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Slope estimation and viewing distance of the observer

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Abstract The overestimation of geographical slant is one of the most sizable visual illusions. However, in some cases estimates of close-by slopes within the range of the observer's personal space have been found to be rather accurate. We propose that the seemingly diverse findings can be reconciled when taking the viewing distance of the observer into account. The latter involves the distance of the observer from the slope (personal space, action space, and vista space) and also the eye-point relative to the slope. We separated these factors and compared outdoor judgments to those collected with a three-dimensional (3D) model of natural terrain, which was within arm's reach of the observer. Slope was overestimated in the outdoors at viewing distances between 2 m and 138 m. The 3D model reproduced the errors in monocular viewing; however, performance was accurate with stereoscopic viewing. We conclude that accurate slant perception breaks down as soon as the situation exits personal space, be it physically or be it by closing one eye.

Keywords Spatial vision · Visual perception

Slope and viewing distance of the observer

Since Kammann's (1967) ground-breaking study it is a well-established phenomenon that slopes of hills or inclines (geographical slant; for a definition see Gibson & Cornsweet, 1952) are being over-estimated, often dramatically. It is common that verbal estimates of slopes reflect overestimations of 15-25 degrees and more. Numerous factors that influence geographical slant estimation have been identified, such as estimation mode, fatigue, fear, climbing surface, and viewing position (Durgin, Baird, Greenburg, Russell, Shaughnessy, & Waymouth, 2009; Feresin & Agostini, 2007; Proffitt, Bhalla, Gossweiler, & Midgett, 1995; Stefanucci, Proffitt, Clore, & Parekh, 2008; Shaffer & Flint, 2011). However, the role of the position of the observer with respect to the slope—the situatedness of the observer—has not been fully explored. We report two experiments that address the issue of situatedness.

It has often been thought that slopes are being uniformly overestimated regardless of the observer's distance from the slope, to the extent that many studies fail to report viewing distance. A closer look at the different existing studies reveals that the overestimation-effects are by no means uniform. Some stimuli produce overestimation errors approaching 25-30 degrees, while others produce smaller overestimation errors on the order of 2-10 degrees. For an [incomplete but representative] synopsis see Fig. 1. It arranges the overestimation results obtained in different studies as a function of the viewing distance of the observer from the base of the slope. Note that many authors have not reported this viewing distance or failed to mention whether the distance they do report refers to the slope's base, some point on the surface, or to the top of the hill. These studies had to be omitted from the synopsis. It is quite striking that verbal overestimation of slope is present at all distances. The size of the estimation error clearly increases with distance from the observer. We have plotted the results with reference to the base of the slope. Note that the synoptic plot in Fig. 1 has to be taken with a grain of salt; many studies used several hills such that we had to pick a result that was representative for the paper. Also, often the

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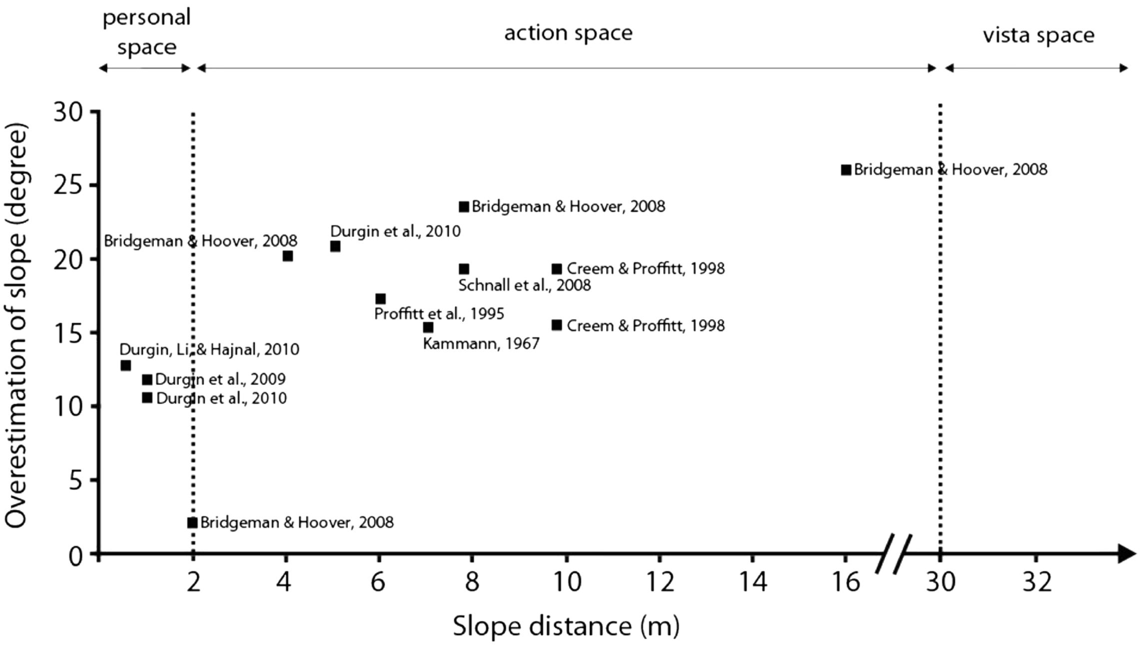

Fig. 1 Overview of studies that solicited verbal judgments of slopes in real environments, as a function of distance to the base of the slope (covering personal, action, and vista space)

respective methods sections did not specify whether or not the distance was measured with respect to the hill's base. Nonetheless, we believe that the trend is clear that the plot does represent a summary of the existing range of results.

Li and Durgin (2010) performed one of the first systematic studies of the effects of viewing distance on slant perception using a high-end stereoscopic virtual reality system. They used five viewing distances (1, 2, 4, 8, and 16 m) and six surface orientations (6, 12, 18, 24, 30, and 36 degrees). When they plotted estimated slant/actual slant as a function of viewing distance, they found that perceived slant increased logarithmically with viewing distance. Their data were then fit into a three-parameter model that simulated the verbal data of Proffitt et al. (1995) very well. Here we perform a real-world investigation that extends the work of the role of viewing distance on slant perception.

In the present study we are not interested in the reasons for the discrepancies between verbal and haptic judgments; we will focus exclusively on the verbal estimates. We hold that there are two classes of verbal overestimation, one accounting for overestimation errors of approximately 2-12 degrees, and another accounting for overestimation errors of 15 degrees and above. They appear correlated with the position of the observer with respect to the judged slope. When the observer finds herself in front of a hill or a ramp that she could climb, then the overestimation is enormous. If on the other hand, the observer finds herself in front of an object, which could in principle be manipulated using the hands, the overestimation effect is rather moderate. In other words, the situation of hill-climbing appears to produce overestimations that are an order of magnitude larger than those obtained within the framework of manipulation. However, two issues are confounded within this interpretation. Near objects—be they small or be they the base of a climbable hill—fall within the range of effective stereovision, whereas far objects do not. And only near objects can be grasped or touched whereas far objects remain outside any immediate action upon them, and fall outside the effectivity of stereopsis, vergence, and accommodation cues. We sought to separate graspability from stereo vision by using a scaled-down model world, in which we can create graspable hills within the stereo range.

Action space and vista space

The underlying taxonomy of space is one originally proposed by Grüsser (1983, 1978). It lends itself to put the notion of situatedness into context. Grüsser divided perceptual space into the two major regions of personal and extra-personal space. In a similar fashion, Cutting and Vishton (1995) subdivided space into three circular, egocentric regions which they called personal space (limited to 2 m), action space (up to a radius of 30 m) and vista space (beyond about 30 m). For the realm of distance estimation, we extended this model to a far vista space (above about 100 m). In far vista space, distances tend to be overestimated (Daum & Hecht, 2009), whereas distance is estimated close to perfection in personal space, and it is compressed in action space and near vista space.

Based on these findings, we hypothesized that slope estimates should also vary as a function of distance. Note that Li & Durgin (2010) found indications of such an effect for a limited range of viewing distances in a virtual reality setting when using head-mounted displays that covered the entire field of view. We are aware of only one study that has addressed the issue of viewing distance when judging slope at larger distances: Ross (2006) found that uphill slopes appear steeper with distance; however, distances were not systematically varied and the context varied vastly among distances as convenient natural scenes were used as stimuli. The notion that the effort needed to climb up the slope may feed into estimates of its slope may or may not have inspired this observation (see also Proffitt, 2009); however, it was not applicable in Durgin et al.'s first experiment. We sought to focus on the issue of viewing distance rather than varying the intended action.

Existing psychophysical studies have demonstrated that the visual system is able to make adaptive use of a variety of visual cues to arrive at an accurate estimate of slant. Among others, the cues of perspective and disparity are being used and weighted depending on their availability (Backus, Banks, van Ee, & Crowell, 1999). Because of this adaptive feature, slope estimation is also rather robust with regard to changes in the inter-ocular distance (Stuart, Flanagan, & Gibbs, 2007). However, this may not hold for the hill-climbing situations. Thus, it may well be that reports of slope or geographical slant being grossly overestimated apply exclusively to viewing distances beyond the range of effective stereo vision in the manipulation-framework and potentially to all distances in the hill-climbing framework. Under normal circumstances, slopes that can be manipulated or grasped are confined to personal space. However, by using a scaled-down model of a landscape, we can bring "large" hills into personal space. When we now remove stereoscopic (3D) cues by means of monocular (2D) viewing, we can separate the potential effect of reachability from that of effective depth cues. Table 1 illustrates this rationale.

We conducted two experiments to investigate the hypothesis that two conditions have to be met for accurate slope perception. Firstly, the slope has to be within personal space. And secondly, the depth cues of stereopsis have to be available. Thus, very near slopes should be perceived accurately only with full visual cues, whereas slopes at larger distances should be over-estimated at all times. Experiment 1 manipulated distance in a real-world setting, while Experiment 2 used a miniature model to measure slope estimations in the lab.

Table 1 Distance of a slope paired with the two situations of reaching vs hill-climbing

Personal Space	Action Space	Vista Space	Potential Action
Model 3D	Model 2D	Model 2D	Manipulation/reach
Real World	Real World	Real World	Hill-climbing
Near	Far	Very far	

Experiment 1: Artificial slopes outdoors

In Experiment 1 we sought to perform a real-world investigation of the role of viewing distance on perceived slant that validates and extends previous work using virtual reality (Li & Durgin, 2010). The underestimation of egocentric distance in the sagittal plane is often taken to indicate a compression of space (see e.g., Indow, 1991). As mentioned before, this holds for action space only. Space compression predicts that right angles of buildings are perceptually flattened in action space, which they are (Hecht, Koenderink, & van Doorn, 1999). Space compression also predicts that slopes should be overestimated. Note that the compression applies to the sagittal dimension only. When the distance between two objects has to be judged which are placed in action space in front of the observer and on a frontoparallel plane, these sagittal distance estimates do not seem to suffer from compression (Loomis, DaSilva, Philbeck, & Fukusima, 1996). If egocentric space is uniformly compressed within the realm of action space but not at all in personal space, and to a lesser extent in vista space, then we should find the following pattern for slope estimates: Slopes viewed from distances up to about 2 m should be judged with great accuracy. Slopes viewed from distances above 2 m up to somewhere around 50-70 m should be overestimated, and slopes beyond 70 m or 100 m should be overestimated to a smaller extent. To test this conjecture, we created a wooden ramp and had observers judge its slope in an outdoor setting at varying distances.

Methods

Participants

Seventy-eight female and 72 male students from Ohio State University who received credit for an introductory psychology course participated in the experiment. Their ages ranged from 18 to 44 years with an average age of 20.67 (SD = 4.31) years. All were naive to the purpose of the experiment.

Stimuli

A wooden ramp was created by connecting two pieces of wood (1 m × 1 m each) by a hinge. This design allowed us to easily carry the ramp to a location where it was easy to manipulate and remained clearly visible even at large viewing distances. The slope of the ramp could be changed from 15 degrees to 45 degrees. The ramp was in the original wood color. At 15 degrees, the top of the hill was 0.37 m high, while at 45 degrees it was 0.71 m high.

Design, procedure, and response measures

We used a design that fully crossed the factor distance from the ramp (between subjects, five levels: 2 m, 8 m, 36 m, 64 m, and 128 m) with slope (within subjects, two levels: 15 degrees and 45 degrees). The study was conducted in a clearing at the Ohio State University Campus in Mansfield, Ohio. The clearing consisted of flat terrain of 200 m × 100 m open field in which there were no familiar objects or salient landmarks. Participants were pseudo-randomly assigned to one of the five distance positions (the 2-m distance was assumed by18 male and 12 female subjects, 8 m: 13 male, 17 female; 36 m: 12 male, 18 female; 64 m: 14 male, 16 female; 128 m: 15 male, 15 female).

The distances between the observer and the artificial hill were measured between the base of the hill and the observer's feet. Participants were blindfolded, so they could not see the hill before they were guided to their designated position. Participants were informed that the study would involve slant and distance estimations and were shown examples of 0-, 45-, and 90-degree angles. These angles were presented schematically to them as a side view of the two hinged lines forming the base and the sloped line. All participants indicated that they understood judging inclination in this way. They viewed the hill at 15 degrees first, then at 45 degrees. This would allow for an unbiased judgment of the shallower slope. They did so with unobstructed view and with both eyes open. After answering questions about the hill at 15 degrees, participants were again blindfolded and asked to turn in the opposite direction. During this time, the angle of the hill was changed from 15 degrees to 45 degrees. When they turned back, their blindfold was taken off and they again estimated the slant of the hill. They also estimated the height of the hill again. Participants were again blindfolded and guided away from the clearing to a laboratory.

Participants gave verbal estimates of the inclination of the hill in degrees. They then gave a motoric estimate where they were asked to hold their elbow against their body and to hold their upper arm perpendicular to their body (and parallel with the ground) until a magnetic angle locator measured their upper arm at 0 degrees (perfectly horizontal). We then had them place their forearm either perpendicular to (0 degrees) or parallel to (90 degrees) the body. They were asked to raise or lower the arm to match the slope of the artificial hill, similar to the method used by Bridgeman and Hoover (2008). We then measured the angle of their forearm relative to their upper arm with the magnetic angle locator.

Results

Effect of distance on verbal slope estimates

Figure 2 shows mean verbal and motor estimates at 15 degrees and 45 degrees plotted against log(distance). A one-way ANOVA analyzing the effect distance had on verbal estimates of the ramp at 15 degrees was significant, $F(4,145) = 3.26$, $p = 0.013$, $\eta^2 = 0.08$. Tukey's post hoc tests showed that estimates of the ramp were steeper when participants stood at 36 m ($p = 0.032$) and 64 m ($p = 0.037$) compared with 2 m (p values < 0.05).

A one-way ANOVA analyzing the effect distance had on verbal estimates of the ramp at 45 degrees was also significant, $F(4,145) = 3.54$, $p < 0.01$, $\eta^2 = 0.09$. Tukey's post hoc tests showed that estimates of the ramp were steeper when participants stood at 36 m compared with 2 m ($p = 0.007$). No other differences were significant. Two paired-sample t-tests showed that verbal estimates were greater than forearm estimates at both 15 and 45 degrees, $t(149) = 2.16$, $p = 0.032$ and $t(149) = 12.26$, $p < 0.001$, respectively.

Figure 2 shows linear fits of the data when plotted against distance up until 36 m. R values for lines analyzed from 2 m to 36 m for the verbal estimates were 0.972 and 0.987 for estimates when the ramp was placed at 45 degrees and 15 degrees, respectively.

Effect of distance on motor estimates

A one-way ANOVA analyzing the effect distance had on motor estimates of the ramp at 15 degrees was significant, $F(4,145) = 3.57$, $p < 0.008$, $\eta^2 = 0.09$. Tukey's post hoc tests showed that estimates of the hill were steeper when participants stood at 36 m ($p = 0.009$) and 64 m ($p = 0.035$) compared with 2 m (p values < 0.05). No other differences were significant. A one-way ANOVA analyzing the effect distance had on motor estimates of ramp at 45 degrees was also significant, $F(4,145) = 3.23$, $p = 0.014$, $\eta^2 = 0.08$. Tukey's post hoc tests showed that estimates of the ramp were steeper when participants stood at 36 m ($p = 0.014$) compared with 2 m (p values < 0.05). No other differences were significant.

Figure 2 shows linear fits of the data when plotted against distance up until 36 m. R values for lines analyzed from 2 m to 36 m for the manual estimates were 0.997 and 1.00 for estimates when the ramp was placed at 45 degrees and 15 degrees, respectively.

Estimates of ramp base and height

Estimates of the base and height of the hill significantly underestimated the actual base and height of the hill at all distances. Base estimates across distances significantly underestimated the actual length of 3.28 ft for both the ramp

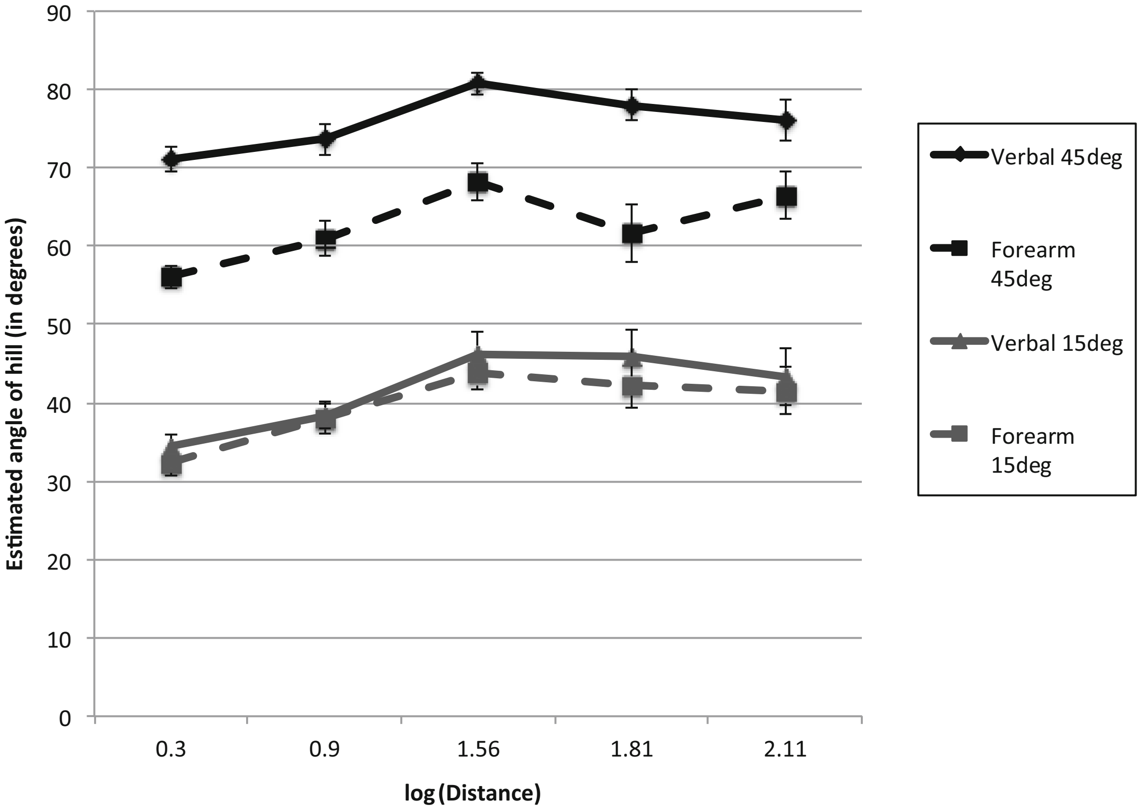

Fig. 2 Mean verbal and forearm estimates of a ramp sloped at 15 and 45 degrees

oriented at 15 degrees, $t(149) = -41.8$, $p < 0.001$, $M = 1.09$ ft, $SE = 0.05$, and at 45 degrees, $t(14) = -43.33$, $p < 0.001$, $M = 1.01$, $SE = 0.05$. Height estimates across distances for the ramp oriented at 15 degrees significantly underestimated actual height (1.21 ft), $t(149) = -14.57$, $p < 0.001$, $M = 0.7$, $SE = 0.04$. Height estimates across distances for the ramp oriented at 45 degrees also significantly underestimated actual height (2.33 ft), $t(149) = -17.88$, $p < 0.001$, $M = 1.38$, $SE = 0.05$.

Correlations of estimates of ramp base and height to verbal estimates of slope

Estimates of the height of the ramp were not significantly correlated with verbal estimates of the slope of the ramp at 15 degrees, $r = 0.091$, or at 45 degrees, $r = -0.021$, both p values > 0.2. Estimates of the length of the base of the ramp were also not significantly correlated with verbal estimates at 15 degrees, $r = -0.094$, or at 45 degrees, $r = -0.141$, both p values > 0.05.

Base/height estimates converted to slope

We also calculated what the slope of the ramp would be if we used participants' estimates of the base and height of the hill.

We first performed two one-sample *t*-tests comparing the base/height conversion (B/HC = $\tan^{-1}$[base height/base length]) to the actual slope of the ramp and found that the B/HC significantly overestimate the actual slope of the ramp at 15 degrees, $t(149) = -16.6$, $p < 0.001$, $M_{B/HC} = 34.51°$, $SE_{B/HC} = 1.18$, and when it was oriented at 45 degrees, $t(149) = 8.63$, $p < 0.001$, $M_{B/HC} = 54.63°$, $SE_{B/HC} = 1.12$

We next performed two paired-samples *t*-tests comparing the slope calculated with the base/height conversion to people's verbal estimates of the slope (*V*). We found that the base/height conversion remained significantly lower than participants' verbal estimates of the ramp, both when the ramp was oriented at 15 degrees, $t(149) = -4.7$, $p < 0.001$, $M_{B/HC} = 34.51°$, $SE_{B/HC} = 1.18$, $M_V = 41.66°$, $SE_V = 1.3$, and when it was oriented at 45 degrees, $t(149) = -15.77$, $p < 0.001$, $M_{B/HC} = 54.63°$, $SE_{B/HC} = 1.12$, $M_V = 75.91°$, $SE_V = 0.92$.

Discussion

Slopes were consistently and severely overestimated irrespective of the method (verbal or motoric) or slope of the ramp (15 or 45 degrees). This result is consistent with existing studies (Bhalla & Proffitt, 1999; Bridgeman & Hoover, 2008; Li & Durgin, 2010; Proffitt, Bhalla, Gossweiler, & Midgett, 1995; Proffitt, Creem, & Zosh, 2001).

Both Bridgeman and Hoover (2008) and Li and Durgin (2010) found that slant estimates increased with the log of viewing distance. This relationship was also found in the current Experiment up to a viewing distance of 36 m. Li & Durgin (2010) attributed this relationship to stereoscopic scaling compression, which varied with viewing distance. Our results are consistent with this interpretation. This relationship is shown in Fig. 2 up to 36 m, outside of which (at 64 and 128 m) stereopsis is largely unavailable. We should point out that while hills would provide stereoscopic depth information at some of the longer distances (64 and 128 m) used in the current experiment, stereoscopic information becomes less available for smaller ramps like the one we used.

We also found that the perception of slant is quite different in different regions of space. This is evidence in favor of the idea of Bridgeman and Hoover (2008), who proposed that differences in neural coding for near and far space would result in differences in the perception of slant. The error is smaller in personal space than in vista space. It is, however, rather surprising that at 2 m distance—which can be considered the edge of personal space as well as still within the realm of effective stereo vision—overestimation was already very large (100 % for the shallower slope regardless of method, in concordance with previous studies [see Fig. 1]). It appears that the pictorial cues that govern vista space for the perception of hills intrude already at 2 m for artificial slopes. While the small wooden ramp we used in the current experiment makes for a rather small hill, our results are consistent with perception of actual virtual geographical slant of large hills at different viewing distances (Li & Durgin, 2010). This would validate the use of the constant-size ramp.

Remember that the observers were positioned at the base of the ramp looking down on it. May this vantage point have produced the effect? The only way to partially disentangle the potential effect of vantage point from a true effect overriding stereoscopic information is to change the vantage point. As the vantage point effect is present but not very large (observers are quite good compensating for perspective foreshortening, see Daum & Hecht, 2009), it is hard to change the vantage point sufficiently in a natural environment. Thus, in our second experiment, we decided to use a scaled-down model to create a substantial variation in vantage point with respect to the hill.

Experiment 2: Artificial hills on an indoor model

In Experiment 1 the observer was situated in front of a small hill, which she could have easily climbed. The most surprising finding was that even at the closest viewing distance of 2 m, slope overestimation was substantial. This distance should in theory have been close enough for the visual system to exploit stereoscopic information. The estimates should have been rather accurate unless the small physical size of the hill (compared with natural hills) and/or the elevation of the eye-point (angular declination) relative to the slope (see e.g. Loomis, 2001) had interfered. To assess the role of stereopsis and to address as directly as possible the relative eye-height concern, we resorted to building a miniaturized model of a naturalistic terrain. We created a Styrofoam model that represented a copy of a naturalistic landscape (scale 1:87) including a grassy surface with hills, meadows, and trees. This allowed us to easily manipulate the observer's eye height. Participants were randomly assigned to one of the three eye-height groups and had to judge two slopes of the model both binocularly and monocularly. We hypothesized that stereopsis would improve the accuracy of slope estimation as stereopsis is known to be a powerful cue within the observer’s personal space. Additionally, we assumed that raising the eye-height of the participants would lead to more accurate slope judgments, as a higher vantage point reduces perspective foreshortening, provides a widened view of the scenario, and delivers more information about the model’s structure.

We considered using a virtual reality rendition instead of the model world. However, the known issues of spatial compression, the lack of resolution and the limits of rendering detail (cf. Willemsen, Gooch, Thompson, & Creem-Regehr, 2008) would have introduced serious shortcomings that weigh more heavily than the scaling of the real-world model.

Methods

Participants

Sixty mostly undergraduate psychology students (30 male, 30 female) participated. The subjects’ age span ranged from 19 to 51 with a mean age of $M = 28$ (SD = 7) years. Participants were randomly assigned to one of the three experimental groups with different eye-heights. Table 2 shows the distribution of all subjects across each group.

Apparatus and stimuli

We sculpted an artificial model from Styrofoam (size 1 m length, 1 m breadth) that represented a typical, rural landscape (see Fig. 3). The surface was prepared with a grassy-like cushion and the model included hills, trees, and various objects (e.g., a car, animals, and a shepherd). All man-made objects were taken from the toy train standard H0, which is

Table 2 Distribution of the participants to the experimental groups

	Eye-height						
	2 cm		10 cm		50 cm		Total
	Male	Female	Male	Female	Male	Female	
N	10	10	10	10	10	10	60

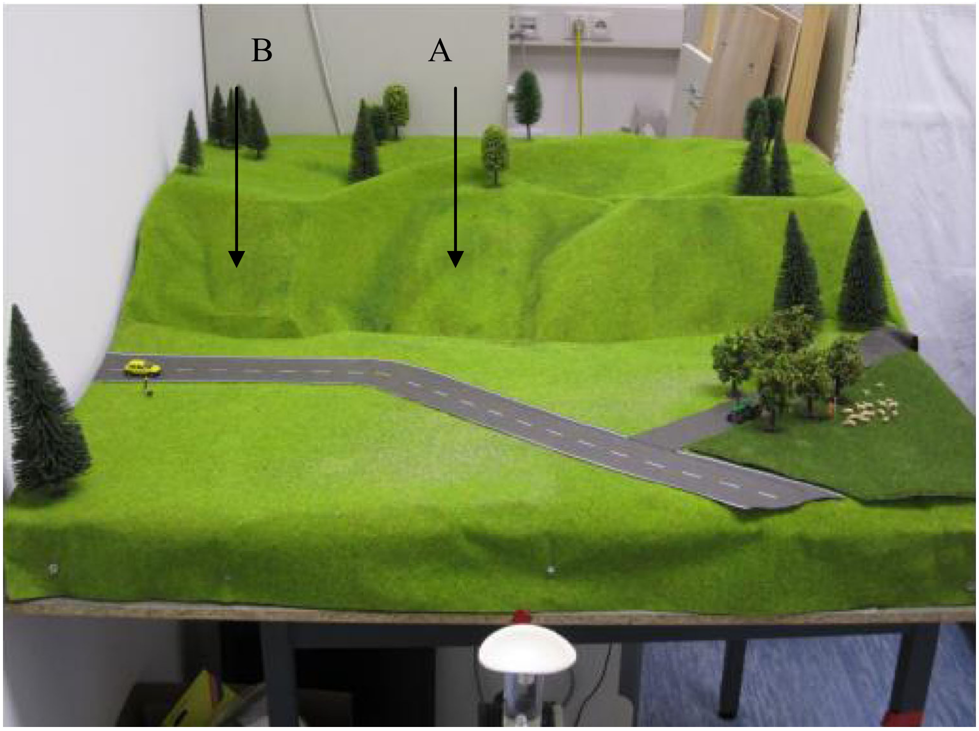

Fig. 3 Front view of the Styrofoam model of a rural environment. The slopes that had to be judged by the observers are marked as *A* (30 degrees) and *B* (45 degrees). A chinrest was positioned centrally in front of the model to adjust the participant's eye-height

scaled at 1:87 with respect to the real world analogs. The model was illuminated by ordinary fluorescent light from the ceiling. The laboratory behind the model was occluded by a black curtain. Depending on the experimental group, the participants' eye-height was adjusted using a height-adjustable chair to enable eye-levels of 2 cm (corresponding to a would-be standing eye-height of 174 cm in the real world), 10 cm (8.7 m), or 50 cm (43.5 m) above the model's surface. We used a chinrest (positioned centrally in front of the model with a distance of 9 cm) to support the participants' head and to restrict head movements during stimulus presentation. In the monocular condition, the non-dominant eye of the participants was covered with an eye patch. The experimental procedure was the same for all groups.

Response measures

All participants had to verbally judge the slopes of two hills of the model (see Fig. 3). The slopes of the hills were 30 degrees (A) and 45 degrees (B) respectively and had to be judged binocularly and monocularly. Thus, each participant had to make four estimations in total. The order of the visual condition that was presented first was balanced; hence half of the participants began the experiment with a binocular judgment and the other half began with a monocular estimations. This was done to control for sequence effects and to minimize the error based on chronological judgments. The order of the hills that had to be estimated was randomized.

Design and procedure

We chose a 3 × 2 × 2 design, including the between-subjects factor eye-height (2 cm, 10 cm, 50 cm) and the within-subjects factors viewing mode (monocular, binocular) and slope (30 degrees, 45 degrees). Prior to the experiment, participants received written instructions about the procedure of the experiment. Additionally, the subjects were exposed to a drawing of two lines forming a 90 degrees angle, which dealt as a reference angle and illustrated the judging procedure. The non-dominant eye of each participant was determined using the Porta-Test and was covered with an eye patch for monocular judgments. Before entering the lab, the subject was blindfolded and escorted into the lab by the experimenter. When seated, the blindfold was removed and she began with the first judgment. The experimenter recorded the verbal judgments of the subjects. After each single judgment, the subject's chair was rotated about 180 degrees so that the subject's back was facing the model. This was done to prevent familiarization with the model and to adjust or remove the eye patch. When all four judgments were done, participants were rewarded and dismissed.

Results

Figure 4 shows the slope estimations (relative error) for all experimental conditions. One-sample *t*-tests for all groups and all judgments revealed significant overestimations in all

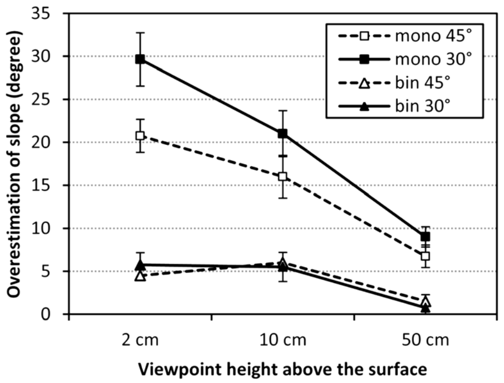

Fig. 4 Overestimation of slope for all experimental conditions. *Mono* monocular estimation, *bin* binocular estimation; *error bars* indicate SEM

conditions, except for judging the 30 degrees and the 45 degrees slope binocularly (see Table 3).

A 2 × 2 repeated-measures ANOVA including the within-subjects factors viewing mode (monocular, binocular) and slope (30 degrees, 45 degrees) was calculated on the relative errors. Additionally, the between-subjects factor eye-height (2 cm, 10 cm, 50 cm) was added to the ANOVA. A significant main effect of slope, $F(1, 57) = 293.193$, $p < 0.001$, $\eta^2 = 0.837$, indicating stronger overestimations for the 30 degrees compared with the 45 degrees slope, was found. Additionally, main effects of viewing mode, $F(1, 57) = 145.260$, $p < 0.001$, $\eta^2 = 0.718$, and eye-height, $F(2, 57) = 15.643$, $p < 0.001$, $\eta^2 = 0.354$, were present. That is, slope estimations were more accurate with increasing eye-height and when participants made their judgments binocularly. Significant interactions exist between eye-height and viewing mode, $F(2, 57) = 12.187$, $p < 0.001$, $\eta^2 = 0.300$, between slope and eye-height, $F(2, 57) = 8.921$, $p < 0.001$, $\eta^2 = 0.238$, and between slope and viewing mode, $F(1, 57) = 40.569$, $p < 0.001$, $\eta^2 = 0.416$. Post-hoc tests (Tukey) for the factor eye-height are presented in Table 4. The results indicate that binocular viewing and increased eye-height improved the accuracy of the slope estimation (see Fig. 4). Furthermore, the overestimation of the 45 degrees slope was less than the overestimation of the 30 degrees slope. A three-way interaction between slope, viewing mode, and eye-height missed significance, $F(2, 57) = 2.964$, $p = 0.060$, $\eta^2 = 0.094$.

Table 3 Results of one-sampled *t*-tests for each slope judgment of every experimental group

	Slope	Eye-height	*t*	*df*	*p*
Monocular judgment	30°	2 cm	9.585	19	<0.001
		10 cm	7.835	19	<0.001
		50 cm	7.621	19	<0.001
Binocular judgment	30°	2 cm	4.056	19	0.001
		10 cm	3.240	19	0.004
		50 cm	.497	19	0.625
Monocular judgment	45°	2 cm	10.758	19	<0.001
		10 cm	6.462	19	<0.001
		50 cm	5.107	19	<0.001
Binocular judgment	45°	2 cm	3.596	19	0.002
		10 cm	3.148	19	0.005
		50 cm	1.189	19	0.249

Table 4 The *p* values produced by post-hoc tests (Tukey) for the between-subjects factor eye-height for each slope

Slope	Eye-height		
	2 cm vs 10 cm	2 cm vs 50 cm	10 cm vs 50 cm
30°	0.132	<0.001	0.001
45°	0.703	<0.001	0.004

Discussion

The worst case of overestimation occurred when eye-height was low, viewing was monocular and the slope was shallower (30 degrees). In contrast, the steeper slope (45 degrees) was judged accurately when viewing was binocular and eye-height was high. Thus, we have to introduce effective stereoscopic information and to reduce the perspective cues by assuming a sufficiently high eye-position in order to make the illusion disappear. In all other cases, the tendency to overestimate slopes is very strong.

The use of the model allowed us to isolate the effect of eye-height, which was very strong. When the eye-height was raised from a standing eye-height (in terms of the model) to 5 and 25 times its value, slope overestimation dropped to about one-third of its value at 1 eye-height. These findings nicely explain why we do not make mistakes when handling sloped objects within our reach as long as we can use both eyes. The strength of the illusion does, however, extend into action space, which would explain why it is often so hard to judge the slope of a fairway accurately when playing golf.

General discussion

In the current work, we advance what is known about slant perception in at least the following two ways. First, we performed a real-world investigation that extends prior work in systematically testing how distance influences slant estimation (cf. Bridgeman & Hoover, 2008, and Li & Durgin, 2010). With normal standing eye height, even at close range (2 m) there is a considerable overestimation of slope. The overestimation of slope continues to grow with increasing distance until about 40 m distance and remains high after that. There is a marked difference of what others have found within personal space (Durgin et al., 2009, Durgin, Li, & Hajnal 2010; see Fig. 1), which equates to around 2–12 degrees of overestimation in slant, to what we found at 2 m (~20 degrees [15 degrees] to ~ 25 degrees [45 degrees] overestimation in slant). While there are apparent "breaks" between 8 m and 36 m where overestimates jump to extremes of 30 degrees (~15 degrees) up to 35 degrees (45 degrees) that coincide with the division of personal and action space, it is difficult to conclude whether these are "breaks" in perception, or would follow smooth curves because we sampled no distances in-between (Bridgeman & Hoover, 2008; Li & Durgin, 2010). However, there does appear to be a different pattern that emerges from 36 m to 128 m (from the division of action space to vista space) from the logarithmic one shown from 2 m to 36 m (from the divisions of personal to action space). This is consistent with Bridgeman and Hoover's (2008) neural coding between near and far space theory. However, we cannot be sure that what we found here (Experiment 2) would also be found with real hills for three reasons. First, stereoscopic information becomes unavailable sooner for small objects like the ramp we used at shorter distances than would a real hill because of its length. Second, we used slants of 30 degrees and 45 degrees, which correspond to really steep hills. Typically in this line of work, hills between 5 degrees and 30 degrees are used (Bridgeman & Hoover, 2008; Li & Durgin, 2010; Proffitt et al., 1995; Bhalla & Proffitt, 1999). Finally, Durgin et al. (2010) found evidence for estimates of 45 degrees and slants in multiples of 10 to somewhat bias observer estimates. Figure 2 seems to show some evidence consistent with this idea, especially at those distances in vista space. The verbal estimates of the 45-degree ramp hover between 80 degrees at 36 m, to 75 degrees at 128 m, while verbal estimates of the 15-degree ramp hover around 45 degrees at all three distances at or outside of vista space.

Second, we have also disentangled eye height or observer position from the effectiveness of stereopsis. While much work has been done concerning the difference between gaze direction and perceived gaze direction (Durgin & Li, 2011), and concerning perceived gaze direction on the perception of slopes (Li & Durgin, 2009), we added the investigation of stereopsis and eye height effects on the perception of slant and attempted to disentangle the two. We have shown that slant perception does indeed depend on the viewing distance of the observer. In general, with stereopsis available for use, eye height had no influence below 50 cm, where slopes are estimated accurately. A loss of stereopsis results in 15-25 degrees' overestimation of slant at eye level. Increasing eye height reduces these overestimations dramatically for both 30-degree and 45-degree slopes. While slant perception breaks down even within personal space (see Durgin et al., 2010), the breakdown is even more dramatic as the situation exits personal space. When viewing photographs of slopes, the observer has—by definition—entered picture space, and overestimation occurs in pictures, no matter from which vantage point they have been taken. Similar but smaller effects can be found by closing one eye. This points to an interaction regarding stereopsis and distance from the slope. When our observers were close to the slope, but lost stereopsis by closing one eye, they overestimated the slope by up to 25 degrees, and when stereopsis was available, the overestimation dropped to ~5 degrees. However, when our observers were in vista space (at 36 m) ostensibly outside the range of stereopsis, the overestimates jumped up to 30 degrees (for the 15-degree slope) and 35 degrees (for the 45-degree slope), respectively. This indicates a more complicated interaction that is outside the scope of this paper, but offers an exciting avenue for future work.

In sum, we have provided evidence of the profound influence of the position of the observer. Slopes are not uniformly overestimated, and depend on both the distance and eye height of the observer. The largest breaks in overestimates depending on the distance of the observer came between personal space and action space, and action space and vista space. This adds to a growing body of work showing that distances from the observer to the slope or from the observer to various distances along the slope affect slant overestimates (Bridgeman & Hoover, 2008; Li & Durgin, 2009).

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