t_{30} = 1.104$, $p = 0.139$). Also, an inspection of the DTs relating to the different route lengths (the number of route segments between two objects varied between one and four) did not show remarkable differences between the two slant conditions. Therefore, the data of each participant was z-transformed, so that only task-specific relative differences could show up in the DTs; the z-transformed data of the two conditions were pooled for further analyses. An inspection of the DTs ordered according to the number of route segments showed no increase of DT with longer route distances between the pairs of landmarks (see figure 10, left panel). In contrast, an ordering of the DTs according to elevation differences (between 6.9 and 20.9 m) showed a clear trend to decreased DTs with increased elevation differences (see figure 10, right panel). Accordingly, in a regression analysis the factor route length was non-significant ($R^2 = 0.001$, $F_{1,286} = 0.409$, $p = 0.523$); the factor elevation differences was highly significant ($R^2 = 0.034$, $F_{1,286} = 10.024$, $p = 0.002$).

3.4 *Map drawings*

The map drawings were used to study the coherent overall spatial knowledge of the participants which was still available to them after the experiment. The quality of the drawings with regard to the mapping of the basic geometrical connections of the eight junctions differed remarkably. The maps of ten participants ranged from very incomplete to incomprehensible; fifteen participants produced partially correct maps, but with two or more missing junctions, with gross geometrical errors (eg several right-angle junctions), confusions of locations, or (an interesting kind of error) two or more

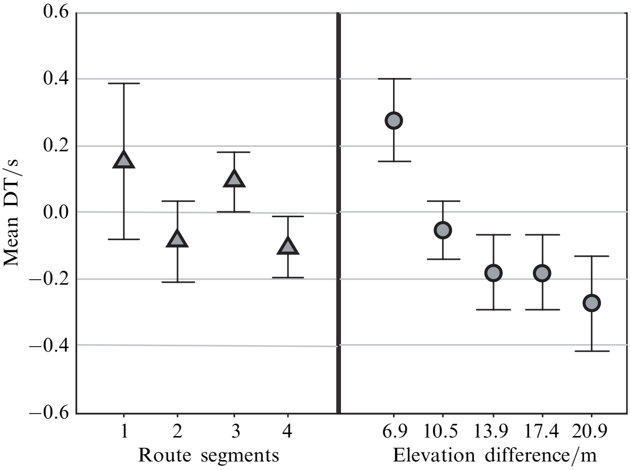
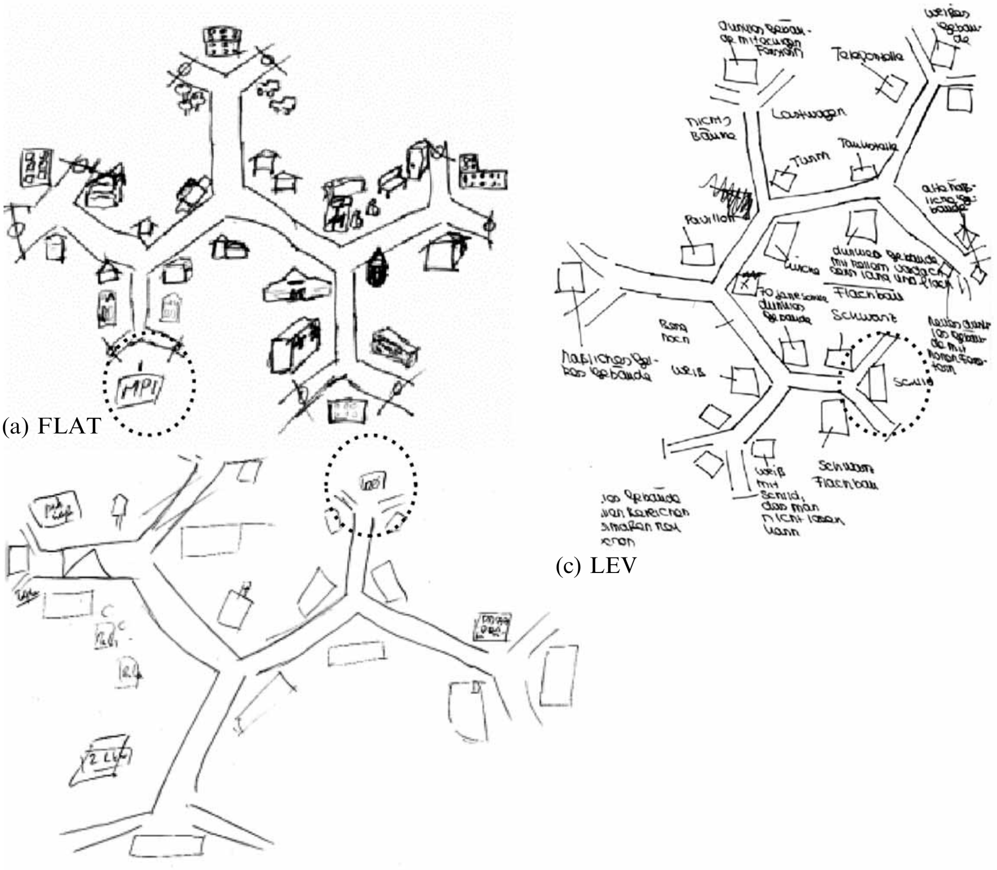


Figure 10. Means of the z-standardised decision times (DTs) of the elevation judgments (the two slant groups are pooled). The distance (route segments) between the pairs of landmarks showed no systematic influence (left panel); higher elevation differences led to smaller DTs (right panel). Bars show ±1 standard error.


(a) FLAT

(b) SEV

(c) LEV

Figure 11. Examples for the preferred single-perspective maps in the three different conditions. (a) The starting place (landmark 15, indicated on all maps with a dotted circle) is at the bottom of the page. (b) The deepest place (landmark 5) is at the bottom of the page. (c) The deepest place (landmark 2) is at the bottom of the page. For comparisons, see figure 4.

junctions too much, often even depicted with landmarks. Nine participants produced maps which were relatively correct (one junction missing or added), and the maps of fourteen participants were very good. Despite these high variations, the overall quality differences were distributed relatively evenly between the three experimental conditions. A comparison of the number of drawn way segments, of the structural correctness of places (depicting three streets meeting approximately at 120° angles), and the number of drawn objects revealed no remarkable differences. The navigation over sloped terrain in the SLANT condition did not lead to noticeably better map drawings.

However, an interesting effect showed up in the study of the maps. About two-thirds of the maps were drawn from a single perspective, which could be determined by the uniform orientation of lettering or the uniform perspective of the drawn objects. In contrast, in the maps with multiple perspectives, lettering or object perspective was oriented locally around the places where the objects were drawn. The presence and bearing of a single perspective was judged by the authors. In comparing the directions of single-perspective maps in the different conditions, a tendency to align this perspective with the gradient direction of the slope could be noticed in the two slant groups: in ten out of twelve maps from the participants in the SEV condition, and six out of eleven maps from the participants in the LEV condition, the chosen perspective roughly accorded with the salient slant axis. This means that the low landmarks were placed near to the drawing participant (at the bottom of the page), the highly elevated landmarks at the far end (at top of the page)—see figure 11. In contrast, the majority of single-perspective-drawing participants in the FLAT condition preferred a perspective which was aligned with the direction of the street leading away from the starting point (six out of nine maps).

4 Discussion

4.1 *Perceived slant during navigation leads to elevation knowledge*

Earlier experimental findings had indicated that information about the relative height of objects on a slanted environment is encoded in the spatial knowledge of persons who navigate in these surroundings (Gärling et al 1990). With the virtual-environment setup used in the present study, we were able to replicate this finding. The outcome of the elevation-judgment task shows that the participants in the two slant conditions possessed elevation knowledge of landmarks which were not visible from each other or together from a third viewpoint. The basis of these judgments has to be the mental addition of the perceived slants of the singular-route segments connecting the landmarks. Similar to the findings of Gärling et al, the DT analysis showed no correlation with the number of connecting segments, but a significant correlation with the elevation differences between the landmarks. This indicates that the relative height of landmarks was already part of the explicit spatial knowledge of the participants and not computed at task time, at least not in a way requiring time proportional to distance (eg with an imagined walk from one object to the other).

4.2 *Slant knowledge facilitates actual navigation and orientation*

In an extension to earlier findings, our experimental results of the navigation and pointing tasks also show that the participants actually used their slant knowledge in navigation, and used it successfully. Both navigation and pointing performances were improved significantly in the SLANT condition. In the following, we present an explanation scheme for these superior performances. We find it reasonable to differentiate between four different processes, each of which will have some influence on the observed navigational improvements. Three of them take place during the encoding of the spatial configuration, the last one takes effect in the test phase.

(a) Perceptual enrichment of the encoded local places: As proposed in the introduction, navigation over slanted terrain can lead to additional perceptual input in encountering local places and landmarks. In the present setting, this enrichment would be the visual perception of the position of the landmarks in relation to the slant gradient (being oriented uphill, downhill, etc) as well as the gradient of the streets and their orientation towards the slant gradient. Also, the elevation level of adjacent places could be perceived directly ("place A is higher than place B"). These additional perceptions should lead to an enriched representation which in turn could lead to an unspecifically enhanced recall.

(b) Improved path integration: A uniform slant gradient as in the present experiment also provides geocentric direction information which can be used as a compass. In the present environment with straight streets, this information could be especially helpful in perceiving the magnitude of turns towards other places; in other environments which are freely accessible, it would also provide the means to walk straight lines. Generally, slant used in this way can lead to improved path integration and, by that, to an improved knowledge of the angles between different places.

(c) Global elevation knowledge: As shown by the outcome of the elevation judgments, the participants also developed general knowledge of the elevation of places in relation to each other, presumably together with global knowledge of the elevation of places along the slant. That means that being in one place, they possessed knowledge about the relative elevation of any other place in relation to the momentary location.

(d) Perception of slant gradient at test time: Finally, the participants in the SLANT condition could perceive the actual slant gradient of their momentary location also during the navigation and pointing tasks. If it is taken into account that the participants possessed knowledge about the relative elevation of the respective target location, they could use the actual slant gradient to orient themselves toward that location.

The first two processes should lead to generally improved and enriched configuration knowledge and thus to a mild general improvement of the navigation performance. The latter two processes together could be helpful especially in cases where participants were momentarily disoriented or insecure, as will be described next.

4.2.1 *The use of global elevation knowledge and perceived slant in the navigation tasks.* In the navigation tasks, errors occurred if participants took a wrong turn at a junction: if they were unsure (or disoriented) about turning left or right to the target location. In the SLANT condition, participants could use their slant knowledge and the actual slant perception in such cases of uncertainty as additional information: they knew (at least often) the relative elevations of the starting position (eg highly elevated) and the target landmark (eg at a low elevation level); and at junctions they could perceive the slope of the outward streets. In cases of uncertainty about turning left or right, they could still choose that street whose slope was reducing the height difference towards the target (in this case, leading downwards). Participants in the FLAT condition did not have this 'backup' orientation possibility.

4.2.2 *The use of global elevation knowledge and perceived slant in the pointing tasks.* Similarly, the knowledge of relative elevation of places and the actual slant-gradient perception could prevent a total loss of orientation which happened much more frequently in the FLAT condition. This effect can be illustrated by the location–target combinations which elicited very high pointing deviations in the FLAT condition, but not in the two slant conditions (see figure 8), as well as the finding that participants in the SLANT condition produced only about one fourth of the amount of high pointing deviations above 60° (5.1% in comparison to 19.4%) produced by the participants in the FLAT condition (see figure 7).

In the orientation task, participants again knew (often) the relative elevations of the starting position and the target landmark; and they could perceive the actual slope and their momentary orientation towards it. This information alone could be used to point approximately in the correct direction. For example, if the target location had a higher elevation in the environment than the momentary position, the participants could point at least 'upwards', even if they were otherwise very insecure about the correct direction. This rough orientation alone would prevent very high pointing deviations.

Admittedly, with increasing deviations of the target locations from the upright slant axis, the slant-direction information should become more and more ambiguous. In the pronounced cases where the target landmarks were at the same height as the momentary location, the participants, were they restricted solely on slant knowledge, could only conclude that the direction to the targets would be either of the two 'sideways' directions. However, even some faint additional spatial information about the direction to the target would be enough to disambiguate these ambiguities and allow a decision for one of the two sideways axes. In turn, pointing to that direction would again be roughly correct, similar to pointing upwards. Accordingly, there were no systematic influences of the slant gradient on the single pointing deviations within and between the two slant conditions. Together with some disambiguating additional spatial knowledge, even the absence of elevation differences between locations can allow a rough orientation in a slanted environment.

4.3 *Additional elevation knowledge does not show up in the map-drawing quality*

On the other hand, the encoded slant knowledge could not be used by the participants to produce more accurate maps. This may be due to the fact that this knowledge is especially useful together with the respective actual slant perceptions, as in the interpretations above. On the other hand, the landmark pictures in the elevation-judgment task were presented without any (slanted) background and their relative elevation could still be rated successfully. Therefore, the lack of superiority of the maps produced by the participants in the SLANT condition cannot be explained by the missing actual slant perceptions alone. The additional elevation information in the spatial representation should lead at least to some unspecific enrichment of the associated knowledge structure, which in turn should lead to enhanced recall performances. In our interpretation, it might be that the differences in the participants' ability to draw maps from navigational experience were so huge that the rather small advantage of the additional slant knowledge did not show up.

4.4 *Transferability to real-world navigation*

In testing the influence of slant on navigation under experimentally controlled conditions, our virtual-environment setup was very advantageous. The question is now if these findings are transferable to navigation in real environments. On the one hand, the experience of 'real slant' might be still more impressive than our simulated slant, which could lead to enhanced effects. On the other hand, a noticeable amount of participants experienced larger difficulties in navigating in Hexatown than in comparable real environments. Indeed, a few were not able to handle this environment at all. Also, it is doubtful that a total loss of orientation will happen so frequently in the real world. Therefore, the introduction of slant as an additional orientation factor could have been especially helpful in the present virtual environment; more helpful indeed than in similar real conditions. Last, it should be mentioned that the slant in our environment was uniform and unidirectional, providing the participants with an unambiguous cardinal direction. It can be assumed that slant will be less useful for navigation in an environment with eg several rounded and merging hills.

However, the obtained results are fairly comparable with analogous results from real environments. On average, the participants in the present study gave 86.9% correct answers in the elevation-judgment task, the participants in the study by Gärling et al produced 76.5% correct answers. In the present study, the correlation between elevation-judgment DTs and height differences was $r = -0.18$; in the study by Gärling, the correlations in the two experimental conditions were $r = -0.32$ and $r = -0.26$, respectively. Concerning the pointing tasks, Chance et al (1998) found in a pointing task situated in a real maze a mean pointing deviation of 49°; while Ruddle et al (1997) reported for a pointing task, to rooms in a building, a mean pointing deviation of 20°. The APDs from the present experiment (35° in the FLAT condition, 20.7° in the SLANT condition) are of a comparable magnitude. It seems reasonable to conclude that the basic navigation processes captured in the results of the present experiment are not very different from the navigation processes in real environments. Hence, our experimental outcomes lend strong support to the notion that slant will also facilitate navigation in real environments.

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