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Effects of symmetry, texture, and monocular viewing on geographical slant estimation

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ABSTRACT

Hills often appear to be steeper than they are. The unusual magnitude of this error has prompted extensive experimentation. The judgment mode, such as verbal vs. action-based measures, the state of the observer – whether exhausted or well rested – all can influence perceived geographical slant. We hold that slant perception is inherently shaky as soon as the slope in question is no longer palpable, that is if it is outside our personal space. To make this point, we have added symmetry, texture, and depression to the list of factors that might modulate slant perception. When the frontal slope of a hill is to be judged, it appears steeper when the side slopes are steep. We have used model hills close to the subject. Their slopes were judged most accurately when binocular stereoscopic vision was permitted. When closing one eye, observers grossly overestimated all slopes. This error was larger for verbal judgments than for judgments made by indicating the slope with their forearm, however, the pattern of the overestimation remained unchanged. Surface texture mattered surprisingly little. Depressed subjects produced exactly the same results as healthy controls. We conclude that in action space and in vista space (outside immediate personal space), slopes are overestimated because the visual system attempts to turn the 2D retinal stimulus into a regular 3D object, akin to the erection tendency (Aufrichtungstendenz) found in diminished or 2D-stimuli. This tendency is inherently instable and can be swayed by a large number of variables.

1. Geographical slant perception

Gibson and Cornsweet (1952), Gibson (1979) distinguish optical and geographical slant. Optical slant is specified by the relation of the given surface and the observer's line of sight, whereas geographical slant is defined as an inclination of a surface relative to earth horizontal. Observers typically and often grossly overestimate geographical slant (Ross, 1974). The error increases when observers leave the canonical position on level terrain and look down from an elevation or lower their eye height (Ross, 1974, p. 67ff.). Ross attributed the effect of slant overestimation to misperception of distance. If distance is perceptually compressed, then a slope should appear steeper than it does when distance is perceived accurately. When looking down from a hill-top into a valley below, the downhill slope appears flattened, the flat valley rises up and the opposite slope rises steeply, which is caused by the "terrestrial saucer" effect (Ross, p. 71). Fig. 1 illustrates the latter point. The terrestrial saucer or concave earth effect is the converse effect of the flattened dome effect, which is one of the manifold theories to explain the moon illusion (Hershenson, 2013).

Interestingly, this slant overestimation is not limited to terrain but it extends to objects (Rausch, 1952). With reference to objects, this has been called Aufrichtungstendenz, the tendency of objects to right or erect themselves in perception. We have discussed this

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Fig. 1. A view of Bolzano, Italy once at nighttime (left panel) and once during the day (right panel) taken from similar view points. Photos Daniel Oberfeld. Note that the runway in the center does not look level in either picture. It looks even more sloped at night. We refer to this effect as Aufrichtungstendenz (erection tendency).

phenomenon extensively with Bruce Bridgeman and had in fact started to experiment with such objects in the lab shortly before his untimely death. The above examples imply that the perceiver can relate the slope in question to the earth-horizontal. Accurate perception of the geographical slant of objects quite obviously requires some reference that tells the observer about the true horizontal. Fig. 2 shows that objects appear to tilt upward when visual reference cues are absent or minimal, and extra-retinal cues, such as vestibular cues are not yoked to the image. The side-walk appears sloped upward. For such cases, where there is uncertainty about the true horizontal, various hypotheses have been put forth.

For instance, Helen E. Ross points out that the raised apparent height of mountains and the apparently raised horizon are caused by such uncertainty and typically cause error of about 6° (Ross, 1974, p. 68). Observers may fail to realize that they are standing on a descending slope or that their eye-level or line-of-sight points lower than normal (Ross, 1974, p. 68), which amounts to the mistaken slope theory, and the mistaken eye-level theory respectively (see Fig. 3).

The mistaken slope theory predicts that the observer (O, ↑) will overestimate the height of T and perceive T′ because the slope OV appears flatter (OV′) than it really is, so that the inclination angle of the opposite slope is raised from VT to V′T′. The mistaken slope and the mistaken eye-level theory demonstrate that distance and slope estimations are intertwined.

In the following, we focus on slope overestimation for cases where information about true horizontal is available. Note, however, that the degree of its availability has to be considered to evaluate the size of the "illusion" when it arises. Note also that the method of assessing perceived slope has in impact on the size of the error. Next to verbal estimates, researchers have used palm boards or elevation of the forearm (see Bhalla & Proffitt, 1999; Chiu, Hoover, Quan & Bridgeman, 2011). The forearm method introduced by Bruce seems to produce the smallest errors, however, the illusion can be captured by all of the above measures (see also Section 9).

Since Ross' publication, a large number of experiments have been conducted to determine the size of this slant estimation error in various contexts (e.g. Bhalla & Proffitt, 1999; Bridgeman & Hoover, 2008; Durgin, Hajnal, Li, Tonge & Stigliani, 2010; Proffitt, Creem & Zosh, 2001; Stefanucci, Proffitt, Banton, & Epstein, 2005). Although a large number of – sometimes controversial – hypotheses have been put forth as to the causes of this unusually large error, the latter is much reduced in personal space (Hecht, Shaffer, Keshavarz & Flint, 2014). Thus, monocular viewing or larger viewing distances beyond the range of effective stereopsis are prerequisite for the error to become spectacular (in the presence of a sufficiently defined horizontal). In the current study, we report three experiments to

Fig. 2. This section of paved sidewalk appears to slope upward for lack of reference cues.

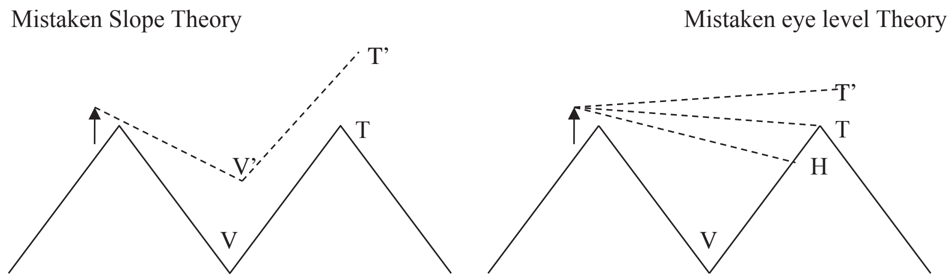

Fig. 3. Two examples for slope illusions: Apparent Aufrichtungstendenz when mountains are viewed across a valley (Ross, 1974, p. 79).

suggest that slant perception is multiply instable in vista space, such that almost any cue can alter our estimates. Note that we follow Grüsser's taxonomy with respect to the segmentation of space into personal space, action space, and vista space (Grüsser, 1983; see also Cutting & Visthon, 1995). To test if slope perception is indeed instable, we added a number of cues hitherto no yet researched, such as the symmetry of the hill in question, the texture of its surface, a depressed state of the observer, and familiarity with terrain features.

1.1. Texture

Provided that a scene is clearly visible and the observer's horizontal is given, the texture of the surface has been proposed as an important cue to depth. For instance, Gibson (1950) implicates the density of texture elements near an object relative to the average density. Also, the steeper the gradient of density change, the greater the perceived distance should be. According to Allekseenko (1989), Baden-Powell (1944), and Ivanov (1969), for a low eye-point (e.g. when the observer is in a prone position) the texture gradient is steeper, that is the retinal density of terrain texture is finer and more compressed. The lower the observer's eye-height the steeper the gradient and hence the more pronounced the compression. Distance judgments should consequently increase with the steepnes of the texture gradient (Higashiyama & Ueyama, 1988). Thus, distance should be overestimated when the observer's eye-point is lowered, which is indeed the case (Daum & Hecht, 2009). Higashiyama (1996), Higashiyama and Ueyama (1988) extend the claim to other postures. More than the density of texture elements, the change of texture density should produce the impression of slant of visual surfaces. We hypothesized that the manipulation of the texture density gradient should affect slope estimates accordingly, even if other pictorial cues remain unaltered.

1.2. Observer states

In a series of experiments, Kammann (1967) found large overestimations for slopes viewed from a high bridge and smaller overestimations for drawings of slopes. He ventured that targets which require more effort to reach produce larger errors than those requiring less effort, as all might be coded in motor-effort units. This has been seconded by Ross (1974, p. 116) who reported that a distance seems longer if great effort is involved or if the route is new, or if the traveler is tired or anxious. Dennis Proffitt and colleagues provided evidence in favor of this motor effort theory; hills appeared steeper to their subjects when they wore heavy backpacks, were fatigued after an exhausting run, fearful, or of generally low physical fitness (e.g. Proffitt, Bhalla, Gossweiler & Midget, 1995; Bhalla & Proffitt, 1999; Stefanucci, Proffitt, Clore & Parekh, 2008). Their arguments that steep hills are more overestimated from the top than from the bottom, because they are more difficult to descend than to ascend, and claims that verbal judgments are more prone to misrepresentation than action measures (e.g. tilt board measures; see Creem and Proffitt, 1998) have been contested (e.g. Durgin et al., 2010) and qualified, among others by Bruce and colleagues (Blaesi & Bridgeman, 2015) and others who claim that the effect is one of memory rather than perception. This is consistent with Kammann's (1967) original finding that in memory, verbal reports showed even more overestimation than did reports made while viewing hills after short and long delays. As an aside, the anticipated effort rather than the actual effort seems to be critical (Proffitt, Stefanucci, Banton & Epstein, 2003; Witt, Proffitt & Epstein, 2004). The role of effort was later contested by Hutchison & Loomis (2006a, 2006b).

Be this as it may, an altogether different approach to investigating the role of the observer's state on slope estimation would be to look at more overbearing disposition rather than acute state. If exhaustion and lack of fitness cause larger estimates, then the same should be true for observers with reduced drive and motivation, such as depressed subjects.

1.3. Symmetry

If the observer assumes perfect symmetry of the hill, then all slopes (front and both sides) should be equal. In those cases where this assumption is violated, we would expect that the slope of the hill's sides is mistakenly factored into the judgment of the front slope of the hill. Such a carry-over effect of irrelevant side slope to the judgment of front slope should be particularly strong if both side slopes are identical but different from the front slope. That is, for hills that are symmetric with respect to their side slopes, the frontal slope should be perceived with a bias toward the inclination of the side slopes. If our contention that slope estimates are inherently shaky is correct, then a mere change of the geographical surround should affect slope estimates, in particular for hills

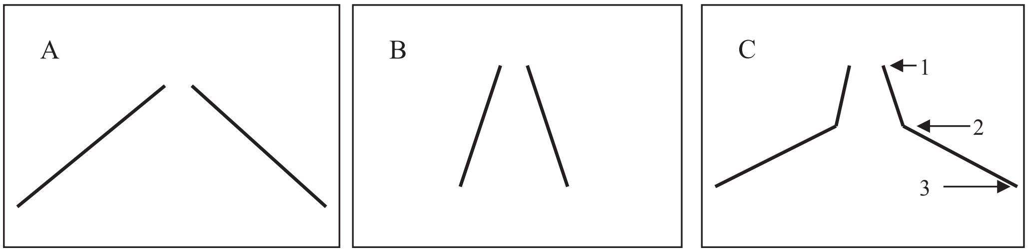

Fig. 4. Examples for two-dimensional slope cues of hills with symmetric side slopes. The would-be slope in (A) appears flatter than in (B). In (C) we can assume a change of convergence at the point 2. Segment 3 appears shallower than segment 1, or even sloped downward (Ross, 1974, p. 72).

where both side slopes differ by equal amounts from the front slope (hills symmetric with regard to side slopes). This should be the case even if a clear reference for true horizontal is given. Thus, a given frontal slope of a hill should look steeper when the hill's side slopes are steep, and the frontal slope should look shallower when the hill's sides are shallow. We are not aware of any published literature on this question.

The rationale for our hypothesis is that pictorial cues for slope seep into the process of slope estimation. These cues include the degree of convergence of vertical lines. As depicted in Fig. 4, a more acute angle tends to look steeper (see also Ross, 1974, p. 70f).

2. Overview of experiments

For purposes of stimulus control, we investigated slope estimation in an artificial laboratory setting. We created symmetric and asymmetric hills and modified the texture and familiarity of the terrain features. We used three inclinations of the frontal slopes paired with side slopes of varying steepness using Styrofoam wedges placed on a tabletop. In Experiment 1, we manipulated the viewing condition: in the first block of each experimental session, subjects had to estimate the front slope with available stereopsis, in the second part, viewing was monocular. In Experiment 2, we manipulated the texture of the frontal slope and added a group of patients suffering from a major depression to a control group of healthy people. In Experiment 3, we took a closer look at the relation between slope and distance estimation. To do so, we created an elaborate model of a lunar site, which constituted entirely unfamiliar terrain.

2.1. General method

2.1.1. Stimuli and design

We constructed an artificial hill with a height of 30 cm. It had a central piece to which various front and side ramps could be attached. All pieces were made of Styrofoam and coated with gypsum and a non-reflective white paint. The frontal ramp, a large wedge sloped by 17°, 30°, 43°, 56°, 69° and 82°, and the two side ramps (sloped 27° and 66° each) could be arbitrarily combined. The space between frontal and side ramps was likewise filled with Styrofoam pieces to form a smooth hill. These pieces were 30 cm high. An exemplar bird's eye view of the setup is shown in Fig. 5.

The experiments were conducted in a laboratory room of the Psychology Department of Johannes Gutenberg-Universität Mainz,

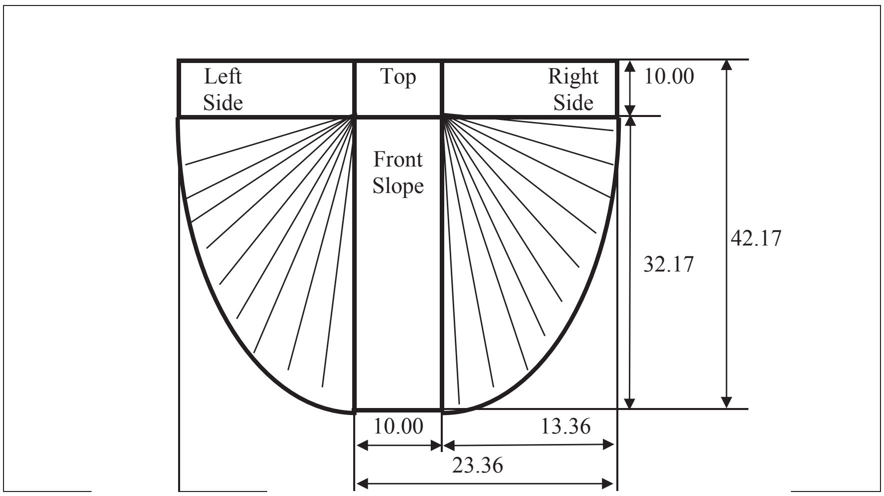

Fig. 5. Dimensions of the Styrofoam hill (aerial view) for a stimulus with a frontal slope of 43° and two side slopes of 66° as well as two lateral curved connecting parts. All measurements are in centimeters.

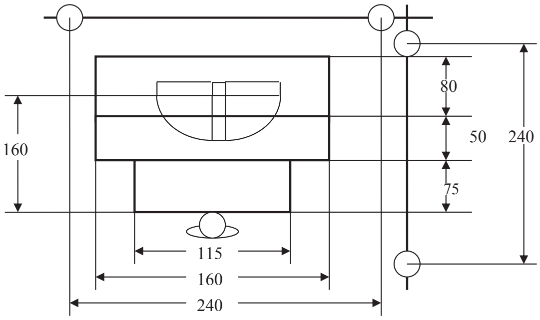

Fig. 6. Experimental setup. All measurements are in centimeters. The square indicates the top of the hill.

Germany. The hill was placed on three tables (72 cm high), which were covered with a black cloth and surrounded with black curtains. The top of the hill was always positioned 160 cm away from the front table's edge, that is the distance between the foot of the hill and the table front varied with the slope of the ramps (e. g. 62 cm at 17° and 156 cm at 82°). Two lamps were mounted at the edges of the front table and adjusted to fully illuminate the ramps.

2.1.2. Subjects

The subjects were naive to the purpose of the experiments. The head was steadied by a chin rest such that eye-height was about 10 cm above the table surface with free view straight ahead to the frontal ramp (see Fig. 6).

2.1.3. Procedure

After giving informed consent, the subject took seat on a stool centered at the table, chin in the chin rest. Then, the scene without the stimuli was illuminated by the side lamps to explain the experimental procedure. Subjects were instructed to estimate the degree of the frontal ramp, verbally and by indicating the estimated slope by the angle between their forearm and the table top (Experiments 2 and 3). They also had to estimate the confidence in their estimation and the difficulty of the task on 10-point rating scales. Between trials, subjects turned around and closed their eyes while the next hill arrangement was set up. Then the subject turned back and made the slope estimation verbally (and haptically). The answers were recorded by one experimenter, while a second experimenter measured the forearm elevation with a protractor. Subjects were allowed to take as long as they needed for their judgment.

2.1.4. Questionnaire

At the end of the experiment, subjects completed a questionnaire to provide information about age, gender, and profession, as well as statements about what they found particularly difficult, whether they were technically skilled, their amounts of time spent outdoors, and how accurate they estimated their sense of direction. The last three questions had to be answered by choosing one of five categories. Finally, they were asked whether they had used a strategy for estimating the slope of the frontal ramp and whether they had expertise in slope, size and distance estimation, such as acquired in sports or professional training.

3. Experiment 1: Monocular and binocular frontal slope estimation as a function of side slope

In the first Experiment, we tested the influence of different side slopes on the verbal estimation of the frontal slope. In the first part of the experiment, subjects viewed the stimuli with both eyes, in the second part, one eye was covered. We hypothesized a carry-over effect. Steep side slopes should lead to an overestimation of the frontal slope, whereas shallow side slopes should not have this effect (or an opposite effect in the case of steep frontal slopes). Binocular viewing should weaken or entirely destroy the effect, given that the hill was well within personal space and in the range of effective stereopsis. In contrast, a model in monocular viewing should produce results that are comparable to real world viewing (see Hecht et al., 2014).

3.1. Method

3.1.1. Subjects

Forty-three subjects (7 male) participated in this experiment. Their ages ranged from 19 to 40 years, with an average age of 25 years (SD = 4.40). All had normal or corrected-to-normal-vision and were naive with respect to the purpose of the study.

Twenty-one subjects (5 male) participated in the first part (binocular condition) of the experiment (average age 25 years, SD = 4.36), the others in the second part (monocular condition) of the experiment (average age 26 years, SD = 4.42).

3.1.2. Stimuli and design

Six front slopes (17°, 30°, 43°, 56°, 69°, 82°) were fully crossed with two left side slopes (27°, 66°) and two right side slopes (27°, 66°), to produce 24 slope pairings.

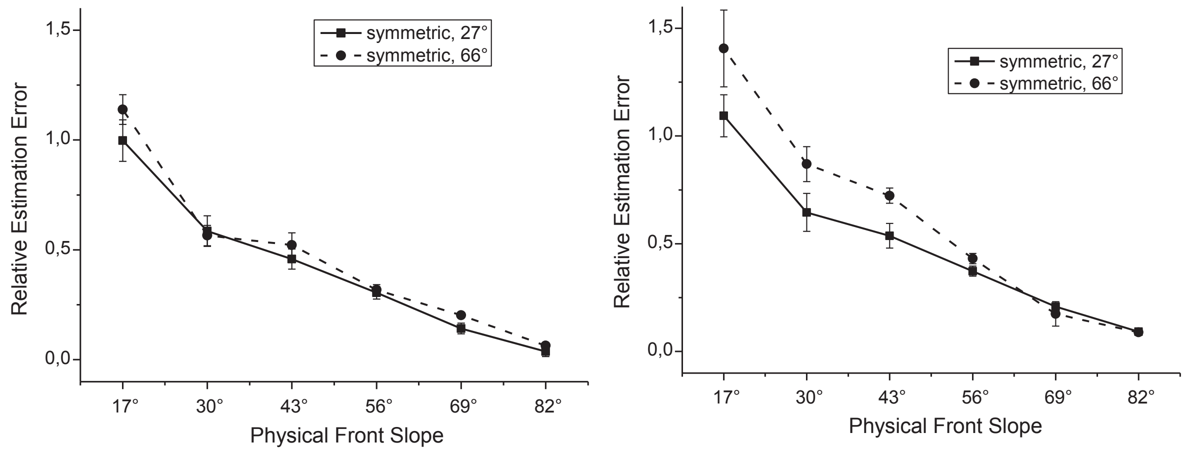

Fig. 7. Relative overestimation of frontal slopes as a function of actual slope separately for shallow and steep symmetric side slopes. Values correspond to binocular (left graph) and monocular (right graph) viewing. Error bars indicated standard errors of the mean.

3.2. Results and discussion

All front slopes were overestimated in all conditions (Fig. 7). Even the almost vertical slope (82°) was overestimated. We could also confirm our hypotheses and found a particularly strong tendency to overestimate the slope of the frontal ramp as a function of side slope steepness. The effect was modulated by the viewing condition and even stronger when subjects had to estimate the slope monocularly. In the binocular condition, the side slope did not have an influence on the frontal slope estimation (see Fig. 8).

The greatest effect of overestimation of frontal slope was observed in the monocular viewing condition (right panel) for the steep side slopes, followed by shallow side slopes, also under monocular conditions. In contrast, the steep and the shallow side slope produced similar (and markedly smaller) errors under binocular viewing. Not surprisingly, the relative error declines as the front ramp gets steeper (Fig. 7).

A closer look at the side slopes shows that the judgments of asymmetric slopes (27°/66° and 66°/27°) fall between those for symmetric slopes (lower border: 27°/27°, upper border: 66°/66°) (Fig. 9). The maximum effect of overestimation was at 43° with the steep side slope (66°). At 56° the overestimation decreased because of a ceiling effect at 90°, which was the maximum possible slope.

A repeated-measures ANOVA with Greenhouse-Geisser correction for the degrees of freedom was conducted on relative estimation errors with the within-subjects factors frontal slope (6 levels), side slope (4 combinations), and the between-subjects factor of condition (binocular vs. monocular viewing). The *df*-correction factor ε is reported as well as partial η^2 as a measure of effect size. The ANOVA showed a significant effect of frontal slope [$F(5, 205) = 189.09$, $p < 0.001$, $\eta_p^2 = 0.82$, $\varepsilon = .34$], side slope left [$F(1, 41) = 6.15$, $p = 0.017$, $\eta_p^2 = 0.13$, $\varepsilon = 1.00$], side slope right [$F(1, 41) = 13.76$, $p = 0.001$, $\eta_p^2 = 0.25$, $\varepsilon = 1.00$] and viewing condition [$F(1, 41) = 10.04$, $p = 0.003$, $\eta_p^2 = 0.20$, $\varepsilon = .87$]. As expected, overestimation errors were larger in monocular viewing as opposed to binocular viewing.

An interaction effect of right side slope and viewing condition could also be shown [$F(1, 41) = 5.31$, $p = 0.03$, $\eta_p^2 = 0.12$] likewise for front slope, left slope, right slope and viewing condition [$F(5, 205) = 3.29$, $p = 0.03$, $\eta_p^2 = 0.07$]. Our hypothesis of the influence of side slope on frontal slope estimation could be confirmed: frontal slope estimation was influenced by the irrelevant side

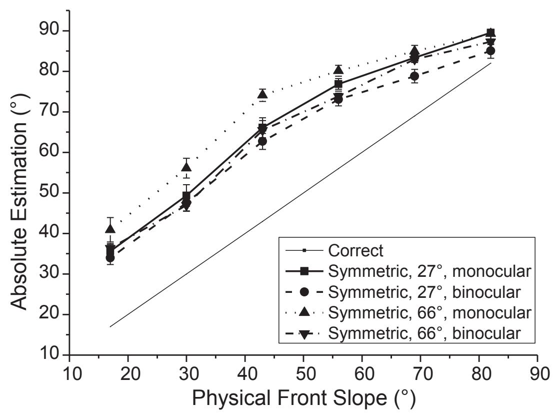

Fig. 8. Absolute estimation of frontal slopes as a function of actual slope separately for shallow and steep symmetric side slopes and viewing condition. Error bars indicate standard errors of the mean.

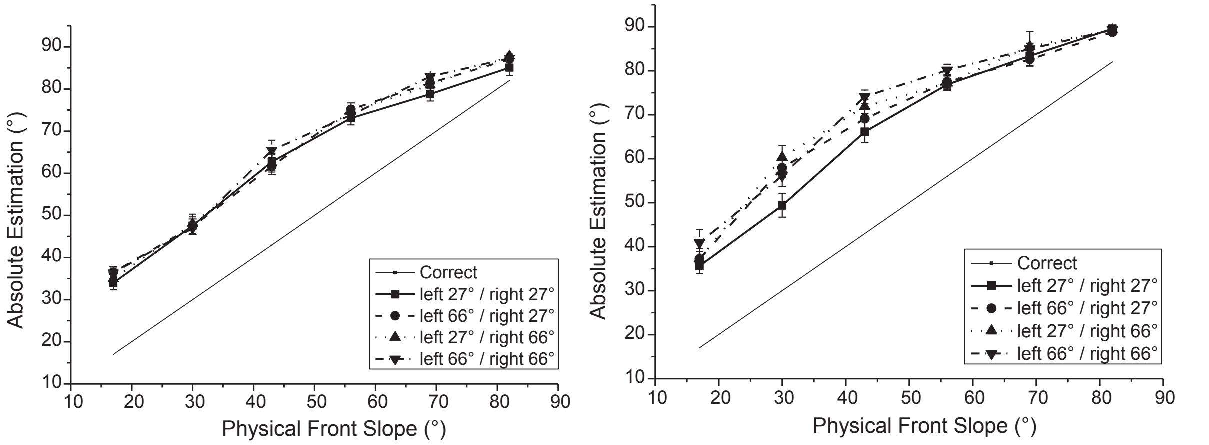

Fig. 9. Absolute overestimation of frontal slopes as a function of actual slope, separately for symmetric and asymmetric side slopes and viewing condition. Values correspond to binocular (left graph) and monocular (right graph) viewing. Error bars indicate standard errors of the mean.

slopes, but only in monocular viewing, where steep side slopes increased the judged steepness of the front ramp.

We conclude that at maximal uncertainty relative to the frontal slope at 43°, the side slopes were used as a reference for the frontal slope estimation. Subjects may have assumed (more) symmetry of the visual object for their strategy of estimation that induced a steeper frontal slope when the side slopes were steep and vice versa. Perhaps the subjects also used an incorrect standard as reference for their strategy. The most frequently estimated value of 45° was made predominantly for actual slopes of 30°. Thus, subjects might have mistaken the 30° to be the 45° reference slope, assuming that they had in mind that this is half way between horizontal and vertical. Note that the frontal ramp had a larger surface area when shallow, which may also have had an influence.

4. Experiment 2: Frontal slope estimation – varying texture and answering mode with a clinical and a control population

In the second Experiment, we tested the influence of different side slopes on the estimation of a frontal slope for three kinds of texture, and two different answering modes. To receive a sense for the robustness of the results, we also added a second group of subjects that was maximally different from our student population. Given the controversy regarding the state-dependency of perception (see e.g. the infamous finding that wearing a backpack makes hill look steeper: Bhalla & Proffitt, 1999; Durgin, Hajnal, Li, Tonge, & Stigliani, 2011; Firestone, 2013), we chose to include a group of depressed subjects whose mental energy should be seriously reduced in the sense of this state-dependency hypothesis. We also hypothesized that the haptic measure would be more accurate than the verbal measure. Here we followed the implementation used by Chiu et al. (2011) who found reduced overestimation when using the forearm as opposed to verbal judgments. Note that we provided a table surface as haptic reference for the forearem, whereas Chiu et al. (2011) had the upright observer move the forearm without such a haptic reference. Finally, we varied the texture of the slope. A texture that is compressed as compatible with a lower eye-height should produce slope overestimation.

4.1. Method

4.1.1. Subjects

In total, eighty-nine subjects participated in this experiment. Their ages ranged from 18 to 61 years, with an average age of 30 years (*SD* = 11.067). Sixty-four subjects were female, twenty-five male. All had normal or corrected-to-normal-vision and were naive with respect to the purpose of the study.

Forty-seven subjects participated in the control group (average age 24 years, 35 female). The experimental group was recruited from the onsite psychotherapeutic out-patient clinic of the Psychological Institute of Johannes Gutenberg-Universität and consisted of forty-two subjects (average age 38 years, 29 female).

Both groups completed the Beck Depression Inventory (BDI I, Hautzinger, Bailer, Worall & Keller, 1994). The control group averaged a value of 5.62 (range between 0 and 26, *SD* = 6.07), compared to the patient average (one did not answer the BDI scale) of 19.46 (range from 7 to 35 (*SD* = 7.610)).

4.1.2. Stimuli and design

The following modifications were made to the general experimental setup. Firstly, we gave up the 82° ramp because the subjects were not able to distinguish this ramp from the 69° ramp. Secondly, we used only steep (66° left and 66° right) and shallow (27° left and 27° right) symmetric side slopes. Finally, we added a texture variable. Texture could be regular (and thus consistent), biased-shallow (compressed as consistent with a very shallow slope), and biased-steep (compressed the opposite way). The design of the texture is schematically illustrated in Fig. 10. The texture gradient was accomplished by adding a card board layer with black-and-white stripes to the entire ramps. For this, we glued 15 stripes of black cardboard on the white ground. The black stripes ranged in

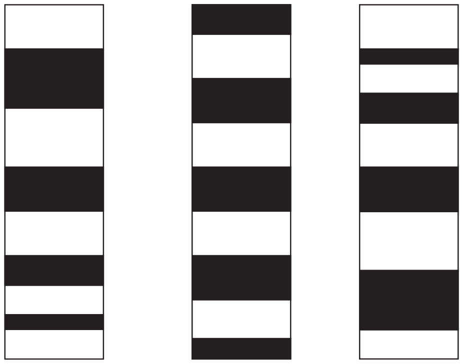

Fig. 10. Texture Design – biased-shallow (compressed as consistent with a very shallow slope), regular (and thus consistent), and biased-steep (compressed that other way).

width from 3.4 cm (for the 17° slope) to 0.4 cm (69° slope; intermediate steps 1.8 cm (30°), 1.2 cm (43°), and 0.7 cm (56°)). In the condition with consistent texture, the width of the white stripes was constant. In the conditions of varying texture, the spacing of the stripes increased or decreased exponentially.

The last change was the addition of a haptic answering mode. The subjects did not only have to estimate the frontal slope verbally but also had to make a judgment with their forearm. We thank Bruce Bridgeman for pioneering this method. To indicate their judgment, they placed their dominant forearm on the table and raised it until they felt it matched the frontal slope. One experimenter measured the arm elevation angle with a protractor, which was then recorded by the second experimenter. The protractor was given to the recording experimenter who silently wrote down the result, such that the subjects received no feedback about their haptic slope estimation. Subjects were not allowed to correct their haptic estimation or to harmonize it with their verbal estimation by having a look at it. Only the front slopes were textured. Five front slopes (17°, 30°, 43°, 56°, 69°) were fully crossed with two symmetric side slopes (27°, 66°) and three textures (regular, compressed-steep, compressed-shallow) resulting in a total of 30 trials per answering mode. All trials were viewed monocularly.

4.2. Results and discussion

As before, slopes were overestimated in all conditions for the verbal response mode, and in all but the steepest (56° and 69° ramps) conditions for the haptic response mode as well (Fig. 11). On average, the haptic response mode was more accurate, but frontal slopes continued to be overestimated. We could also confirm our symmetry hypotheses and found larger overestimation of the frontal ramp when the side slopes were steep.

A repeated-measures ANOVA with Greenhouse-Geisser correction for the degrees of freedom was conducted on relative slope estimation. The *df*-correction factor ε is reported as well as partial η^2 as a measure of effect size. The factors were frontal slope (5 levels) side slope (2 levels, steep – shallow), texture (3 levels), answering mode (verbal vs. haptic), and experimental group (control vs. depressed). Frontal slope had a significant effect [$F(4, 344) = 594.98$, $p < 0.001$, $\eta_p^2 = 0.87$, $\varepsilon = 1.00$], and so did answering mode [$F(1, 86) = 125.08$, $p < 0.001$, $\eta_p^2 = 0.59$, $\varepsilon = 1.00$]. Verbal slope estimation produced consistent overestimation, as in Experiment 1, whereas the haptic answering mode did not. In nearly all conditions, the verbal slope estimation of frontal slope with shallow side slopes produced even more overestimation than the haptic estimation with the steep slopes. The haptic answering mode even tended toward underestimation at the steepest ramp inclinations of 56° and 69°, whereas the verbal estimations stayed in the range of overestimation. Merely for the biased shallow compression of texture of the frontal ramp, did verbal estimations approach the zero line for conditions with shallow side-slopes. The steep side-slope condition remained consistently within the realm of overestimation. Both answering modes had similar curve progression.

The hypothesized effects for texture [$F(2, 172) = 49.17$, $p < 0.001$, $\eta_p^2 = 0.36$, $\varepsilon = 1.00$] and side slope [$F(1, 86) = 208.30$, $p < 0.001$, $\eta_p^2 = 0.71$, $\varepsilon = 1.00$] were found. As in Experiment 1, the steeper symmetric side slope produced larger overestimation both in the haptic and the verbal condition. The effect size of texture was weaker than those for slope and answering mode, maybe because the texture manipulation was rather limited compared to real-world textures The compressed shallow texture produced underestimation, the steep one the expected overestimation.

The sample of depressed patients did not differ from the student group [$F(1, 86) = 0.84$, $p = 0.36$, $\eta_p^2 = 0.01$, $\varepsilon = .15$]. One could argue that the model slope did not sufficiently evoke an increased effort as would be required to climb a large hill. Moreover, the age differences would have made it difficult if not impossible to interpret group differences. By this as it may, the comparable results in both samples suggest that the effects of slope symmetry, texture, and answering mode are robust across different observer groups.

We also found interaction effects of front slope × side slope [$F(4, 344) = 15.36$, $p < 0.001$, $\eta_p^2 = 0.15$, $\varepsilon = 0.99$], of front slope × answering mode [$F(4, 344) = 5.75$, $p = 0.002$, $\eta_p^2 = 0.06$, $\varepsilon = 0.90$], of answering mode × side slope [$F(1, 86) = 27.69$, $p < 0.001$, $\eta_p^2 = 0.24$, $\varepsilon = 0.99$] and of front slope × answering mode × side slope [$F(4, 344) = 5.22$, $p = 0.006$, $\eta_p^2 = 0.06$, $\varepsilon = 0.83$].

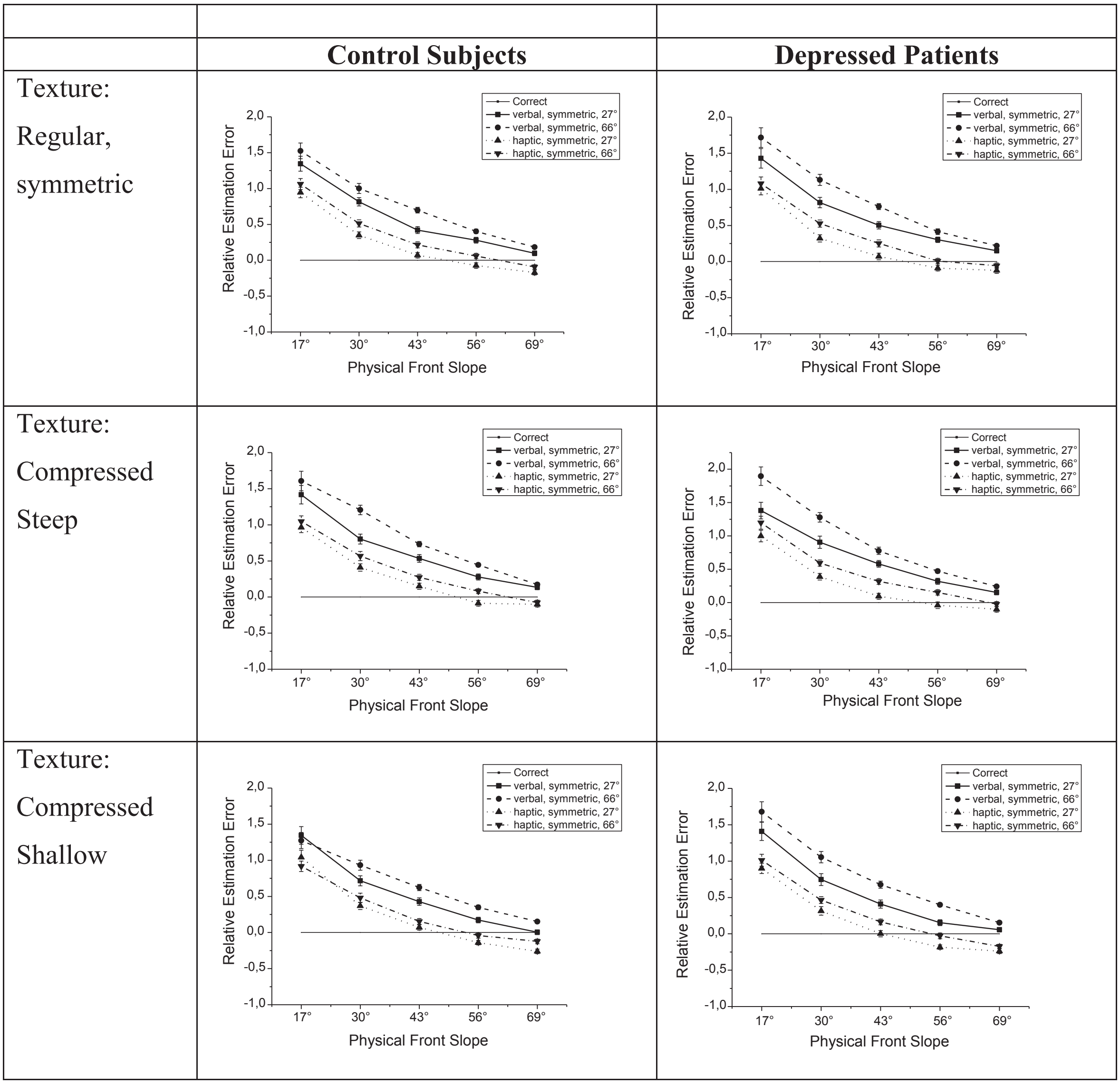

Fig. 11. Slope estimations of the control and the experimental group for regular, compressed-steep, and compressed-shallow frontal slope texture. Error bars show the standard error of the mean.

5. Experiment 3: Slope and distance estimation using a moon model

In the third Experiment, we investigated the relationship between perceived distance and slope estimation in an unfamiliar environment. Larger distances – similar to the removal of stereoscopic cues - should lead to less accurate slope estimates. Remember that Bridgeman and Hoover (2008) as well as Hecht et al. (2014) found increased overestimation at larger distances beyond action space. We attempted to replicate and extend this effect using a model made up of an artificial piece of lunar terrain (the Mainz moon model), which we sculpted from Styrofoam and covered with special sand also used by NASA to simulate lunar regolith. The terrain simulated the landing site of Apollo 17 (scale 1:72) and included three inclines of slopes similar to those tested in Exp. 1 and 2. We also used toy astronauts (at scale 1/72) as reference cues for intended size. Monocular viewing at the appropriate eye-height should produce retinal stimulation similar to that of an observer on the moon. Our first hypothesis was that the presence of these familiar objects would produce smaller slope estimation errors in comparison to the same terrain devoid of any familiar features. Our second hypothesis was that under low lighting conditions, slope and distance estimations should be more variable. As before, we used the verbal and haptic response modes assuming that verbal responses would produce larger overestimation than the haptic measure.

5.1. Method

5.1.1. Subjects

Forty subjects participated in this experiment. Their ages ranged from 16 to 61 years, (M = 26.18 years, *SD* = 9.526). Thirty-one subjects were female, nine male. All had normal or corrected-to-normal-vision and were naive with respect to the purpose of the study.

Twenty subjects each participated in the cue and the non-cue condition. In the cue condition, their ages ranged from 20 to 54 years (M = 25.10 years, *SD* = 7.33). Fifteen subjects were female, five male. The ages of the non-cue group ranged from 16 to 61 years (M = 27.32 years, *SD* = 11.45). Sixteen subjects were female, four male.

5.1.2. Stimuli and design

The moon model was three meters deep, with a width of one meter in the front and 3 m in the rear. It consisted of eight Styrofoam plates with a total surface area of 58,000 cm^2. The Styrofoam plates were glued onto wooden plates, which rested on two tables (180 × 75 cm). One prominent terrain feature was the side wall of a lunar crater with a height of 30 cm and a varying slope.

The Styrofoam plates were molded into a lunar crater landscape by carving it and adding a layer of Pufaplast and one of wallpaper glue to cover it with powdered granite. The entire terrain was then dusted with JSC-1A standard lunar mare regolith stimulant (Orbitec – a volcanic ash with a granularity smaller than 1 mm). The ash is mined from a volcano field near Flagstaff, Arizona, and has the same properties (friction, reflectance) as typical lunar regolith.

Outside the moon lab, we individually instructed the subjects, identified the dominant eye and guided them into the lab and positioned them with a chin rest in the front of the model before turning on the lights. We took the usual questionnaire data and used the verbal and haptic answering mode for slope estimation. Viewing was monocular. Three slopes (30°, 43, °56°) were crossed with two lighting conditions (diffuse light from above vs. parallel light originating behind the observer). Each subject merely performed the resulting six trials in a counterbalanced block design. The absence/presence of the reference cue was varied between subjects. As before, the inclination of the three slopes, all in the rear of the moon model (about 250 cm away), had to be judged verbally and with the forearm. Also the distance from the observer to the foot of the 30° incline had to be judged in the scale of the model (1:72), that is judgments were made verbally in meters.

5.2. Results and discussion

All slopes were overestimated in all conditions for the verbal answering mode (Fig. 12). As before, the haptic answering mode was more accurate, but overestimation was still significant. Similar to Experiments 1 and 2 the relative overestimation was stronger for the shallower slopes than for the steeper slopes. The reference cue tended to increase slope estimation for the 30° slope with parallel light from behind, both in the verbal as well as the haptic mode. All in all, the cue was not able to calibrate the estimations toward a correct perception of the slope.

The distance to the 30°-slope was also overestimated – speaking against compression as the cause for slope overestimation. Note that the reference cue seemed to have a positive effect on distance calibration. When the astronaut was present, subjects estimated the distance to the slope almost accurately, whereas without this cue, they overestimated the distance (Fig. 13). This effect was modulated by the lighting condition: Without reference cue, subjects tended to overestimate more when the light source was diffuse compared to parallel from behind. When the cue was present, the light condition did not have this effect.

A repeated-measures ANOVA with Greenhouse-Geisser correction for the degrees of freedom was conducted on the relative slope estimation errors. Main effects were found for frontal slope [$F(2, 76) = 93.38$, $p < 0.001$, $\eta_p^2 = 0.71$, $\varepsilon = 1.00$] and answering mode

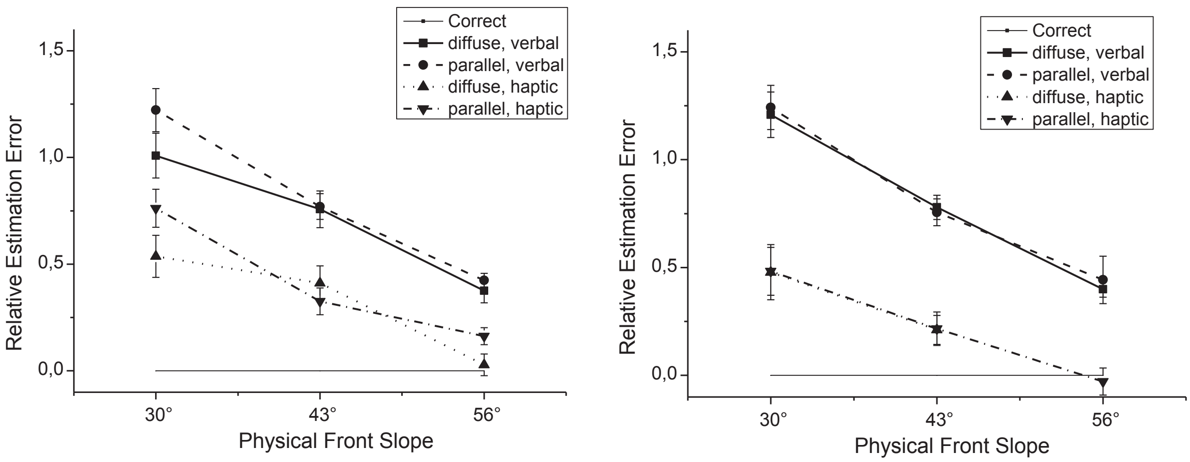

Fig. 12. Slope estimations with (left panel) and without (right panel) reference cue for three lunar slopes with diffuse ceiling light from above or parallel light from behind. Error bars show the standard error of the mean.

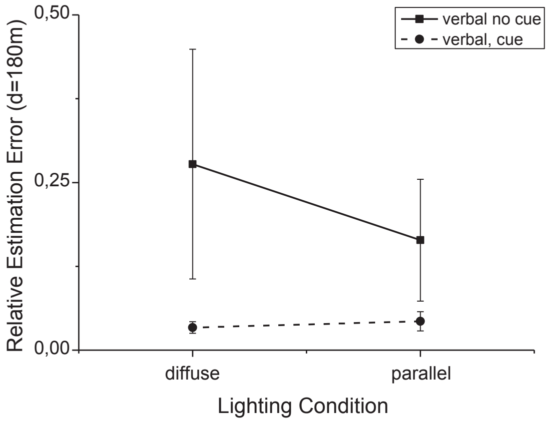

Fig. 13. Relative distance estimation error for the object at 180 m in the model world (1:72 → 250 cm) from the observer. Error bars show standard errors of the mean.

[$F(1, 38) = 198.41$, $p < 0.001$, $\eta_p^2 = 0.84$, $\varepsilon = 1.000$]. As before, relative overestimation was larger for the shallower slope, and verbal errors were smaller that haptic errors. Lighting [$F(1, 38) = 2.83$, $p = 0.100$, $\eta_p^2 = 0.07$, $\varepsilon = .38$] and reference cue [$F(1, 38) = .69$, $p < 0.42$, $\eta_p^2 = 0.02$, $\varepsilon = .13$] failed to reach significance. There was a trend to make steeper estimates in diffuse lighting as compared to rear lighting. We also found significant interaction effects for answering mode × cue condition [$F(1, 38) = 8.22$, $p = 0.007$, $\eta_p^2 = 0.18$, $\varepsilon = .80$] and front slope × answering mode [$F(2, 76) = 15.56$, $p < 0.001$, $\eta_p^2 = 0.29$, $\varepsilon = .99$].

For distance estimation, the reference cue condition produced slightly more accurate estimates in both lighting conditions, but not significantly so (lighting condition: [$F(1, 38) = 1.39$, $p = 0.25$, $\eta_p^2 = 0.04$], cue: [$F(1, 38) = 1.96$, $p = 0.17$, $\eta_p^2 = 0.05$] and light × cue [$F(1, 38) = 1.93$, $p = 0.17$, $\eta_p^2 = 0.05$]. Also, distance and slope estimates were not significantly correlated. Note that distance error should correlate negatively with slope overestimation if distance compression was responsible for the slope overestimation.

6. General discussion

In our first experiment we have modified the immediate vicinity of the slope that had to be judged. The shape of irrelevant parts of the hill had a significant effect on the target slope. The results point to a straight-forward integration of the irrelevant side slopes with the relevant front slope. The latter was judged to be particularly steep when both adjacent sides of the hill were steeper. When the side slopes were not symmetric (one side steeper than the other) their influence on the target slope was attenuated. This finding seems to indicate that even pictorial information of secondary nature intrudes upon slant judgments.

In the second experiment we took a closer look at answering mode (verbal vs. forearm), subject variables (age, depression), and slope texture. Rating errors were generally but not qualitatively reduced with the forearm method, and subject variables had no effect. Texture appeared to be a weaker cue than others. Note, however, that we used a reduced laboratory task, and texture was adapted to the small scale ramp setting. So the black and white horizontal stripes of the texture might have reduced the normal impact of texture. This is compatible with the conclusion drawn by Jim Todd and colleagues that observers are less sensitive to variations in apparent slant from texture than they are to variations in 2D-cues that are unrelated to the perception of slant (Todd, Christensen & Guckes, 2010).

Our third experiment used unfamiliar terrain, namely the simulation of a lunar landscape, and we also collected distance ratings to find out if slope overestimation might be mediated by distance underestimation, which would indicate consistent compression of perceived space. The latter was not the case. We also modified the lighting conditions. When the light source was behind the observer, slope tended to be judged more accurately. This is compatible with our observation that light in the observer's face produced gross overestimation.

Thus, the picture is more complex than previously thought. We can summarize the results as follows. Judgments of geographical slant are volatile and even more prone to extraneous influences than previously thought. Various reference cues and viewing conditions do alter the perceived slope. Haptic responses are lower than verbal responses throughout. However, it would be plain wrong to say that haptic measures are accurate whereas verbal estimates are not. Quite to the contrary, they seem to behave in remarkable synchrony. Thus, the findings do not support the notion of two separate systems, be it action vs. awareness (Creem & Proffitt, 1998) or be it explicit and implicit perception. Instead, they support the notion that the act of mapping one's forearm to a perceived slope uses a somewhat smaller scaling factor than the act of assigning a number between 0 and 90°, which simultaneously have to be mapped into representations of horizontal and vertical.

We had long discussions with Bruce about possible origins of the general tendency to overestimate slant. It cannot be reduced to memory effects. Although memory, even immediate recall of a just seen slope, seems to amplify the error (Blaesi & Bridgeman, 2015), our experiments confirm a genuine perceptual error. Could it be that geographical slant is such a remarkable case because pictorial cues intrude into the perceptual outcome much more so than in other phenomenal aspects of the action world? Our results on hill

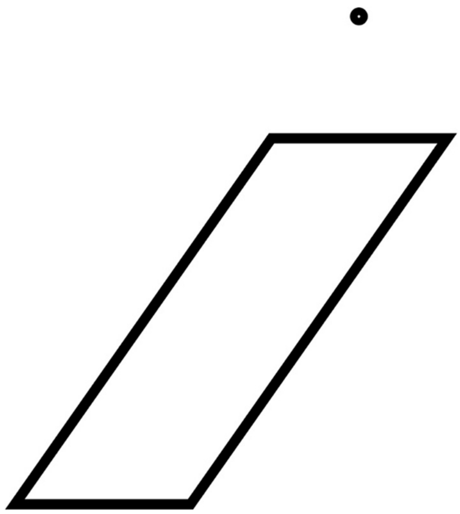

Fig. 14. Parallelogram adapted from Rausch (1952). The left side and the dot are aligned, however, the parallelogram appears to be tilted upward, thus producing an apparent misalignment. The dot appears to the right of the extension of the left edge.

symmetry would suggest so. An effect so obvious in drawings, may be at work here. We have referred to it as Aufrichtungstendenz (see Rausch, 1952) in the introduction. Asymmetric or unbalanced objects placed flat on the ground sometimes appear to tilt upwards toward the observer. For instance, the dot aligned with the left edge of the parallelogram in Fig. 14 appears to be too far to the right. It is in fact perfectly aligned. Rausch explains this with the tendency of the object (parallelogram) to appear tilted upwards. That is, its perceived slant toward the observer is overestimated. The general tendency to overestimate slopes may be an intrusion of this Aufrichtungstendenz into a richer stimulus context.

We can draw the following conclusions from our study: (1) In personal space, up to a couple of meters and well within the range of effective stereopsis and vergence information, geographical slant perception is most accurate, in particular, if the base of the slope is on the observer's ground surface, the eye-point is relatively high (Hecht et al., 2014), and information about the true environmental horizontal is given. Note, that the error does not entirely disappear, especially when the viewer is deprived of the visual environmental horizontal (Durgin, Li & Hajnal, 2010). (2) Beyond personal space, in action space and in vista space, pictorial cues play a decisive role even if earth horizontal is well-defined. Symmetry is one such cue. Our findings in this respect are compatible with those of Li & Durgin (2010), who could show that slope overestimation increases even further as the observer's distance to the slope in vista space increases. (3) Effort seems to play a minor role. Its role was inconclusive before, and if anything, a state of depression should maximize any feelings of effort and energy required for actions in this context. It did not have any noticeable effects. (4) We could show, however, that we can add to the list of extraneous variable that might influence slope estimates, such as familiarity with the scale of the environment and lighting of the scene.

In sum, perception of geographical slant is such an intriguing field for perceptual psychology because it reveals the enormous feat of the visual system to provide a phenomenal 3D world on the basis of retinal images, which are inherently 2D. The tendency of objects toward phenomenal erectness (Aufrichtungstendenz) is pervasive. As viewing conditions stray from ideal (binocular viewing of a close slope viewed from a high vantage point), the error increases and assumes spectacular dimensions in vista space.

Quite ironically, the most outspoken critic of the constructivist theory of perception, which is implicit in the above statement – James Gibson – was among the first to investigate geographical slant and even coined the term. Can we reconcile Gibson's radical realism with any of the results we obtained outside the realm of stereoscopic vision in personal space? One would have to admit that effective invariants are no longer present in action space and beyond, which would put a damper to the evolutionary slant in Gibson's theory. Or one would have to entertain a direct accurate perceptual system for personal space and a constructive visual system for things in action space. We contend that such a notion of separate systems would make more sense than the two-system approach that distinguishes between implicit perception for action and explicit perception for awareness, as popularized by Goodale and Milner (1992). Although Bruce has held this position long before its popularization (e. g. Bridgeman, Lewis, Heit & Nagle, 1979), he seemed to agree with our purely constructivist views when we exchanged our views on it a few years ago. Then again, his agreement may just have been a courtesy toward colleagues who can pronounce Aufrichtungstendenz without an accent. We miss him sorely.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.concog.2018.06.015.

References

Allekseenko, V. (1989). Nepreryvno, tschtschantel'no i svoevremenno [Principles of reconnoitering]. *Voennyj Vestnik, Nr. 5*(17), 42–44.

Baden-Powell, R. S. S. (1944). *Scouting for boys.* London: C. Arthur Pearson.

Bhalla, M., & Proffitt, D. R. (1999). Visual-motor recalibration in geographical slant perception. *Journal of Experimental Psychology: Human Perception and Performance, 25*(4), 1076–1096.

Blaesi, S., & Bridgeman, B. (2015). Perceived difficulty of a motor task affects memory but not action. *Attention, Perception, & Psychophysics, 77*(3), 972–977.

Bridgeman, B., & Hoover, M. (2008). Processing spatial layout by perception and sensorimotor interaction. *The Quarterly Journal of Experimental Psychology, iFIRST,* 1–9.

Bridgeman, B., Lewis, S., Heit, G., & Nagle, M. (1979). Relation between cognitive and motor-oriented systems of visual position information. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 692–700.

Chiu, E. M., Hoover, M. A., Quan, J. R., & Bridgeman, B. (2011). Treading a slippery slope: Slant Percetion in near and far space. In B. Kokinov, A. Karmiloff-Smith, & N. J. Nersessian (Eds.). *European perspectives on cognitive science*. New Bulgarian University Press.

Creem, S. H., & Proffitt, D. R. (1998). Two memories for geographical slant: Separation and interdependence of action and awareness. *Psychonomic Bulletin and Review, 5*(1), 22–36.

Cutting, J. E., & Vishton, P. M. (1995). Perceiving layout and knowing distances: The integration, relative potency and contextual use of different information about depth. In W. Epstein, & S. Rogers (Eds.). *Handbook of perception and cognition, Vol 5; Perception of space and motion* (pp. 69–117). San Diego, CA: Academic Press.

Daum, S. O., & Hecht, H. (2009). Distance estimation in vista space. *Attention, Perception and Psychophysics, 71*(5), 1127–1137.

Durgin, F. H., Hajnal, A., Li, Z., Tonge, N., & Stigliani, A. (2010). Palm boards are not action measures: An alternative to the two-systems theory of geographical slant perception. *Acta Psychologica, 134*, 182–197.

Durgin, F. H., Hajnal, A., Li, Z., Tonge, N., & Stigliani, A. (2011). An imputed dissociation might be an artifact: Further evidence for the generalizability of the observations of Durgin et al. 2010. *Acta Psychologica, 138*, 281–284.

Durgin, F. H., Li, Z., & Hajnal, A. (2010). Slant perception in near space is categorically biased: Evidence for a vertical tendency. *Attention, Perception, & Psychophysics, 72*(7), 1875–1889.

Firestone, C. (2013). How "paternalistic" is spatial perception? Why wearing a heavy backpack doesn't – and *couldn't* – make hills look steeper. *Perspectives on Psychological Science, 8*(4), 455–473.

Gibson, J. J. (1950). The perception of visual surfaces. *American Journal of Psychology, 63*(1), 367–384.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Hillsdale, NJ: Erlbaum.

Gibson, J. J., & Cornsweet, J. (1952). The perceived slant of visual surfaces – optical and geographical. *Journal of Experimental Psychology, 44*(1), 11–15.

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences, 15*, 20–25.

Grüsser, O. J. (1983). Multimodal structure of the extrapersonal space. In A. Hein, & M. Jeannerod (Eds.). *Spatially oriented behavior* (pp. 327–352). New York: Springer.

Hautzinger, M., Bailer, M., Worall, H., & Keller, F. (Eds.). (1994). *Beck-Depressions-Inventar BDI*. Bern: Huber.

Hecht, H., Shaffer, D., Keshavarz, B., & Flint, M. (2014). Slope estimation and viewing distance of the observer. *Attention, Perception, & Psychophysics, 76*(6), 1729–1738.

Hershenson, M. (Ed.). (2013). *The moon illusion*. Psychology Press.

Higashiyama, A. (1996). Horizontal and vertical distance perception: The discorded-orientation theory. *Perception and Psychophysics, 58*(2), 259–270.

Higashiyama, A., & Ueyama, E. (1988). The perception of vertical and horizontal distances in outdoor settings. *Perception and Psychophysics, 44*(4), 151–156.

Hutchison, J. J., & Loomis, J. M. (2006b). Reply to Proffitt, Stefanucci, Banton, and Epstein. *Spanish Journal of Psychology, 9*, 343–345.

Hutchison, J. J., & Loomis, J. M. (2006a). Does energy expenditure affect the perception of egocentric distance? A failure to replicate Experiment 1 of Proffitt, Stefanucci, Banton, and Epstein (2003). *The Spanish Journal of Psychology, 9*(2), 332–339.

Ivanov, A. (1969). O metodike obucebija glazomeru [The methods for distance estimation training]. *Vojennyj Vestnik, 3*(33), 114–116.

Kammann, R. (1967). The over-estimation of vertical distance and slope and its role in the moon illusion. *Perception and Psychophysics, 2*(12), 585–589.

Li, Z., & Durgin, F. H. (2010). Perceived slant of binocularly viewed large-scale surfaces: A common model from explicit and implicit measures. *Journal of Vision, 10*(14) 13 13.

Proffitt, D. R., Bhalla, M., Gossweiler, R., & Midgett, J. (1995). Perceiving geographical slant. *Psychonomic Bulletin and Review, 2*(4), 409–428.

Proffitt, D. R., Creem, S. H., & Zosh, W. D. (2001). Seeing mountains in mole hills: Geographical slant perception. *Psychological Science, 12*(5), 418–423.

Proffitt, D. R., Stefanucci, J., Banton, T., & Epstein, W. (2003). The role of effort in perceiving Distance. *Psychological Science, 14*(2), 106–113.

Rausch, E. (1952). *Struktur und Metrik figural-optischer Wahrnehmung [Structure and metrics of figural optical perception].* Kramer: Frankfurt a. M.

Ross, H. E. (1974). *Behaviour and perception in strange environments.* London: George Allen & Unwin Ltd.

Stefanucci, J., Proffitt, D. R., Banton, T., & Epstein, W. (2005). Distances appear different on hills. *Perception & Psychophysics, 67*(6), 1052–1060.

Stefanucci, J. K., Proffitt, D. R., Clore, G. L., & Parekh, N. (2008). Skating down a steeper slope: Fear influences the perception of geographical slant. *Perception, 37*(2), 321–323.

Todd, J. T., Christensen, J. T., & Guckes, K. C. (2010). Are discrimination thresholds a valid measure of variance for judgments of slant from texture? Journal of Vision, 10(2):20, 1–18, < http://journalofvision.org/10/2/20/ > , 10.1167/10.2.20.

Witt, J. K., Proffitt, D. R., & Epstein, W. (2004). Perceiving distance: A role of effort and intent. *Perception, 33*, 577–590.