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Discrimination of travel distances from 'situated' optic flow

Harald Frenz [a], Frank Bremmer [a,b], Markus Lappe [a,c,*]

[a] Allgemeine Zoologie und Neurobiologie, Ruhr-Universität Bochum, D-44780 Bochum, Germany
[b] Fachbereich Physik, AG Neurophysik, Philipps-Universität Marburg, 35032 Marburg, Germany
[c] Psychologisches Institut II, Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany

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Abstract

Effective navigation requires knowledge of the direction of motion and of the distance traveled. Humans can use visual motion cues from optic flow to estimate direction of self-motion. Can they also estimate travel distance from visual motion?

Optic flow is ambiguous with regard to travel distance. But when the depth structure of the environment is known or can be inferred, i.e., when the flow can be calibrated to the environmental situation, distance estimation may become possible. Previous work had shown that humans can discriminate and reproduce travel distances of two visually simulated self-motions under the assumption that the environmental situation and the depth structure of the scene is the same in both motions. Here we ask which visual cues are used for distance estimation when this assumption is fulfilled. Observers discriminated distances of visually simulated self-motions in four different environments with various depth cues. Discrimination was possible in all cases, even when motion parallax was the only depth cue available. In further experiments we ask whether distance estimation is based directly on image velocity or on an estimate of observer velocity derived from image velocity and the structure of the environment. By varying the simulated height above ground, the visibility range, or the simulated gaze angle we modify visual information about the structure of the environment and alter the image velocity distribution in the optic flow. Discrimination ability remained good. We conclude that the judgment of travel distance is based on an estimate of observer speed within the simulated environment.

Keywords: Visual motion; Optic flow; Navigation; Path integration

1. Introduction

Knowledge of travel distance is important for spatial orientation and navigation. Classical cues to travel distance are translational vestibular signals (Berthoz, Israel, Georges-Francois, Grasso, & Tsuzuku, 1995; Israel & Berthoz, 1989), proprioception of walking movements (Thomson, 1980), or other self-generated or "idiothetic" signals (Mittelstaedt & Mittelstaedt, 1973, 1980). Recent studies in animals (Esch & Burns, 1995; Srinivasan, Zhang, & Bidwell, 1997) as well as in humans (Bremmer & Lappe, 1999; Harris, Jenkin, & Zikovitz, 2000; Redlick, Jenkin, & Harris, 2001) have suggested that self-induced visual motion signals can also be used to estimate travel distance. The optic flow experienced during self-motion carries much information that is useful for different sub-tasks of visual navigation (Lappe, Bremmer, & van den Berg, 1999). It can be used for the perception of heading (Warren & Hannon, 1990) the control of walking speed (Prokop, Schubert, & Berger, 1997), or the estimation of time to contact (Tresilian, 1999). Strictly speaking, however, optic flow does not specify travel distance, because the image speeds in the optic flow are mutually influenced by the speed of the observer and the distances of the visible objects from the observer (Lee, 1974). For a forward moving observer with speed V, the optical velocity θ of an individual environmental element at distance Z is

$$\theta = V/Z.$$

Travel distance might be estimated by measuring observer speed V and the duration of the movement. But inferring observer speed V from the optic flow speed θ alone is impossible, as one also needs to know Z to solve the above equation.

* Corresponding author. Address: Allgemeine Psychologie, Psychologisches Institut II, Westf. Wilhelms-Universität, Fliednerstrasse 21, 48149 Münster, Germany. Tel.: +49-251-83-34172; fax: +49-251-83-34173.
E-mail address: mlappe@psy.uni-muenster.de (M. Lappe).

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However, the respective travel distances of two successively presented optic flow sequences can be discriminated very accurately by human subjects when both sequences simulate movement in the same environment (Bremmer & Lappe, 1999). In this case, the distances Z of the visible objects from the observer are the same in both sequences. This allows observers to use optic flow speeds θ (or flow-based estimates of ego-speed V) together with movement duration to compare travel distances without explicit knowledge of Z. Thus, when the two visually simulated self-motions are from the same environmental situation travel distances are not ambiguous. The 'situated' optic flow provides enough information to discriminate travel distances. The initial part of the paper describes the ability of human observers to generalize travel distance across variations in flow speed and movement duration provided by the same environment.

The main objective of the paper is to investigate how the ability to estimate travel distance is affected by changes to the environment that lead to changes in the optic flow speeds but do not change observer speed. In this case, the relation of flow speeds to observer speed depends on the environment. The task, then, involves a transfer of information from one environment to another. Therefore, it requires a more general representation of travel distance, i.e., a representation that cannot be based directly on flow speeds. We study four different variations of the environment that affect the flow and the task in different ways. First, distances of objects in the environment can be specified by a variety of cues. We use environments that lack some of these cues but that always have the same depth structure. In this case, the distribution of the flow speeds is unchanged and the task can be completed as described in the beginning, i.e., based directly on flow speeds under the assumption that Z is always the same. Second, we vary the height of the observer above the ground. A change of height affects the flow speeds independently from observer velocity. Thus, observers have to register their height change and infer its consequences on the flow field in order to make correct ego-speed and distance judgments. Third, we vary the visibility range by truncating the visible scene at a certain distance. This removes slow flow speeds originating from distant objects and modifies the distribution of flow speeds. Fourth, we vary the viewing angle, and, respectively, the tilt of the ground plane. This changes the distribution of flow speeds presented on the screen. In all cases we find that observers are able to compensate for these changes.

2. General methods

2.1. Apparatus

All stimuli were generated on a Silicon Graphics Indigo2 workstation and back-projected on a 120×120 cm screen (Dataframe, type CINEPLEX) using a CRT video projector (Electrohome ECP 4100) with a resolution of 1280×1024 pixel. Vertical refresh rate of the projector was locked to 72 Hz. The frame rate at which new images were rendered was 36 Hz for textured stimuli and 72 Hz for random dot stimuli. Subjects were seated in front of the screen at a distance of 0.6 m. This resulted in a 90×90 deg field of view. Subjects were instructed to keep the distance to the screen constant and their head steady. Subjects viewed the stimuli binocularly.

2.2. Procedure

Each trial consisted of two visually simulated forward movement sequences. The first sequence served as a reference and was constant in velocity (2 m/s), duration (2 s) and simulated height above the ground (2.6 m). The second sequence varied in velocity and duration and in experiment 2 also in height above ground. Ranges of variation are given in the description of each experiment. Usually reference and test motion of a single trial were from within the same virtual environment. An exception was experiment 1b in which different environments were used for reference and test in single trials. The motion was always simulated with a rectangular velocity profile, i.e., starting instantaneously with the chosen velocity and terminating immediately after the determined duration. Before the experiment the subject was presented with an optical flow field (dot pattern) without further information and asked about his or her perception. All subjects reported that they perceived an ego motion in the forward direction. Then the subject was instructed that the task in the experiments was to indicate which of two successively presented ego motion simulations covered a greater distance. They signaled their judgment by pressing the left mouse button if they believed that the first ego motion simulation covered a greater distance or the right mouse button if they believed that the second ego motion simulation covered a greater distance. Before and after each motion sequence the environment was presented statically for 300 ms to ensure that subjects perceived the whole motion sequence. After the second motion of each trial, the environment remained visible until the response of the subject. Between the two simulations of each trial and also between trials the screen turned black for 500 ms.

2.3. Data analysis

We determined subjective equivalence of travel distance as a function of speed ratio between the reference and the test movement. For a given speed, the distance of the second motion was varied by changing the duration of the simulation. The duration for which subjects reached the point of subjective equivalence (PSE) we estimated by an adaptive threshold estimation procedure based on a maximum-likelihood method (Harvey, 1986). Responses were used on-line to determine the most likely psychometric curve representing the obtained answers. The 25% or the 75% point on the psychometric curve was randomly chosen and presented in the next trial. The range for the tested duration was 0.5–6 s in steps of 0.01 s with slopes between 1 and 130 in steps of 2. These ranges were based on prior tests. The experiment ended if a confidence interval of 95% was reached or every condition was presented 10 times.

2.4. Participants

Ten subjects (21–29 years of age) participated in the experiments, including the first author. All had normal or corrected to normal vision.

2.5. Environments

2.5.1. Textured ground plane

A 8 m × 8 m texture pattern (Iris Performer type "gravel") was mapped on a 400 m × 400 m virtual ground plane (Fig. 1(a)). Blue sky (rgb code: 0.1, 0.3, 0.7) was presented above the textured plane to make the stimulus appear more realistic. The starting point for each movement sequence was chosen at random on the plane in order to avoid recognition of the placement of individual texture elements in the successive movements. Mean luminance was 3.1 cd/m^2. This textured ground plane provided ample static depth cues, contained in gradients of texture density and texture size towards the horizon (Cutting, 1997). It also provided dynamic depth cues in the motion sequence, most notably motion parallax and the change of size of texture elements as they approach the observer. It is also conceivable that the trajectories of the ground plane elements may be used as a cue towards depth structure or travel distance (Table 1).

2.5.2. Dot plane 1

This plane consisted of 3300 white light points on a black background (Fig. 1(b)). The light points were first set on a grating every 6 m within a distance of 30 m to each side of the starting position of the movement and every 2 m within 52 m in front of the observer. Afterwards they were jittered up to 5 m forward or backwards and to one side. Therefore, on average 970 light points were visible on the screen. During the simulation dots stayed constant in luminance and size, eliminating size change as a distance cue. Mean luminance was 2.0 cd/m^2. Frame rate was 72 Hz.

2.5.3. Dot plane 2

For dot plane 2, 150 white light points were randomly distributed on the lower part of the screen on a black background (Fig. 1(c)). During the motion simulation these dots moved as if they lay on a ground plane, i.e., they obeyed the pattern of motion parallax of a ground plane. In the absence of motion, however, there was no cue about distance of these light points from the observer or about the structure of the environment. Dots remained constant in size and luminance. Furthermore, dots had only a limited life time so that subjects could not obtain information about travel distance from the trajectories of the light points. Each light point could disappear with a probability of 10% in each frame and

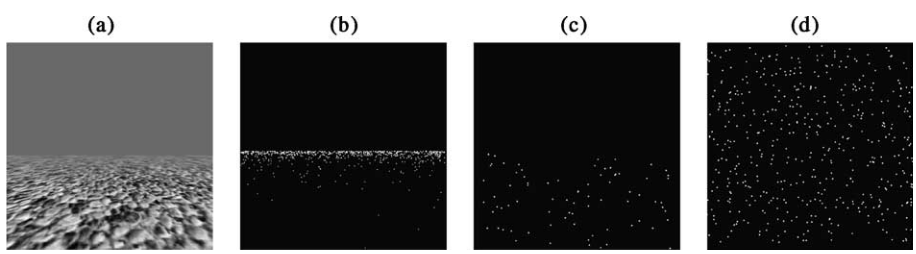

Fig. 1. Screen shots of the four environments. (a) Textured ground plane; (b) dot plane 1; (c) dot plane 2; (d) cloud of dots. See text for description of environments.

Table 1
Different depth cues contained in the four environments

	Density gradient	Change in size	Motion parallax	Trajectories
Textured ground plane	+	+	+	+
Dot plane 1	+	–	+	+
Dot plane 2	–	–	+	–
Dot cloud	–	–	+	+

A plus marks the presence of a cue, a minus its absence. "Density gradient" refers to the increase of texture density towards the horizon. "Change of size" is the looming of objects as they approach the observer. "Motion parallax" is the scaling of visual velocity of an object with its distance from the observer. "Trajectories" means that objects can be tracked as they cross the screen.

reappear at another position on the screen. With a frame rate of 72 Hz the mean lifetime of each dot was 138.89 ms. The mean luminance was 0.6 cd/m^2.

2.5.4. Cloud of dots

The fourth environment consisted of a random arrangement of dots in three-dimensional space. This cloud of dots was generated with 3250 white light points on a black background (Fig. 1(d)). To each side of the starting position the dots were set every 6 m within 30 m and then jittered up to 5 m left/right and towards or away from the observer. Along the frontal plane the dots were set every 2 m within 50 m and jittered up to 2 m away/towards the observer. The dots were constant in size and luminance regardless of there distance to the observer. Frame rate was 72 Hz. Mean luminance was 3.1 cd/m^2.

3. Experiment 1a: Different velocities, same environment

In the first experiment we wished to confirm the earlier finding (Bremmer & Lappe, 1999) that travel distance can be discriminated independently of velocity changes between the first and second movement sequence. Furthermore we wanted to know whether the presence or absence of depth cues in the environment influences the discrimination of the distances of two visually simulated self-motions.

3.1. Methods

Velocity (2 m/s) and duration (2 s) of the first (reference) sequence were kept constant. The second (test) sequence was presented with a velocity of 1.0, 1.5, 2.0, 2.5, or 3.0 m/s (factors 0.5, 0.75, 1.0, 1.25, and 1.5 of the references velocity). The duration of the test sequence was varied in order to determine the PSE. We used the four environments described above. In any single trial reference and test sequence were always from within the same virtual environment. Six subjects participated in the experiments with the textured ground plane and dot plane 2. Five of the six subjects also took part in the experiments with dot plane 1 and the dot cloud. The simulated height above the ground was 2.6 m. From the PSE we calculated the ratio of the distances of the test and the reference movement. We plotted this ratio as a function of the ratio of observer velocity in the test and the reference movement. A linear regression was fitted on these values in order to indicate the amount of compensation for the change in observer velocity. Failure to compensate for observer velocity change would predict a slope of one: if speed is increased, subjective equality is reached at a greater distance. A slope of 0

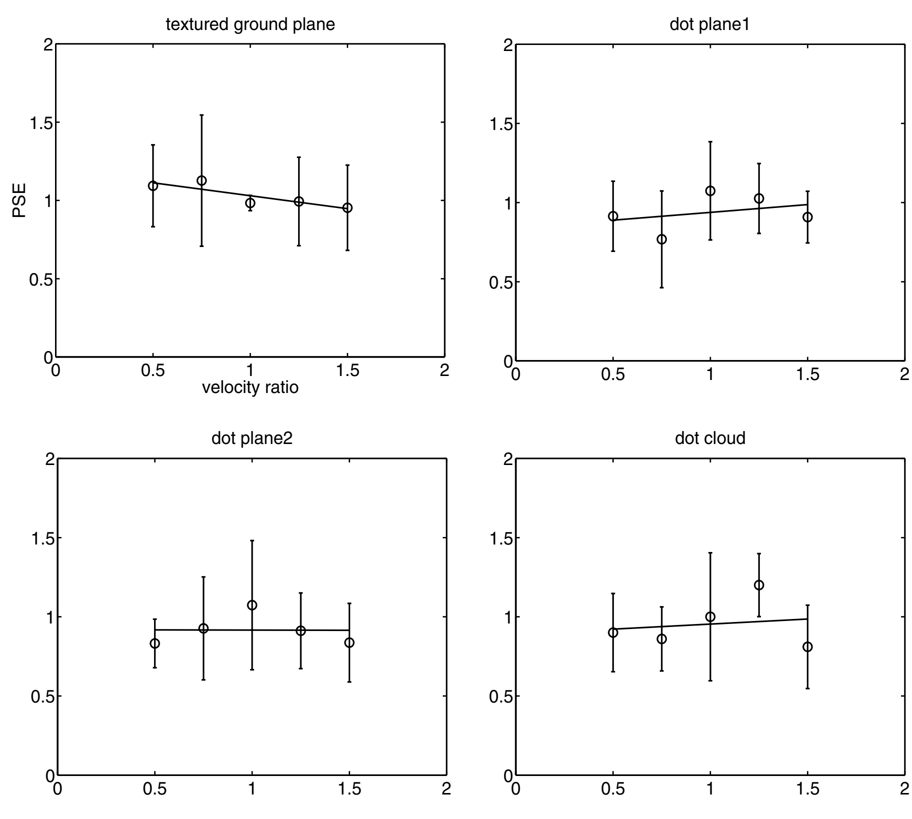

Fig. 2. PSE's as a function of velocity ratio between second and first motion sequence in four different environments. Points are means across subjects, error bars give standard deviations across subjects.

indicates perfect compensation: subjective equality is always reached at the same distance, independent of a change in observer speed.

3.2. Results

Fig. 2 shows the results for the four tested environments. In all four environments the regression lines were fairly flat. Slopes were −0.17, 0.1, 0.0, and 0.06 for the textured plane, dot plane 1, dot plane 2, and the dot cloud, respectively. t-tests revealed that all slopes were significantly different from 1, but not from 0 (all environments $p < 0.05$). A two way ANOVA gave no significant differences for either the different velocities ($p = 0.232$) or the different environments ($p = 0.416$) and no significant interaction ($p = 0.689$). Correlation coefficients between the PSEs of all subjects and the velocity ratio were low (−0.219 for the textured ground plane, 0.140 for dot plane 1, −0.003 for dot plane 2, and 0.081 for the dot cloud). This suggests that the PSE is not correlated to the velocity ratio between the first and the second movement sequence. Hence, compensation for changes in velocity was good.

4. Experiment 1b: Different velocities, different environments

Information about the 3D-structure of the scene is important to relate visual motion to travel distance. In experiment 1a, the 3D scene in both movement sequences of each trial was the same and the information about the scene was given by the same depth cues. In experiment 1b we tested the ability to discriminate travel distances when depth cues differ between the two sequences.

4.1. Methods

The reference movement was shown on the textured ground plane. In the test movement dot plane 2 was used. During the scene change the screen was black for 500 ms. Velocity and duration were constant in the reference movement and varied in the test movement. All parameters were the same as in experiment 1a. Six subjects participated, the same as in experiment 1a with the textured ground plane and dot plane 2.

4.2. Results and discussion

Fig. 3 shows the results. The slope of the regression line was 0.21. The correlation coefficient between the PSE and the velocity factor was 0.206. The slope was significant different from 1 (t-test, $p < 0.05$) but not from 0. Thus, the compensation for velocity changes was almost as good as in experiment 1a. A two-way-ANOVA gave no significant difference between the results of experiment 1a (textured ground plane, dot plane 2) and 1b ($p = 0.232$) and the different velocities ($p = 0.653$). The interaction was also not significant ($p = 0.378$). We conclude that the change of the scenes between the two movement sequences and the associated change in depth cues did not influence distance perception. Hence depth information provided by the density gradient, the change in size of approaching objects, and the trajectories of single objects were not necessary to fulfill the task.

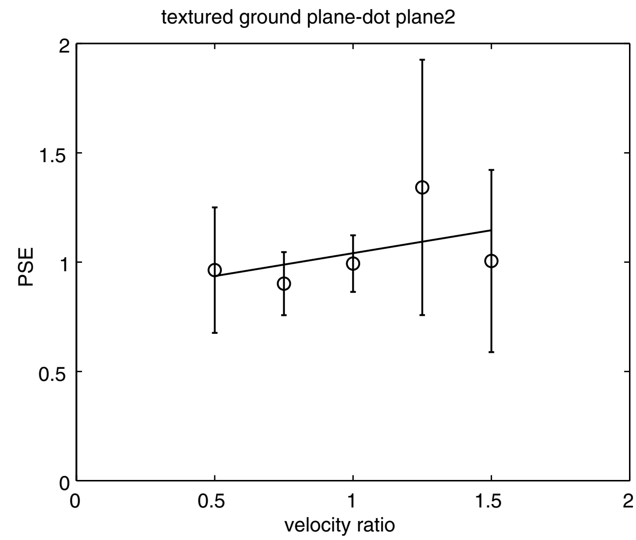

Fig. 3. PSE's as a function of velocity ratio between second and first motion sequence when different environments are used in the first and in the second sequences. Points are means across subjects, error bars give standard deviations across subjects.

The results from experiments 1a and 1b show that subjects can discriminate travel distance of two simulated movements from visual motion cues when the depth structure of the environment is the same in both cases. In this situation, subjects may simply integrate the image velocities produced by the first scene and compare the result to that produced by the second scene. Alternatively, subjects may use optic flow to establish an estimate of observer velocity with regard to the scene and perform the comparison on the basis of an integration of observer velocity over time. In order to decide between these two possibilities experiments 2–4 present paradigms in which flow field speeds are altered independently of observer speed.

5. Experiment 2: Height above ground

The elevation of the observer is one parameter that determines the structure of the optic flow field. If eye height is reduced, the velocities in the optic flow field increase and vice versa. Travel distance, in contrast, is independent of eye height. It depends only on the translation velocity of the observer. When comparing travel distances from optic flow displays with variable eye height the observer, therefore, has to determine both the change of flow speed resulting from a change of eye height and the change of flow speed resulting from a change of observer velocity. This requires extra information about the change in eye height and the ability to predict and compensate the associated changes in flow speed. To investigate this ability, we asked subjects to discriminate travel distance in two displays with different eye height. The change in eye height could either be made explicit, thus giving extra information to the subject, or hidden by a dark interval, in which case predictable errors may be expected.

5.1. Methods

The reference motion was constant in velocity (2 m/s), duration (2 s) and the simulated eye height above the ground (2.6 m). The test motion was simulated with four different observer velocities (factors: 0.5, 0.75, 1.25 and 1.5) and four different eye heights (only visually simulated; no physical movement of the subject). These eye heights resulted in changes of image speed by factors of 0.78, 0.88, 1.26, and 1.41. The viewing angle remained constant parallel to the ground plane in the reference and in the test motion sequence. The 16 conditions (4 observer speeds $\times$ 4 eye heights) were randomly interleaved and the PSEs determined as described above. The median for each condition was determined over all subjects. A two-dimensional regression was fitted to the median PSEs. The slopes of the regression describe the influence of observer speed-induced and eye height-induced changes in image velocity on the distance estimate. Correct distance judgments would predict slopes of 0 in both directions, corresponding to perfect compensation for the changes of both parameters. If subjects fail to compensate for the height-induced changes of image velocity they should attribute the speed change to a change of observer velocity and reach the PSE at a shorter travel distance. Hence the slope for height-induced changes of image velocities should be -1.

In a first set of this experiments (A) eye height was changed invisibly between the two simulation of one trial as the screen turned black during that period. In a second set of experiments (B) the change was visibly simulated between the two motions of one trial. In this case, the subject saw an up or down motion with respect to the plane. The velocity of the up/down motion was chosen randomly between 0.5 and 4.5 m/s. The duration of the vertical motion varied therefore between 0.167 and 1.5 s. Experiments were performed on the textured ground plane and on dot plane 2. Seven subjects participated.

5.2. Results

In Fig. 4 the slopes of the fitted regressions (textured ground plane, condition A: $r^2 = 0.7$, $p < 0.01$, condition B: $r^2 = 0.77$, $p < 0.01$; dot plane 2, condition A: $r^2 = 0.83$, $p < 0.01$, condition B: $r^2 = 0.49$, $p = 0.012$) are shown for the different conditions.

When the height change occurred during the dark interval between the two motion sequences the compensation for height-induced changes of image velocity was weak. The slope of the regression in the direction of eye height was -0.64 for the textured plane and -0.68 for dot plane 2, indicating that the distance estimates were strongly biased by the change in flow speed that was induced by the height change. The slopes became shallower (-0.19 for the textured plane and -0.06 for dot plane 2), indicating that compensation ability became better, when the change of eye height was visibly simulated. At the same time, however, slopes for the

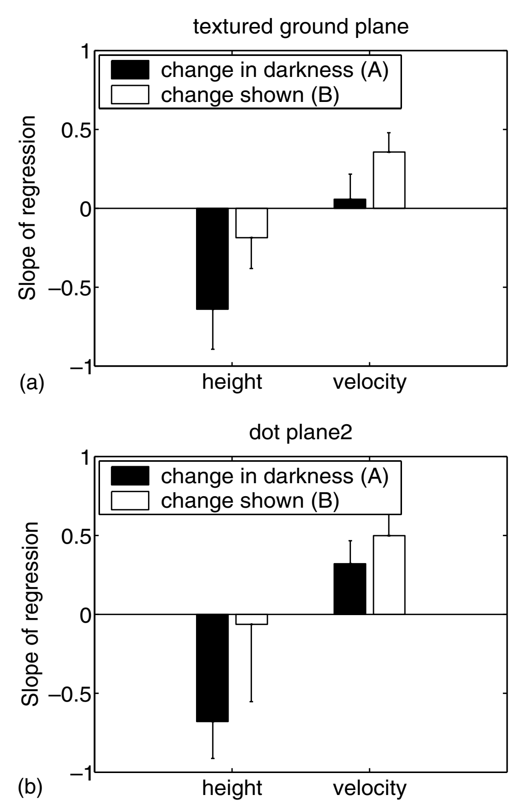

Fig. 4. Slopes of two-dimensional regression for simultaneous changes of height above ground and observer velocity. (a) Textured ground plane. (b) Dot plane 2. In each panel, black bars indicate the results in the condition in which the change of height was performed in the dark interval between the two motions. White bars indicate the results in the condition in which the change of height was visibly simulated by up- or down movement of the observer. The bars on the left (labeled 'height') show the slope of the regression for image speed changes induced by a change of eye height. The bars on the right (labeled 'velocity') show the slope of the regression for image speed changes induced by a change of observer velocity.

change of observer speed became steeper, indicating less compensation for speed changes. For the textured plane, the slope increased from 0.06 in condition A to 0.36 in condition B. For dot plane 2, the slope increased from 0.33 in condition A to 0.5 in condition B. Slope decreases for eye height and increases for observer speed were significant ($p < 0.01$) in the case of the textured plane, only.

Analysis of variance in the different conditions confirmed this pattern of results. When the height change was performed in the dark interval, the parameter height change showed a significant effect on the PSE ($p < 0.01$ for the textured plane, $p < 0.01$ for dot plane 2). The parameter speed change showed a significant effect for dot plane 2 ($p < 0.01$ for dot plane 2), but not for the textured plane. When the height change was visibly simulated by up or down movement, height change showed no significant effect on the PSE but speed change did ($p < 0.01$ for the textured plane, $p < 0.01$ for dot plane 2). A significant interaction between the height change and speed change was observed for dot plane 2 in the dark interval condition but not in any of the other conditions.

5.3. Discussion

Two factors influenced the visual image speeds of the optic flow in this experiment: the speed of the observer and the observer's height above the ground. Therefore, in order to estimate travel distance, subjects must separate the change of the flow speeds resulting from the change of eye height from the change of the flow speeds resulting from a change in observer motion. The experiment presented two conditions. In the first condition, eye height above the ground plane changed during an interval in which the screen turned black. In the second condition, an up or down movement simulated the height change visibly for the subjects. When eye height changed during the black interval, we observed a predictable error resulting from the inability to compensate for the change in eye height. Subjects attributed almost the entire change of the flow speeds to a change of observer velocity and therefore misjudged travel distance. Thus they did not compensate for the change of eye height. In this condition, information about the change of eye height was available in the accompanying change of the position of the visible horizon on the screen and by changing texture cues resulting from the changed viewing angle of the ground plane. Apparently this information was not used. When subjects were afterwards asked whether they had noticed any changes occurring in the interval between the two motion sequences they only reported a change of observer velocity.

The results of this experiment also show that the basis for the internal representation of the visually simulated ego motion distance cannot be simulated ego-displacement. The change of height affects visual speed but not ego displacement. For instance, subjects would pass the same number of texture elements regardless of the simulated eye height. Thus, if the judgment were based on simulated ego displacement one would expect good distance estimation regardless of whether the vertical movement is shown or not. Because subjects failed to compensate for the difference in eye height in the dark condition, the internal representation does not seem to be ego-displacement in 3D space but rather must be perceived ego-speed.

In both conditions of the experiment a gap separated the two forward motion simulations. In condition A the screen turned black for 500 ms, in condition B the display depicted an up or down motion with variable duration between 0.167 and 1.5 s. We did not find any effect of the gap duration on the subject's decision. Control experiments showed that also the speed of the vertical motion had no effect on the distance perception.

The simulation of up or down movement with the height change allowed subjects to estimate the change of flow speeds resulting from the change of eye height. Subjects fairly well compensated for the height change in this condition. However, the enhanced ability to compensate for height changes was accompanied by an increased misjudgment of the change in observer velocity. The compensation for speed changes became weaker. This may suggest that subjects have a limited overall ability to compensate for changes in flow speeds when estimating travel distance. However, because subjects had to estimate the influence of two parameters (observer velocity and eye height) the task was more difficult than those of the previous experiments. The increased difficulty may also account for the weaker performance.

We conclude from experiment 2 that human observers can calibrate the image velocities from the optic flow with respect to the height above the ground to derive an estimate of travel distance. This suggests that travel distance is estimated not simply on the basis of image velocities but also takes environmental parameters into account. However, the image velocities in the optic flow are linearly related to the height above ground. Thus the distance judgment may still be based on an integration of image velocities, albeit followed by normalization with respect to eye height, rather than an estimate of observer velocity. Experiments 3 and 4 involve manipulations of the *distribution* of image velocities that further reduce the possibility to use image velocities directly.

6. Experiment 3: Visibility range

If subjects were to base their discrimination of travel distance simply on the total accumulated flow speeds in the two movement sequences, manipulations of the distribution of flow speeds should impair performance. One possibility to manipulate the average flow speeds in the display without changing observer velocity or eye height is to restrict the visibility range. If the visibility range is reduced, slow flow field speeds are omitted and the average speed becomes higher. We were interested in whether subjects are influenced by the average flow speed or whether they are able to take changes in visibility between the two motion sequences into account. To test this, we changed the visibility range between the two motion sequences either by adjusting the maximum distance at which scene elements were drawn, or by introducing fog of varying density.

6.1. Methods

The first motion was always simulated with constant velocity (2 m/s), duration (2 s), height above ground (2.6 m) and visibility range (20 m). The second motion was randomly presented with four different velocities and four visibility ranges (both with factors of: 0.5, 0.75, 1.25 and 1.5 of the first motion). For each visibility range we calculated the associated change in the average image velocity present on the screen. These visibility range-induced speed changes were 0.76, 0.97, 1.05, and 1.15.

Visibility range was manipulated in two ways. In the first condition (A), the ground plane was simply truncated at a certain distance from the observer. In this case, the virtual ground plane was visible only up to the clipping distance.

In the second condition (B), virtual fog was added to the environment. White fog (RGB: 1.0, 1.0, 1.0) started at the virtual position of the observer and linearly increased in density with distance. When the chosen visibility range was reached, the fog was completely opaque. The fog was created in the following way: First, a color index f was determined for each pixel

$$f = (\text{visibility range} - \text{distance})/(\text{visibility range} - \text{start position of fog}).$$

With this index, the new color of the pixel was calculated:

$$C' = f \cdot C_r + (1 - f) \cdot C_f$$

where C' = new color of the pixel; C_r = original color of the pixel; C_f = fog color; f = color index.

Hence, fog changed the contrast of each pixel depending on the pixel's distance to the observer. The experiments were simulated on the textured ground plane. Seven subjects participated. For data analysis we determined the median over all subjects for the 16 conditions and fitted a two-dimensional linear regression on the result. The slopes of this regression indicates the ability to compensate for the changes between the two motion sequences.

6.2. Results

The slopes of the regressions (clipped condition (A): $r^2 = 0.62$ and $p < 0.01$; fog condition (B): $r^2 = 0.137$, $p = 0.38$) are plotted in Fig. 5.

In the clipped condition, there was no compensation for the change of the visibility range. The slope of the regression was −1.51. In the fog condition, compensation for the change in visibility range was better (slope of −0.32). Compensation for changes of velocity was very good in both conditions.

Analysis of variance showed a significant effect of visibility range in the clipped condition ($p < 0.01$) but not in the fog condition. There was no significant effect of velocity in either condition and no interaction between velocity and visibility range.

6.3. Discussion

When the visibility range is altered, objects at greater distances from the observer's virtual position are removed from or added to the flow field. Because of motion-parallax, distant objects have a lower velocity in the optic flow field than near objects. Thus, changing the visibility range between the two motions caused a change of the average velocity of flow elements. If subjects base their judgment of travel distance on the av-

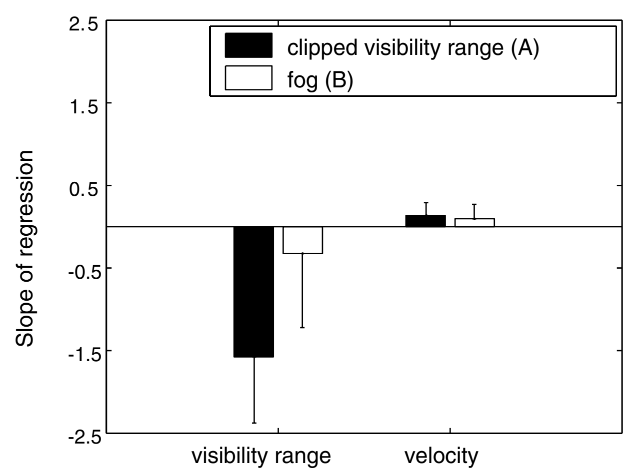

Fig. 5. Slopes of two-dimensional regression for simultaneous changes of visibility range and observer velocity. Black bars indicate the results in the condition in which visibility was restricted by clipping the display of the ground plane in a specified distance. White bars indicate the results in the condition in which visibility was restricted by simulated fog. The bars on the left (labeled 'visibility range') show the slope of the regression for changes in average image speed induced by a change in visibility range. The bars on the right (labeled 'velocity') show the slope of the regression for image speed changes induced by a change of observer velocity.

erage flow field velocity, and do not compensate for the change of the different viewing distances, they should make a predictable error. In this case, the PSE for travel distance should decrease as flow velocity increases, i.e., with decreasing viewing distance. Errors in the clipped condition followed this prediction, suggesting that subjects did not compensate for the difference in visibility range, or that they did not notice the change. In the fog condition, however, errors were negligible and subjects estimated travel distance correctly. This suggests that subjects can compensate for changes in visibility range if they notice the change. As in experiment 3, we conclude that human observers can combine scene information with flow information to estimate travel distance.

Bremmer and Lappe (1999) also investigated the effect of changes in visibility range on perceived distance of simulated self-motion. They altered the visibility range in an environment consisting of a three-dimensional cloud of dots. Such an environment lacks all depth cues beyond motion parallax. Hence the alteration of visibility range is not unambiguously specified in the stimulus. Their experiments revealed predictable errors that could be explained if subjects assumed that the scene has not changed and used the average flow velocity for their distance estimate. Unlike the experiment of Bremmer and Lappe, our experimental conditions contained depth cues that could inform the observer about the alteration of the visibility range independently from the optic flow. Because our subjects were able to compensate for the changes we conclude that they must not simply rely on average optic flow speed.

A different experiment dealing with fog-limited visibility during simulated self-motion was described by Snowdon, Stimpson, and Ruddle (1998). In their experiment, subjects had to report perceived speed with a virtual car in different visibility conditions. When visibility was reduced, subjects experienced the velocity of their ego-motion to be slower. In our experiment, we did not explicitly ask for speed judgments. But effects on speed perception could also have lead to errors in perceived distance. A perceptual decrease of ego-speed due to fog might have contributed to the compensation of the increase of average flow velocity due to decreased visibility in that condition.

7. Experiment 4: Viewing angle

In experiment 4, we varied the simulated angle under which subjects view the ground plane. In the reference movement, simulated gaze was parallel to the ground plane. In the test movement, simulated gaze was tilted upward or downward. This manipulation changed the entire distribution of flow speeds on the display. In order to perceive travel distance correctly, subjects must estimate the orientation of the plane and calculate ego-speed from flow speed using the plane orientation.

7.1. Methods

The reference movement was constant in velocity (2 m/s), duration (2 s) and simulated viewing angle (parallel to the ground plane). The test movement was simulated with four different observer velocities (factors: 0.5, 0.75, 1.25 and 1.5) and four different viewing angles. The different viewing angles changed image speed by factors of 0.76, 0.97, 1.08, and 1.49. The subjects were instructed to keep their heads upright during the experiments.

In the first condition (A) viewing angle was changed while the screen turned black between the two movement sequences. In the second condition (B) the change was visibly simulated between the two movements such that subjects saw an up or down rotation of the scene. The velocity of the rotation was chosen randomly between 10 and 30 deg/s. This experiment used the textured ground plane. Five subjects participated.

7.2. Results

The slopes of the regressions (condition A: $r^2 = 0.58$, $p < 0.01$, condition B: $r^2 = 0.5$, $p < 0.01$) are plotted in Fig. 6. In both conditions we found good compensation for the change of image velocities introduced by the change of viewing angle (condition A: 0.07, condition

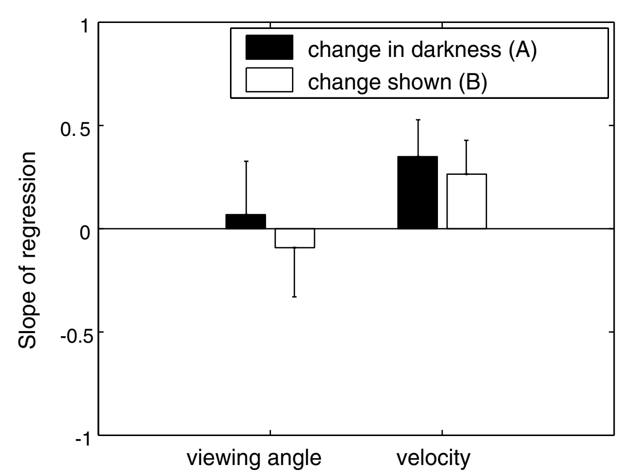

Fig. 6. Slopes of two-dimensional regression for simultaneous changes of viewing angle and observer velocity. Black bars indicate the results in the condition in which the change of viewing angle was performed in the dark interval between the two motions. White bars indicate the results in the condition in which the change of viewing angle was visibly simulated by up- or down rotations of the scene. Left bars (labeled 'viewing angle') show the slope of the regression for changes in average image speed induced by a change of viewing angle. Right bars (labeled 'velocity') show the slope of the regression for image speed changes induced by a change of observer velocity.

B: −0.09). Compensation for changes in observer velocity was less good but comparable to that observed in experiment 3 (condition A: 0.35, condition B: 0.26). Analysis of variance revealed a significant effect of observer velocity in condition A ($p < 0.01$), but no other significant effects.

7.3. Discussion

This experiment is probably the most challenging because the change of viewing angle not only influences the average image velocity in the flow field but the entire distribution of image velocities. Yet, subjects were well able to compensate for changes of the viewing angle. To do this, they must have estimated the tilt of the plane and used this information to estimate observer speed with respect to the plane. This shows again that travel distance estimation is performed from an estimate of observer motion not image motion.

Compensation for the change in viewing angle was possible in both conditions of experiment 4, even when the change occurred during the dark interval between the movement sequences. In experiments 2 and 3, the change of height or visibility range could only be compensated when it was presented visually to the subject. We believe that this happened because subjects did not notice the change in those experiments. The change if the viewing angle is possibly more salient than the change of height in experiment 3 or the truncation of the ground plane in experiment 3. Therefore, in experiment 4 subjects may have been able to notice the change of viewing angle even when it was carried out in the dark interval.

8. General discussion

We investigated the perception of travel distance of visually simulated self-motion. Because of the ambiguity of the optic flow field with respect to absolute speed or distance we chose a comparison task in which the distances of two movement sequences had to be discriminated. The first (reference) movement was always constant. The second (test) movement varied in duration and observer velocity and could also vary in the number of depth cues provided by the scene (experiments 1a and 1b), the height above the ground (experiment 2), visibility range (experiment 3), or viewing angle (experiment 4). The first question we asked is whether observers can discriminate travel distance despite variations in observer speed. Experiments 1a and 1b clearly showed that distance judgments were independent of the change of observer velocity between the reference and the test movement. This result corroborates earlier findings by Bremmer and Lappe (1999) who performed similar experiments but collapsed data across observer speeds in the analysis. The second question we asked in experiments 1 and 2 was about the use of various visual distance cues for discriminating travel distance from optic flow. Systematic elimination of distance cues from the stimulus revealed that pure visual motion, which includes motion parallax as a cue to distance, is sufficient to discriminate travel distance.

The discrimination of travel distance of two successive movement sequences requires the integration of the motion signal from each sequence and a comparison of the two results. If both movements are performed in the same environment this comparison is sufficient. If they are performed in different environments the motion signals must be taken relative to the environment in order to allow a meaningful comparison. Therefore, travel judgments should be based on perceived egomotion relative to the environment rather than directly on the image velocities. Experiments 2–4 provide evidence that supports this hypothesis.

In experiment 2 the simulated height of the observer above the ground was varied. This led to an additional variation of image motion in the flow field which is independent of the variation of the translational velocity of the observer. When subjects experienced the change of height by a simulated up or down movement they were able to compensate for the associated changes in flow speed and retain their ability to discriminate travel distance, albeit with slightly larger errors. In experiment 3 we manipulated the distribution of image speeds in the flow field by varying the visibility range in the test movement. When the alteration of the visibility range was made explicit by the introduction of fog subjects could well compensate for the associated changes in the distribution of image speeds. In experiment 4 we varied the simulated viewing angle under which the scene was presented. This manipulation again changed the distribution of image velocities in the presented flow field but subjects were able to compensate for this change. All three experiments hence suggest that our observers did not use image velocities directly. Rather they must have used an estimate of observer speed with respect to the environment.

This leads to the question of which cues subjects use to estimate the structure of the environment. Observations from several experiments suggest that motion parallax is a sufficient cue. Experiments 1a and 1b showed that motion parallax is sufficient if the environment is the same in both sequences. In experiment 2, subjects were able to compensate for visible changes in eye height even for the limited-lifetime constant-density ground plane (dot plane 2) in which depth is only specified by motion parallax. This shows that motion parallax during the up or down movement of the observer could be used to update the observer's representation of the environment and the associated relationship of ego-speed to flow field speed. Motion parallax might also have been used to detect changes to the scene in experiments 3 and 4, but other cues were available as well in those experiments.

Our experiments provide evidence that the discrimination of travel distance from visual motion is based on a representation of ego-speed with respect to the environment. This representation is derived from image motion in the optic flow together with structural cues about the environment provided by the visual input. How general is this representation? Specifically, does it pertain only to the discrimination of movement sequences or does it allow more abstract judgments of travel distance? Bremmer and Lappe (1999) used a task in which subjects had to reproduce the distance of a visually simulated movement sequence with an active movement simulation in which speed and duration were controlled by the subject with a joystick. They found excellent distance reproduction. This suggests that the representation of travel distance generalizes from passive judgments to active control behavior. Redlick et al. (2001) and Harris et al. (2000) have asked subjects to compare travel distance during a movement simulation to the remembered distance to a previously seen static target. Subjects had to indicate the time at which they reached the target's position in the simulated environment. This task requires a match of travel distance from visual motion to distance measured from static visual cues. Redlick et al. (2001) found that subjects indicated the correct time of arrival at the target position for accelerated movements but responded too early for movements of constant velocity. They suggested that travel distance estimates from visual motion can be compared to static distance estimates, but distances are overestimated for movements of constant velocity. Since our results show that travel distances of constant velocity movements can be discriminated successfully, we suggest that errors might occur in the conversion between distances obtained from static and dynamic visual cues.

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