The perceptual experience of slope by foot and by finger

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Keywords: Slope perception, haptic-perception, proprioception, blind

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Abstract

Historically, the bodily senses have often been regarded as impeccable sources of spatial information and as being the teacher of vision. Here it is reported that the haptic perception of slope by means of the foot is greatly exaggerated. The exaggeration is present in verbal as well as proprioceptive judgments. It is shown that this misperception of pedal slope is not caused by calibration to the well-established visual misperception of slope, because it is present in congenitally blind individuals as well. The pedal misperception of slope is contrasted with the perception of slope by dynamic touch with a finger in a force-feedback device. Although slopes feel slightly exaggerated even when explored by finger, they tend to show much less exaggeration than when equivalent slopes are stood upon. The results are discussed in terms of a theory of coding efficiency.

THE PERCEPTUAL EXPERIENCE OF SLOPE BY FOOT AND BY FINGER

A growing body of empirical evidence has shown that the visual perception of surface slant may be distorted both when judged in reference to the direction of gaze (optical slant) and with respect to the ground plane (gravitational slant or geographical slope – Gibson & Cornsweet, 1952). In the present contribution we investigated the perception of gravitational slant, that is, the dihedral angle defined by the horizontal ground plane (perpendicular to gravity) and the plane containing an inclined surface. Whereas prior research has focused primarily on visually perceived slope (Bhalla & Proffit, 1999; Bridgeman & Hoover, 2008; Clark, Smith & Rabe, 1956; Gibson, 1950; Gibson & Cornsweet, 1952; Gruber & Clark, 1956; Knill, 1998; Perrone, 1982; Proffitt, Bhalla, Gossweiler & Midgett, 1995; Ross, 1974), we examined the haptic perception of surface slope by foot and by finger. We will show that the perceived slant of a slope on which one stands is greatly exaggerated, whereas the exploration of a slope by a finger allows for relatively accurate verbal estimation among the sighted.

The notion that the bodily senses are somehow infallible has a long history. How could one be wrong about one's own body? But being right about the body really means being right about action, not perception. When we walk on a surface our steps need to properly make contact with the surface and carry us forward, but our perceptions about surface orientation need not be accurate to accomplish this. We could feel like we are walking on a 30-deg slope, act in a way that we think is suited to a 30-deg slope and nonetheless our actions can be successful (on, say, a 10-deg slope) if they are guided by a proprioceptive experience in the relevant effector that is distorted in a manner corresponding to our haptic experience.

Moreover, the perceptual coding space that we use to guide our actions can satisfy cognitive constraints of being maximally informative without needing to be accurate. For example, Durgin and Gigone (2007) demonstrated that the misperception of optic flow speed while walking served to improve visual discrimination of deviations from expected walking speed. That is, the perceived rate of optic flow during self-motion is substantially reduced in a manner that appears to approximate a subtractive shift consistent with sensory recoding (Durgin, Gigone & Scott, 2005). Durgin and Gigone argued that the recoding of sensory variables can facilitate discrimination performance, which is critical for action, by fitting the perceptual coding space to the expected values of input. During walking, the amount of optic flow expected is quite predictable and the neural coding of optic flow can therefore take advantage of this predictability by contingently tuning its coding space to the expected range of optic flow speed values (Durgin, 2009).

In the present paper we will show that the perceptual coding of geographical slope by means of pedal contact appears to be grossly distorted. For the range of slopes that are typically encountered in the terrestrial environment, which is rather small, our perceptual experience is quite exaggerated. We will show that this surprising distortion in haptic perception can be measured both by verbal estimates and by proprioceptive estimates made by the hand. This kind of perceptual exaggeration is consistent with perceptual recoding theory, the idea that perceptual systems can enhance their effective sensitivity by expanding certain parts of their coding spaces. The expansion is accomplished for the purpose of coordinating actions with increased precision. Devoting one's coding space to the range of probable slopes should serve to maximize perceptual sensitivity to variations in ground-surface slope, thereby facilitating effective action. We emphasize that this kind of perceptual distortion is completely benign insofar as motor actions can be guided by relative measures rather than absolute spatial representations. We take the position that the control of action is really the predictive control of perceptions (Durgin, 2009; see also Hommel, Müsseler, Aschersleben & Prinz, 2001; Powers, 1973; Prinz, 1997). Motor calibration for taking a successful step on a ramp can be reduced to being able to predict the perceptual consequence of the application of forces. So long as perceptual prediction works (perceptual consequences match expectation), action is effective, even though the scaling of perceptual variables can be quite exaggerated.

Even when action is inaccurate, the perceptual information available to make adjustments is, in theory, enhanced by the recoding. A simple analogy is the utility of magnification to a watchmaker: the perceived sizes of the objects viewed through a magnifying glass as well as the magnitude of the watchmaker's actions are all exaggerated, but this allows for more exact manual control. If the watchmaker intends to install a gear on a shaft and "misses", the visual feedback he receives will help him to improve his aim on the second shot. Thus, our recoding theory is compatible with the idea that perception is sensitive to the affordances of surfaces (e.g., Kinsella-Shaw, Shaw & Turvey, 1992). The goal of perceptual recoding is to maximize perceptual sensitivity in the expected range. We propose that perceptual recoding is a general mechanism of perceptual systems that improves motor control and calibration. An increase in the resolution of the perceptual range (be it visual, proprioceptive or haptic) makes the mapping between perception and action dense, thus improving motor output, and providing more reliable and more specific sensori-motor feedback.

The Pedal Perception of Surface Slope

In the experiments we will report, perceivers had the opportunity to haptically (pedally) experience slope as they were stepping onto and standing on various inclines. Our general procedure was to have people step onto and stand on a sturdy ramp that they did not see and let them provide verbal or proprioceptive estimates of the slope of the ramp. We used a small range of slopes (4-16 deg) in order to avoid the risk that our participants would lose their balance. (Note that the famously steep Lombard Street in San Francisco is a 15 deg slope, so our range, although it sounds low, extends into the range of psychologically steep surfaces). We first describe the general method and then describe three specific experiments we conducted on the pedal perception of slope.

General Methods

Participants

A total of 75 undergraduate sighted students from Swarthmore College participated for course credit or a payment of $5. An additional group of 8 blind individuals from the Philadelphia area (including one Swarthmore College student) also participated for pay (age range 16-59). There were 50 students (25 in each condition) in the first experiment, 25 in the second experiment, and eight (blind) participants in the third. Experimental procedures in these and all subsequent experiments reported in the paper were approved by the local research ethics committee. Participants (or their parent, as required in one case) gave informed consent before the study began.

Materials and equipment

Two large unpainted beechwood-veneer plywood surfaces (19 mm thick, one measuring 243.8 x 96.5 cm, the other 209.6 x 96.5 cm) served as ramps. The long sides of both ramps were reinforced with wooden beams to prevent bending of the plywood. The ramps could be propped up at one end on one of three steps. A total of seven different inclinations (4, 6, 8, 10, 12, 14, and 16 degrees) were produced by the combination of ramps, steps, and two sturdy step-risers made out of wood. The experimental situations are schematically depicted in Figure 1.

During visual estimation of the ramp two black felt curtains were used to isolate the ramp from the surroundings. One of the felt curtains hung vertically at the side of the ramp. The back curtain hung down roughly vertically, but was crumpled at the bottom and made irregular in appearance where it contacted the upper surface of the ramp so as to avoid forming a dihedral angle.

General Procedure

Sighted participants were greeted in an antechamber near the experimental set-up. After receiving instruction and filling out informed consent, participants were led to the base of each test slope without vision. After stepping up onto the ramp and making their judgment of its slope, participants were led back to the antechamber to wait while the experimenter prepared the next ramp. After all seven ramps had been judged, a final ramp was sometimes placed in position for a single visual judgment of ramp orientation.

General Design

Two sub-sets of the seven slopes were presented in blocked random order. Thus, the slopes of 4, 8, 12, and 16 deg (created with the longer ramp) and the slopes of 6, 10, and 14 deg (created with the shorter ramp) were each presented as a block. In experiments in which head orientation was manipulated, first head orientation (down or forward) was crossed with first angle set.

Experiment 1: Verbal and proprioceptive judgments of pedal slope while blindfolded

In this experiment, 50 participants wore a blindfold (Sharper Image sleep mask) throughout, except for a final visual trial for half of them. Twenty-five participants gave verbal judgments of the slopes of seven inclines while standing on them. The other 25 held out their hand so as to match, priopprioceptively, the seven slopes on which they stood. They were instructed to position the palm of their hand so that it was parallel with the ramp on which they stood. A digital camera placed on a tripod aligned in front of the chest was used to record hand position on each trial in the proprioceptive response group. One set of (3 or 4) inclines was judged while the head was held forward. The other set (4 or 3) was judged while the head was held downward. We manipulated head orientation because we wanted to compare haptic estimates with visual ones, but visual estimates required lowering the head to look at the ramp. Initial head orientation and initial slope set were crossed factors.

After the seven pedal estimates were completed, participants in the verbal condition stood at the base of (but not on) one of the slopes (either 6, 10, or 16 deg), inspected it visually (necessarily looking down), and gave a single verbal judgment concerning its apparent slope.

Proprioceptive data analysis

We measured the orientation of participants' hands from digital photographs using a technique similar to that employed by Bridgeman and Hoover (2008), though developed independently. The calculation of hand angle from digital images was accomplished by drawing a straight line from the base of the little finger to the end of the palm near the wrist. A photograph of the hand resting on a horizontal palm board was used to define this line relative to the palm itself. The measured orientation of the line with respect to the gravitational vertical in each photograph was calculated relative to a doorframe visible in the photographs. Because the camera was positioned only about 1 m from the gesturing hand, and the hand was typically slightly above the midline of the image, projective image distortions could tend to slightly reduce the apparent angle of the hand.

Results and Discussion

Pedal perception. Average slope estimates for pedal slopes are shown in Figure 2. Verbal judgments were approximately twice the magnitude of the actual incline (linear fit: $y = 2.40x - 3.88$, $r^2 = .989$, power fit: $y = 1.28x^{1.19}$, $r^2 = .991$). Proprioceptive judgments had about the same gain, but were elevated relative to the verbal judgments (linear fit: $y = 2.32x + 2.41$, $r^2 = .978$, power fit: $y = 3.60x^{0.856}$, $r^2 = .974$). A hierarchical mixed models analysis found no evidence that head orientation had any effect on perceived slope either within or between subjects, and neither on the raw data, nor on data transformed into ratios to true angles. However, the analyses did confirm that proprioceptive judgments were higher than verbal judgments: A mixed model including judgment type fit the data better than one that did not, $X^2(1) = 6.38$, $p = .0116$. The model estimate of the effect was 5.3 deg (95% C.I.: 1.0 to 9.3 deg).

The close correspondence between proprioceptive and verbal judgments (by different participants) is striking. It clearly suggests that manual proprioception is not calibrated to pedal experience. Indeed, the small discrepancy between verbal and proprioceptive estimates might be caused by participants construing their hands as a uniformly thick surface – whereas the back of a typical hand is sloped by about 13 deg relative to the palm. The difference between verbal and proprioceptive measures could therefore reflect a 6.5 deg difference between the interior central plane that the participants may have intended as "their hand", and the (steeper) surface of their palm. It is in any case clear that the perceived orientation of the ramps is greatly exaggerated as measured by either report method.

Visual perception. The verbal estimates of visual slope are shown in comparison to the verbal estimates of haptic slope by the same participants in Figure 3 (upper panel). For the highest physical slope (16 deg) the mean visually-based estimate (22.1 deg, *SD* = 8.08) was lower than the felt slope (34.9 deg, *SD* = 12.7), $t(32) = 2.81$, $p = .0084$. This comparison is not ideal because order was not counterbalanced across participants; however, very similar values have been obtained by our lab in a follow-up experiment in which estimates were made based on vision first (Durgin, Baird, Greenburg, Russell, Shaughnessy & Waymouth, 2009). The estimates based on vision are somewhat lower than are typically reported for large scale hills, but this is consistent with the observation of Bridgeman and Hoover (2008) that very near portions of slopes appear shallower than farther portions.

Experiment 2: Pedal perception of slope with non-informative vision.

People do not normally stand on slopes with their eyes closed, and visual information is normally used to stabilize posture while standing. We sought to ensure that the high pedal slope estimates obtained with blindfolds were not caused by wearing the blindfolds. To accomplish this, we next collected verbal judgments of pedal slope from participants who wore a lightweight collar (see lower left panel of Figure 1) that occluded the slope they stood on, but allowed them visual experience of their immediate surroundings. For these participants, the ramps were surrounded on one side by a wall, and on the other two sides by black felt curtains, providing a small space for controlling sway without providing much information about vertical motion. This was to discourage participants from attempting to monitor their vertical motion as they stepped onto the ramp. The procedure was similar to that of Experiment 1 except that gaze was always forward. Again, a single verbal judgment was collected at the end for one of three slopes presented visually.

Results

Verbal estimates while wearing a collar were, if anything, more exaggerated than those while blindfolded (linear fit: $y = 2.90x – 4.74$, $r^2 = .969$, power fit: $y = 1.17x^{1.30}$, $r^2 = .983$). These data are also shown in Figure 2. Because the collar was supported by holding the hands forward, it is possible that the increase in pedal slope perception was due to the postural effects of holding the collar. In any case, it is clear that the results of Experiment 1 were not due to fear or instability induced by being blindfolded and that the misperception of pedal slope is not limited to conditions where the eyes are closed.

Similarly, the single verbal estimates of the visually observed slopes showed again that the steepest physical slope of 16 degrees looked less steep (*M* = 24.3 deg, *SD* = 11.2) than it had felt (*M* = 39.5 deg, *SD* = 14.1), $t(32) = 2.92$, $p = .0064$, as shown in the lower panel of Figure 3.

Experiment 3: Pedal perception of slope by blind observers

Is pedal slope perception exaggerated because of being associated with the well-established visual overestimation of slope? That is, if we commonly walk on hills that visually appear very steep to us, is it our eyes that have trained our feet how to perceive? One simple way to test this is to measure pedal slope perception in people who have never had visual experiences of slopes. To this end we recruited eight blind participants in the Philadelphia area, including a Swarthmore student. Four (2 male, 2 female) of our participants were early blind, having had no meaningful visual experience since the second year of life. Another four (2 male, 2 female) had been without geographical visual experience for at least ten years.

The procedure was the same as in Experiment 1. We first ensured that our participants understood verbal angle units by asking them to hold their arm at 45 degrees. None had any trouble understanding this task. All of them had been educated in basic trigonometry; two of them had been math majors in college. Each participant completed 7 pedal trials using verbal responses.

Results

The data for each participant, coded by onset of blindness (early or late), are shown in Figure 4, along with the overall means. There were no meaningful differences between the data of the early blind and late blind observers. As a group, our blind participants showed slightly more overestimation in pedal slope perception than our sighted observers had when blindfolded (linear fit: $y = 3.21x – 2.74$, $r^2 = .960$, power fit: $y = 1.96x^{1.17}$, $r^2 = .976$). We again used hierarchical mixed models, combining the verbal data from Experiment 1 with the data from blind participants to determine whether a model that took visual experience into account would be a better fit than one that did not. Indeed it was, $X^2(1) = 9.23$, $p = 0.0024$. The model estimate was that slopes were judged by the blind to be 9.3 degrees steeper on average (95% C.I.: 3.5 to 15.2 degrees). The mean regression slope computed for the seven judgments of each blind participant (3.2) was marginally greater than mean regression slope for the participants in the verbal condition of Experiment 1 (2.4), $t(31) = 2.01$, $p = .0528$. Because our blind population differed from our sighted population in more than just vision (e.g., age), we are reluctant to make strong claims about this difference. Our main question was whether the overestimation of pedal slope arose from calibration to visual experience. We think that question has been settled: pedal overestimation is not caused by visual experience, though it may actually be reduced somewhat by it.

The Digital (by Finger) Perception of Surface Slope

The experiments above concerned estimation of surface orientation based on stepping onto and then standing on a ramp. In our pedal experiments, the range of slopes used was necessarily small for safety purposes, and the dynamic experience of the slopes was limited to a step or two. Although proprioceptive measures appeared to be in substantial agreement with verbal reports, we worried that some intrinsic bias in the judgments of slope might be affecting verbal reports. We therefore sought to determine whether a different kind of haptic perception might be more accurate. We chose, specifically, to study the perception of slope by means of dynamic exploration with a finger.

Unlike the foot, a finger is unconstrained in the orientations it can explore. Moreover, whereas coordination of finger movements often involves visual perception of the finger, coordination of the feet, during locomotion, for example, typically does not entail vision of the feet (Patla & Vickers, 1997, 2003). Finally, the perception of surface orientation by finger does not require a representation of the orientation of the finger itself, but only of the set of points of contact that the surface affords. Because, at least for sighted individuals, the perception of finger location is likely to be well-calibrated to near visual space, this form of haptic exploration might be expected to be fairly accurate. On the other hand, if errors in verbal estimation of pedal slope are due to vagaries of verbal coding, then we would expect to see them in digitally-explored slope as well.

To control the information available to participants, the slopes were entirely virtual. They were experienced using a force-feedback device (Phantom) that allowed the controlled manipulation of orientation information for dynamic exploration. Such a device carries the fingertip in a small thimble that is made free to move into all parts of space except those specified by a virtual surface. Thus, a person using a Phantom can explore the orientation of a surface by moving along it smoothly, but is limited to a single point of contact at any one time (see Figure 5).

In Experiment 4 we tested a full range of slopes from horizontal to vertical. In Experiment 5 we examined the consequences of using a highly compressed range of slopes as stimuli, for comparison with the pedal experiments. Finally, in Experiment 6 we tested both sighted and blind observers with an intermediate range of slopes and additionally introduced a proprioceptive estimation procedure ("drawing" the slope in the air with the fingertip) to supplement the verbal reports.

Experiment 4. The perception of slope by finger

How accurate is the verbal estimation of slope perceived by finger? To test this we had naïve participants give verbal estimates of virtual haptic slopes in the range from 0 (horizontal) to 90 deg (vertical).

Methods

Participants. Eighteen students participated for payment. None had prior experience with the Phantom.

Apparatus. A robotic arm with force feedback (Phantom Premium; Sensable Technologies, Woburn, MA, USA) was used to present the virtual surfaces. A person is depicted interacting with the device in Figure 5. The arm was controlled by custom software using the OpenHaptic libraries. The robot arm works by cradling the (index) finger in a plastic thimble that serves as the interface point. It simulates a surface by applying appropriate forces to the thimble whenever it is moved into proximity to the virtual surface. The impression provided is that one is touching a solid surface with the thimble. The forces that the finger experiences are consistent with those it would experience in contact with a real surface. For example, the movement trajectory is constrained by forces normal to the (virtual) surface orientation. We note that the task is to perceive slope, not to memorize a trajectory. It would be so if the Phantom constrained finger movement to a single line of movement (a “trajectory”), but this was not the case. Our situation is equivalent to someone exploring a real surface by finger tip. The orientations of the virtual surfaces were checked by direct measurement.

Design. Sixteen angles from 0 to 90 degrees were presented twice in random order (increments of 6 deg). The surfaces specified in the virtual environment had nominal friction coefficients of 0.1, so that movement along the surface included a small resisting force. The surfaces were rectangular (22 cm wide x 33 cm long) and had walls at the sides and the far edge to prevent people from "falling off" the surface. The height of the center of the surface was varied from trial to trial.

Procedure. Participants were blindfolded and stood approximately 40-50 cm away from the Phantom during the experiment. The base of the Phantom (and of the action space used) was 94 cm above the ground, which was a comfortable height for all participants. The right index finger was placed into the thimble attached to the robot arm, and snugly fit by a thin rubber band wrapped around the outer rim of the thimble. The function of the Phantom was illustrated for participants prior to the presentation of the virtual slopes. On each trial, participants could explore the sloped virtual surface for as long as they wished. They were required to give a verbal estimate of the slope of the virtual surface to the nearest degree. Participants lifted their fingers between trials and lowered them to feel the next surface.

Results and Discussion

Average estimates were computed for each slope for each participant. The means and standard errors of these estimates are plotted by slope in Figure 6 (linear fit: $y = .98x + 6.33$, $r^2 = .992$). It is evident that there is a persistent overestimation by about 6 degrees for most of the range of tested slopes, with the exception that the estimates tended to reach a ceiling at 90 degrees. Linear fits to individual participant's data had an average intercept of 6.4 (SD = 10.7), average slope of 0.98 (SD = 0.14), and an average r^2 of 0.94 (SD = 0.04). Average deviation scores were used to assess accuracy. Participants overestimated slopes reliably (M = 5.4 deg, SD = 6.2), $t(17) = 3.656$, $p = .002$. Evidently the perception of slope by dynamic touch is fairly accurate compared to the perception by virtue of standing on a surface. The relatively accurate performance also supports the notion that our participant population is skilled with verbal judgments of angle.

Experiment 5. Control for small range of angles in the perception of slope by dynamic touch

Although the verbal estimates from dynamic touch in Experiment 4 were clearly more accurate than the verbal estimates from pedal contact, they may have been constrained by the larger range of angles given. The present experiment sought to test haptic slope perception by dynamic touch using the same range of angles as in the pedal experiments.

Methods

Participants. Fourteen students participated for course credit. None had prior experience with the Phantom.

Design and procedure. The seven (even) angles from 4 to 16 degrees were presented in split-blocked order, as in Experiments 1-3. The apparatus and procedure was as in Experiment 4 except that participants explored a horizontal surface first on each trial. This was intended to represent the pedal experience of the floor prior to each trial in the pedal experiments. Participants then lifted their fingers and lowered them to feel the sloped surface (the horizontal surface was replaced by the sloped surface). As in the pedal experiments, only one trial of each slope was presented.

Results and Discussion

The means and standard errors of the slope estimates are plotted by slope in Figure 7 (linear fit: $y = 1.40x + 1.17$, $r^2 = .876$, power fit: $y = 1.99x^{0.88}$, $r^2 = .863$), along with the regression fit to the dynamic touch data from Experiment 4. Again, average deviation scores were used to assess accuracy. Participants overestimated slopes reliably ($M = 5.2$ deg, $SD = 8.1$), $t(13) = 2.411$, $p = .03$. It is evident that performance in Experiment 4 did not depend on the larger range of slopes used. Even when a very small range of angles was presented, participants' responses were about the same as when a much larger range was presented (no difference was detected in deviation scores between Experiment 4 and 5, $t < 1$).

Experiment 6: Dynamic touch slope estimates by the blind and the sighted

We have shown that, for the sighted, dynamic touch by finger provides a more accurate representation of slope than does pedal contact. One reason we have suggested for this is that sighted participants have opportunity to calibrate dynamic touch with vision in near space. That is, it may be that dynamic touch is not intrinsically accurate, but that the finger, unlike the foot, is typically in view for the sighted and becomes calibrated to near visual space.

In this experiment we tested both blind and sighted participants to test whether blind participants would show similar calibration to sighted participants. We used an intermediate range of slopes. In addition to verbal reports we had participants provide a proprioceptive slope estimate that consisted of drawing the slope in the air. Even if haptic slope perception were perceptually distorted in near space, we expected that action with the same effector would be calibrated to itself.

Methods

Participants. Six blind individuals from among those tested in Experiment 3 participated. Three of these were early blind (2 male, 1 female), and three were late blind (1 male, 2 female). Eight sighted individuals who were college students also participated (2 males, 6 females).

Apparatus. The apparatus was the same as that used in Experiments 4 and 5.

Stimuli. Nine angles from 4 to 36 deg were used for verbal estimation. Ten angles from 4 to 40 degrees were used for the drawing task.

Design. In the first part of the experiment participants provided verbal estimates of the surface orientation obtained by exploring it with their finger. Nine orientations were presented in random order. In the second part of the experiment, participants were asked to trace the remembered orientation of each slope in the air. That is, after exploring the slope to their satisfaction, they lifted their hand and then lowered it to a new (horizontal) surface (varied in position from trial to trial) that indicated the starting point of their drawing. Participants then “drew” in the air with their finger while the robot arm recorded their movements. The robot arm offered essentially no resistance. Two blocks of ten randomized trials were completed in this part. Because of equipment problems, one late-blind female was unable to complete this part of the experiment.

Procedure. Sighted participants were blindfolded; three legally blind participants who had some light perception were asked to close their eyes, whereas three participants who had no vision were not required to close their eyes or wear a blindfold. An upright posture was assumed on all trials. On each trial a virtual rigid surface was generated that represented a frontally sloped flat rectangular plane as in Experiments 4 and 5.

Participants were allowed to explore the surface any way they wished, but were told that the most efficient way to estimate the slope was to move their finger backwards and forwards a few times along the surface. On each trial they were requested to express the felt inclination of the virtual surface verbally, in degrees. No horizontal reference surface was provided during the verbal task. Participants made nine verbal judgments, one for each virtually generated physical pitch angle of the surface. There was a short two-minute break between the verbal slope estimation task and the finger tracing task. Another optional break was offered to participants halfway through the finger tracing task.

The perceptual part of the finger-tracing task was similar to the verbal estimation task in that exploration of the slanted surface was done by moving the finger backwards and forwards along the surface for at least 4 seconds. After exploring the virtual slope with the finger, participants were told to lift their finger up until a beep was heard, and then lower their finger down again until they touched a virtual horizontal surface, which was varied in its vertical position from trial to trial either well below or well above the original location of the stimulus slope. The height of where drawing was to be initiated was varied for two reasons. First, we wanted to discourage efforts to reproduce the slope by pure motor memory. Second, we were interested in whether slope productions would have egocentric radial biases, as has been found for perceived haptic parallelism in the horizontal plane (Kappers & Koenderink, 1999). Such radial biases in the sagital plane would predict that when starting from a higher position, drawn slopes would be steeper. The horizontal surface disappeared once the finger left contact with it so that “drawing” proceeded without further feedback. A few participants chose to explore the horizontal surface before drawing, as if seeking to establish a relative reference. Finger movements were recorded by the Phantom device at 1000 Hz with sub-mm precision and stored on a computer for later analysis. No feedback concerning accuracy was provided in either task.

Data reduction. Finger tracings in free air were processed by linear regression. In order to get a numeric estimate of the traced pitch angle, analysis was restricted to projections onto the sagittal plane. The two-dimensional movement data were fitted by a regression line. Often this line was based on a subset of the movement data (because not all motions were drawing motions), but always included the first forward sweep of the finger. The slope of the regression line, converted into degrees, served as the slope response on any given trial. The drawing data from some trials (8%) was un-interpretable.

Results

The results of both the verbal estimation and the proprioceptive drawing tasks are summarized in Figure 8.

Verbal judgments. The verbal judgments of blind participants showed evidence of accelerated exaggeration (linear fit: $y = 1.73x + 1.44$, $r^2 = .931$, power fit: $y = 2.64x^{0.87}$, $r^2 = .902$), with an average slope of 1.73, which was reliably different from 1, $t(5) = 3.91$, p

= .0113. The mean slope of sighted participants (1.18), as in Experiments 4 and 5, did not differ from 1, $t(7) < 1$ (linear fit: $y = 1.18x + 1.17$, $r^2 = .961$, power fit: $y = 2.28x^{0.80}$, $r^2 = .940$). The mean regression slope of the blind (1.73) was marginally higher than that of the sighted, $t(12) = 2.05$, $p = .063$. It thus appears that orientation perception from dynamic touch of blind participants is not as well calibrated to Euclidean space as that of our sighted participants. Although we cannot rule out the possibility that other differences between the groups (e.g., age) may account for this difference, it is consistent with our hypothesis that visual experience may help to calibrate the haptic perception of near visual space.

Proprioceptive responses. Mean proprioceptive (drawing) responses are shown for sighted and for blind participants in the right panel of Figure 8. The gain of these proprioceptive measures tended to be low, such that the overall regression slopes for both blind (0.89) and sighted (0.79) participants were numerically less than 1, while the intercepts were high (4.4 and 10.7 deg, respectively). Given the high intercepts, linear deviation scores were computed for each trial and average deviation scores were used to assess the presence of bias in the drawing measures. Whereas sighted participants had shown no evidence of bias in their verbal responses, their drawings overestimated slopes reliably (M = 5.9 deg), $t(7) = 2.937$, $p = .0218$. The mean deviation for blind participants was only 1.3 deg, which did not differ reliably from 0, $t < 1$, nor, however, did it differ reliably from the sighted mean, $t(10) = 1.45$, $p = 0.178$.

A hierarchical mixed models analysis, which is robust to missing data, also failed to show that blind and sighted proprioceptive means differed overall. That is, including Vision in the mixed-model, along with drawing Height and slope Angle, did not reliably improve the fit, $X^2(1) = 2.23$, $p = 0.135$. However, the mixed models analysis was able to detect an effect of drawing Height that interacted with Vision, $X^2(2) = 6.571$, $p = .0374$, so we looked for effects of Height separately in the two groups of participants. There was no reliable influence of Height in mixed-models of the drawings of the sighted, $X^2(1) = 2.32$, $p = .128$, but a mixed-models analysis of the data from the blind participants showed that including Height in the analysis improved the fit significantly, $X^2(1) = 12.87$, $p = .0003$. The model estimate of the Height effect for the blind participants was that proprioceptive drawings were 8.4 deg lower when drawn at the higher position (95% C.I. 3.2-11.2 deg). On the one hand, the direction of this effect is a bit surprising because other work on perceived parallelism in blind participants suggests that parallelism is perceived when orientations radiate outward (e.g., Kappers, 1999). If this pattern had been reproduced in the sagittal plane, drawings from the lower starting height should have a lower slope than those from the upper starting point. On the other hand, if blind participants were biased by absolute position memory for the location of the top part of the original stimulus slope (i.e., the endpoint of their drawing motion was pulled toward an absolute position memory), then their drawing would be biased in the manner found.

Discussion

Whereas sighted participants demonstrated fairly accurate calibration both with respect to verbal and proprioceptive estimates, blind participants verbally overestimated virtual slopes explored by finger. We have suggested that the natural haptic calibration of space need not be accurate to be useful. Blind participants drew with reasonable accuracy the same slopes that they overestimated verbally. Having perceived a slope of 30 deg to be 50 deg, blind participants may have drawn a 30-degree path intending and believing it also to be 50 degrees. There is no paradox in this. Indeed, it would be stranger if they had been unable to reproduce, proprioceptively, what they had felt haptically. Our argument is that during the reproduction, as during the initial exploration, their *perception* of the slope of the trajectory of their finger was overestimated. The idea that actions can be misperceived while also being effective (accurate with respect to presented stimuli) is a central theme of our paper. The performance of the blind in this experiment is similar to the performance of the sighted walking on ramps in one important aspect: The sighted misperceive the ramp even as they act on it effectively. The close correspondence of haptic and proprioceptive perception in the blind may be the result of using the same body part, namely the finger, for both tasks. Further tests are needed to provide a definitive answer. The calibration of action and perception does not require accurate perception (Durgin, 2009).

Conclusions regarding the haptic perception of slope by finger

In Experiments 4, 5, and 6, verbal estimates of slope by sighted participants were fairly accurate, though slightly elevated. This was true whether the range of angles tested was large or small and whether or not a horizontal reference was provided prior to each trial. Because blind participants showed dramatic exaggerations in their verbal estimates, we suspect that the more Euclidean performance of sighted individuals depended on calibration to their visual experience of near space.

In Experiment 6 we showed that both groups could fairly accurately reproduce felt slopes proprioceptively. The fact that blind individuals could accurately draw a slope that they believed was much steeper than it was provides another demonstration that accurate perception is not necessary for effective action.

Our investigations of haptic perception by finger help clarify that verbal estimates of angles can be fairly accurate and thus help to validate the striking results reported for pedal slope in Experiments 1-3.

General Discussion

We have shown that the haptic perception of the surface orientation of ramps is quite exaggerated in both the sighted and the blind. A ramp of 6 degrees was judged to be about 12 deg, both by haptic contact and later by vision; a ramp of 16 deg was judged to be nearly 40 deg when stood upon, but only 25 deg when viewed directly.

Evidence from verbal measures of ramp inclination was supported in a separate set of participants with a proprioceptive measure (hand orientation) in Experiment 1. Moreover, when the same low range of angles was presented haptically, via the finger/Phantom interface in Experiment 5, verbal judgments were not nearly as exaggerated for the same slopes. Thus, our data clearly show that the pedally-perceived slopes of ramps are quite exaggerated, and that this is not simply an artifact of verbal report or of the range of slopes presented.

There is no obvious cost to misperceiving the orientation of a surface so long as one correctly perceives the actions it affords. All of our surfaces afforded standing. The specific scaling we observed may reflect an efficient use of coding space for normal pedestrian use. Moreover, because the foot can be flexible and adaptive in its orientation as it makes contact with surfaces and because the foot need not be calibrated to vision, the exact scaling is not terribly important. As we have noted before, believing that a surface is inclined at 45 deg and acting as if it is 45 deg will not have any ill consequences so long as the actions taken with respect to the hill end up being appropriate.

In their study of visual slope perception, Proffitt et al. (1995) have also considered the idea that perceptual exaggeration enhances sensitivity for typical low slopes. However, they argued that this was solely for the purposes of long-range planning, not immediate action, and they explicitly attribute the overestimation to properties of visual information (e.g., texture gradients) rather than to a principled coding strategy. Proffitt et al. argued that accurate motor action required the existence of a separate, undistorted perceptual representation to guide action. Coding theory rejects this view.

We think that the fact that congenitally blind and sighted individuals both have an exaggerated sense of the slopes on which they are standing better supports the view that this form of expanded coding is relevant for immediate action rather than merely for planning. Strangely, in response to a recent study (Durgin, Baird et al., 2009) that questioned the generality of his behavioral potential theory, Proffitt (2009) has argued that his theory of behavioral potential does not apply to ramps because they are not a sufficiently extended surface.

In that study we observed that estimates of surface slant when wearing a heavy backpack were not elevated unless participants indicated later that they believed both that (a) the backpack was intended to affect their slope judgments and also (b) that it had affected their judgments (Durgin et al., 2009; see also Russell & Durgin, 2008).

Participants with such beliefs showed elevated verbal estimates of a slope both when they judged slope based on vision and when they judged it based on haptic (pedal) contact. Their awareness of the experimental intent and their expression of cooperation with it render their verbal estimates suspect. Participants who wore the same heavy backpack but were successfully deceived into believing they were carrying monitoring equipment necessary for the experiment gave verbal estimates of slope in both instances that did not differ from those who wore no backpack (Durgin et al., 2009). Crucially, even when participants were standing on the ramp, wearing a heavy backpack did not, in itself, affect their haptic perception of the ramp's orientation.

It is possible that the systematic exaggerations of felt slope we have documented here partly reflect musculo-skeletal potential (physical affordances related to the coordination of bodily action). This would not subvert the value of having an expanded coding space, but it might mean, for example, that slippery slopes, would be judged steeper than frictional ones.. However, the absence of an effect of a heavy burden on haptic slope judgments (Durgin et al., 2009) suggests that the pedal haptic system may be fairly robust in its coding strategies.

Our preferred theory of the pedal exaggeration of slant emphasizes the possibility that the most useful coding of perceived slope depends on the range of slopes with which one interacts. That is, theories of coding efficiency emphasize the idea that neuro-perceptual coding is most efficiently allocated when it is used to code expected deviations from normal. Terrestrial behavioral environments are sculpted in part by gravity; thus the horizontal plane plays a central role. Even if most surfaces are slanted, the direction of slant varies, and thus the average expected orientation is horizontal. The exaggeration of perceived pedal deviations from the horizontal is precisely the kind of coding space expansion that a theory of coding efficiency predicts.

Perceptual coding need not be accurate to be useful. To hit a nail with a hammer can be accomplished even if both the perceived location of the hammer and of the nail are misperceived, so long as they are misperceived in the same way. For perception-action cycles, a perceptual coding system that is more precise (even if wildly inaccurate in Euclidean terms) will be a better system for the control of action than a perceptual coding system which is a slave to accuracy at the price of precision. The magnitude of the deviations from the horizontal are fairly limited in range in our locomotor experience. It is quite rare that we interact on foot with a surface as steep as 15 degrees. The perceptual coding of pedal slope therefore does not suffer by being inaccurate with respect to a Euclidean metric. Moreover, even to the extent that conflicts might arise between differing visual and tactile representations of surface orientation locomotor action is self-correcting. As the ball of the foot lands on the ground surface, any misalignment that occurs during initial contact will be corrected by the compliant motion of the foot. In this way, a stable environment functions as a constraint that is exploited by a precise perception-action system to achieve successful locomotion.

In contrast with the relationship between pedal locomotion and the terrestrial ground plane, the interaction of the finger with the near visual environment provides a basis for coding slopes in a multisensory Euclidean space. Although the finger is also subject to gravity, its typical actions are not limited to contact with surfaces within 15 deg of horizontal. Even among our blind participants the exaggeration of digital slope perception was far less dramatic than the exaggeration of pedal slopes.

Differences we observed between the calibration of blind and sighted participants for slopes experienced by dynamic touch of the finger suggest that vision can play a role in affecting haptic perceptual coding. Even in the blind, however, proprioceptive reproduction of digitally-experienced surfaces by drawing in the air was quite successful. This illustrates the principle that sensory coding need not be calibrated in a traditional sense (i.e., in units of degrees) to successfully guide action. We assume that for purposes of visually coordinated action of the hand in near, reachable space, the entire range of possible motion is well represented.

Our investigations of the haptic perception of surface orientation by foot and by finger have revealed surprising distortions in the perceptual experience of surface orientation in the sighted and in the blind. However, our emphasis has been on the fact that absolute perceptual coding need not be accurate for action to be accurate. In the case of the pedal overestimation of surface inclination our findings are quite compatible with the idea that our coding space for terrestrial slopes experienced by foot is well adapted to making fine perceptual discriminations necessary for evaluating the immediate locomotor affordances of the environment. By magnifying deviations from horizontal in our internal coding of ground surface orientation, we provide a basis for more precise motor control.

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Figure captions

Figure 1. The experimental setup for various conditions in Experiments 1 and 2. Participants were asked to step onto a ramp blindfolded or while holding a lightweight foam board at neck level to occlude the view of their feet and the ramp (lower left). They were either asked to verbally judge how steep the ramp felt or set their right palm parallel with the felt inclination (middle). In the blindfolded conditions participants were asked to orient their head either straight ahead (left top and middle) or downward (right top and middle). Hand orientation was recorded by a digital photo camera (not shown here) approximately 1 m away from the hand. Visual judgments were later made from the base of the ramp (lower right).

Figure 2. Results of Experiments 1 and 2 by condition and angle. The diagonal line indicates perfect correspondence between perceived and actual angles. Data in the blindfolded conditions are collapsed over head orientation. Error bars reflect ±1 standard error.

Figure 3. Visual slope judgments compared with corresponding pedal slope judgments in Experiments 1 (top) and 2 (bottom). Error bars reflect ±1 standard error, n.s. indicates non-significant t-tests with $p > .10$, * indicates significant two-tailed t-tests at $p < .05$.

Figure 4. Results of Experiment 3. Pedal slope perception of blind participants is exaggerated. Individuals are grouped by late (open circle) or early (dark squares) onset of blindness. The overall mean is shown in bold with error bars that reflect ± 1 standard error. The diagonal line at the bottom of the graph is the identity line.

Figure 5. Apparatus for Experiments 4-6. The Phantom robot arm provides the haptic experience of a virtual sloped surface (dashed line) to the finger in the thimble interface.

Figure 6. Results of Experiment 4. Average verbal slope estimates for virtual haptic surfaces explored by finger. Error bars reflect ± 1 standard error.

Figure 7. Results of Experiment 5. Average verbal slope estimates for virtual haptic surfaces explored by finger when the range was matched to the pedal slopes of Expeirments 1-3. The dashed line represents the regression line from the data of Experiment 4, when the full range of angles was presented. Error bars reflect ± 1 standard error.

Figure 8. Results of Experiment 6. Verbal and finger tracing responses of blind (open circles) and sighted participants (filled squares). The diagonal line indicates perfect correspondence between perceived and actual angles. Error bars reflect ±1 standard error.

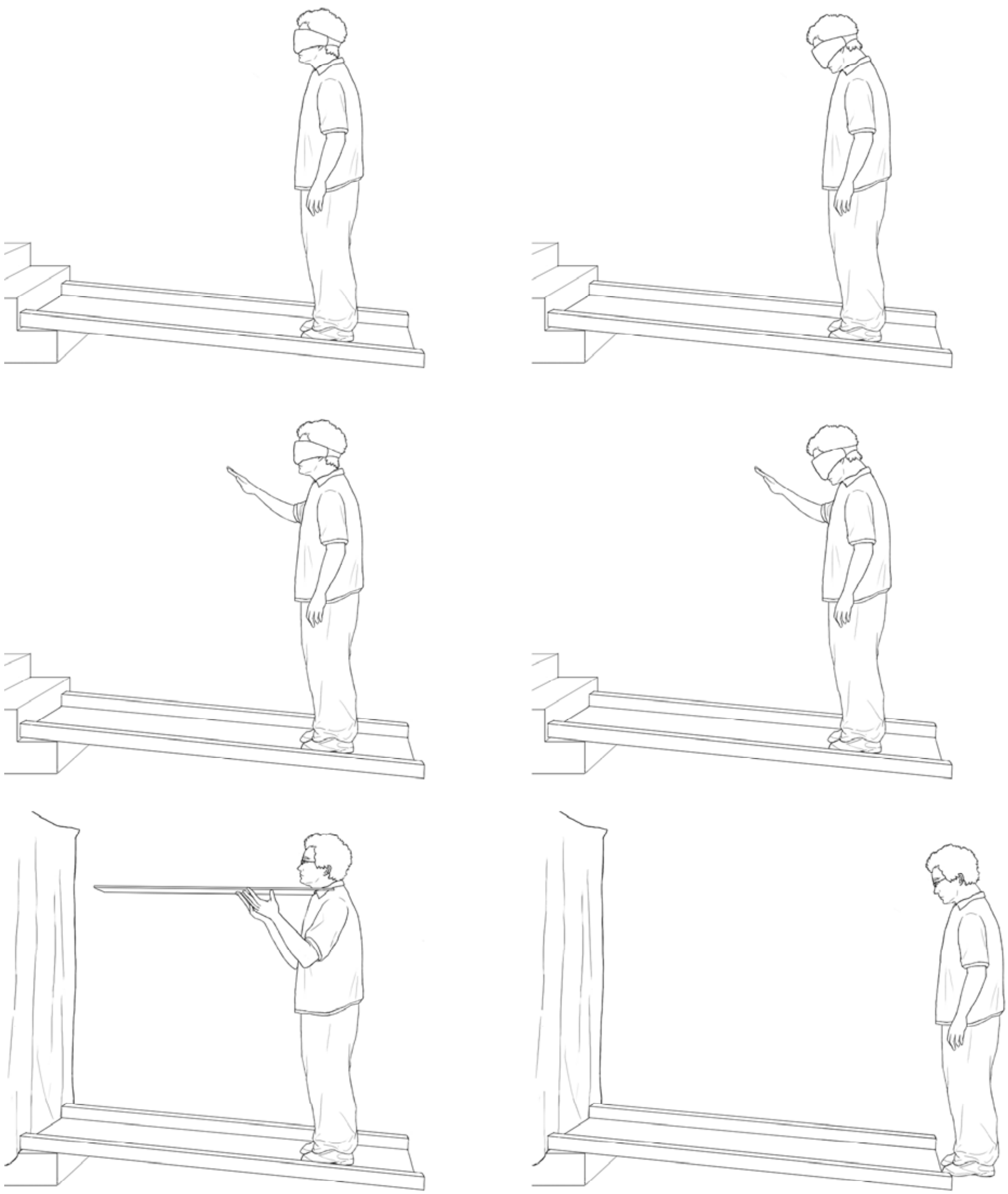


Figure 1

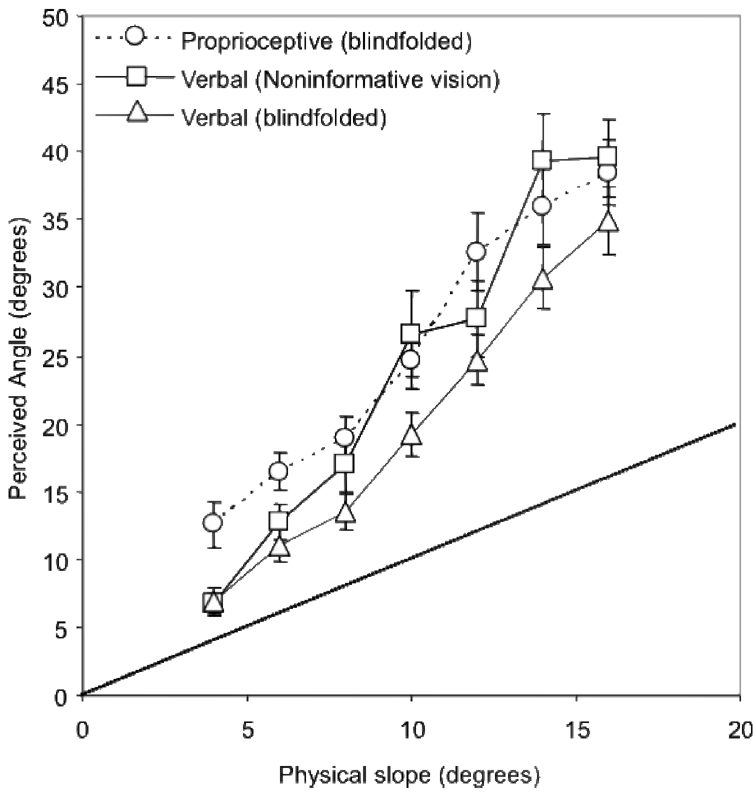

Proprioceptive (blindfolded)
Verbal (Noninformative vision)
Verbal (blindfolded)
Perceived Angle (degrees)
Physical slope (degrees)
0
5
10
15
20
25
30
35
40
45
50
0
5
10
15
20

Figure 2

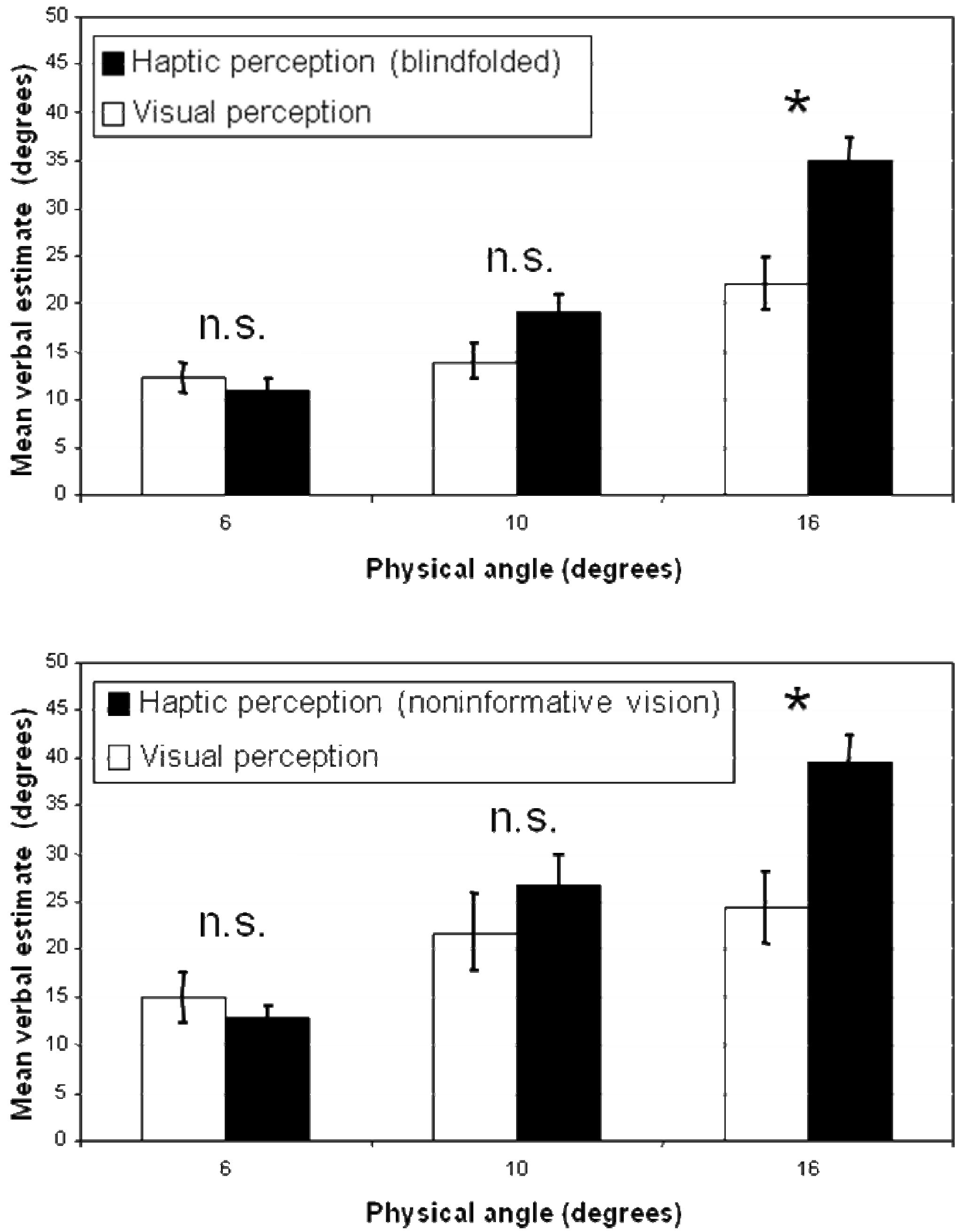
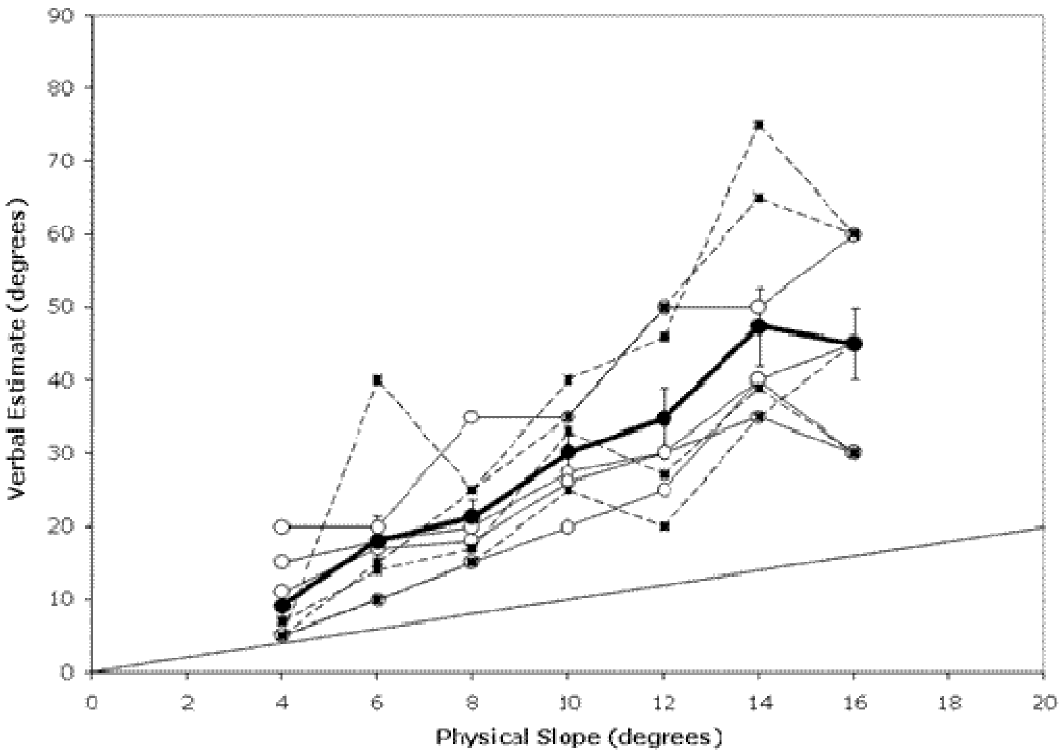

Haptic perception (blindfolded)
Visual perception
n.s.
n.s.
*
Mean verbal estimate (degrees)
Physical angle (degrees)
0
5
10
15
20
25
30
35
40
45
50
6
10
16
Haptic perception (noninformative vision)
Visual perception
n.s.
n.s.
*
Mean verbal estimate (degrees)
Physical angle (degrees)

Figure 3



Verbal Estimate (degrees)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
Physical Slope (degrees)

Figure 4

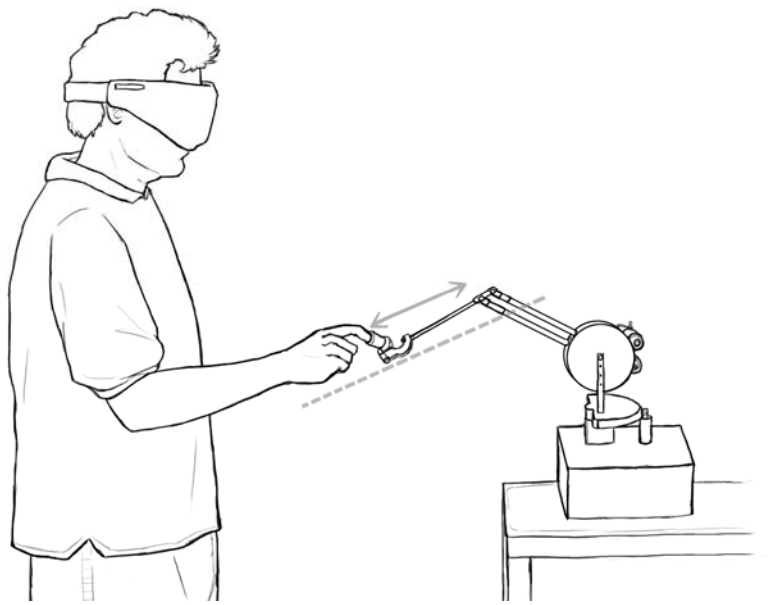


Figure 5

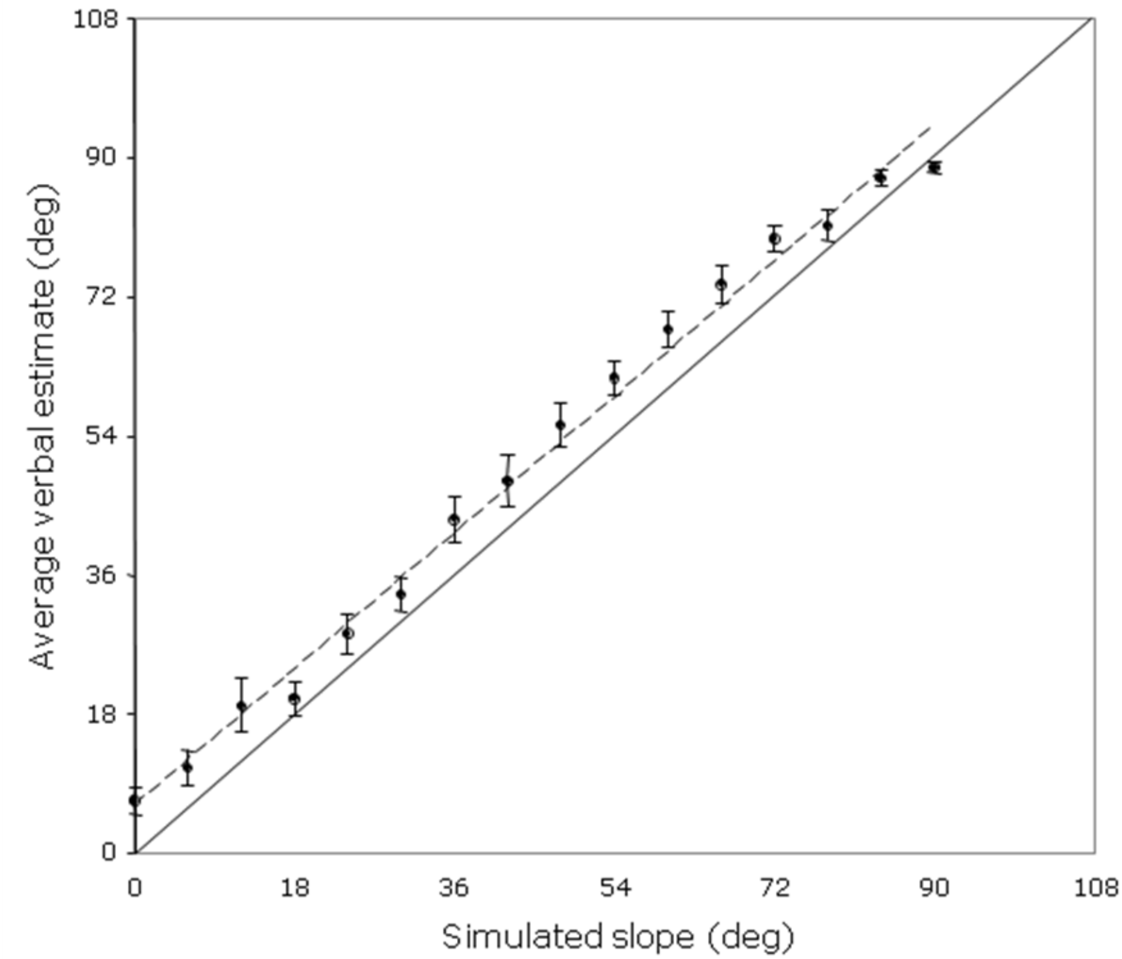

108
90
72
54
36
18
0
0
18
36
54
72
90
108
Average verbal estimate (deg)
Simulated slope (deg)

Figure 6

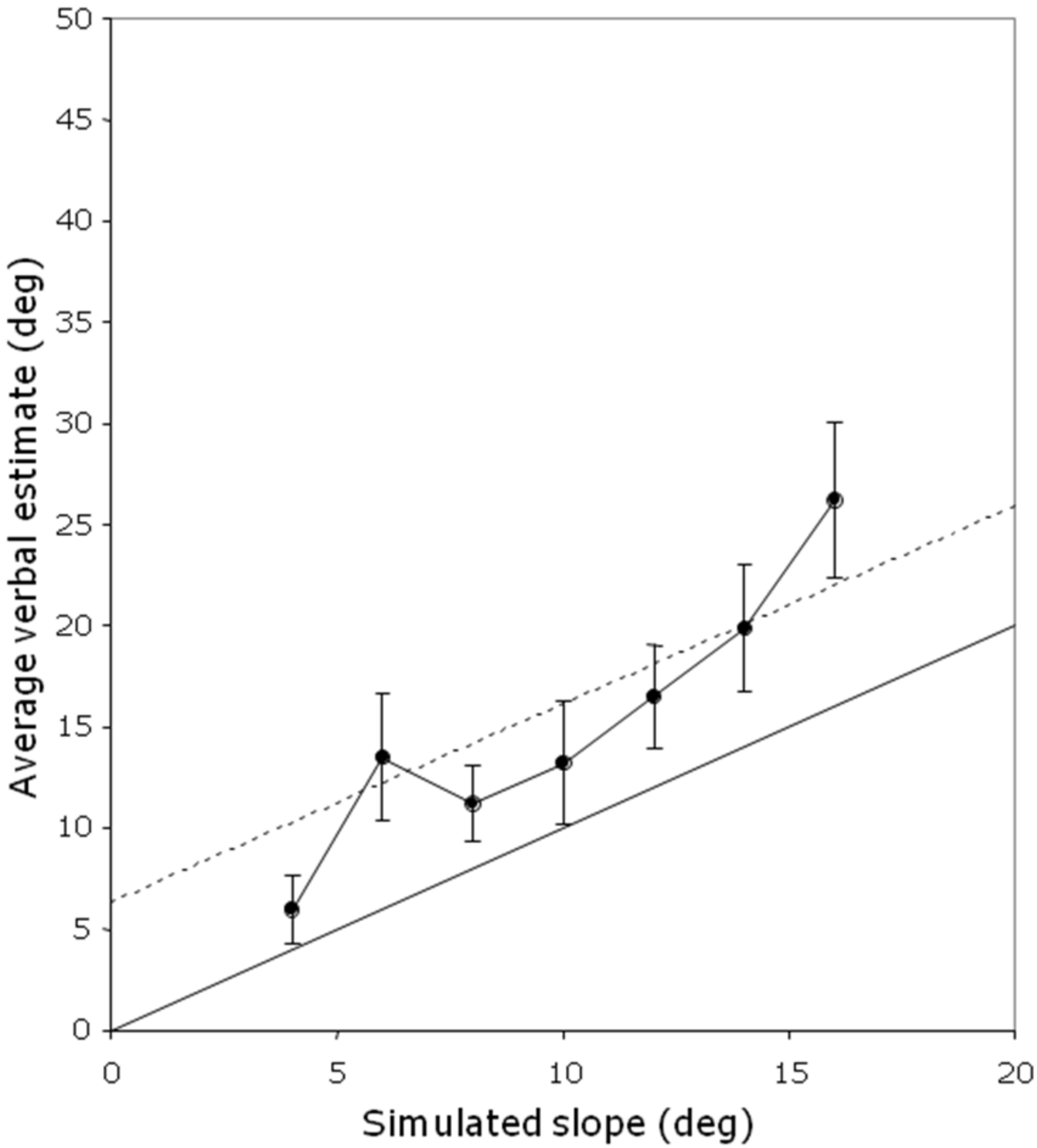

50
45
40
35
30
25
20
15
10
5
0
Average verbal estimate (deg)
0
5
10
15
20
Simulated slope (deg)

Figure 7

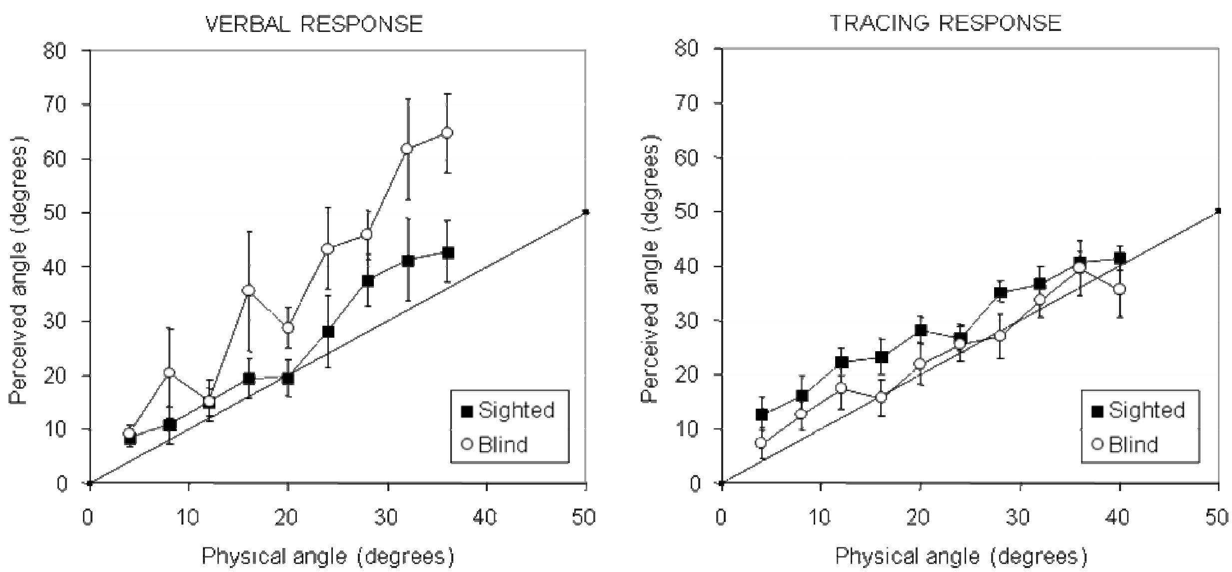

VERBAL RESPONSE
Perceived angle (degrees)
Physical angle (degrees)
Sighted
Blind
TRACING RESPONSE
Perceived angle (degrees)
Physical angle (degrees)
Sighted
Blind

Figure 8