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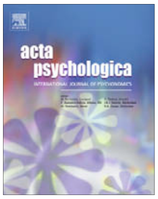

Palm boards are not action measures: An alternative to the two-systems theory of geographical slant perception

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ABSTRACT

Whereas most reports of the perception of outdoor hills demonstrate dramatic overestimation, estimates made by adjusting a palm board are much closer to the true hill orientation. We test the dominant hypothesis that palm board accuracy is related to the need for motor action to be accurately guided and conclude instead that the perceptual experience of palm-board orientation is biased and variable due to poorly calibrated proprioception of wrist flexion. Experiments 1 and 3 show that wrist-flexion palm boards grossly underestimate the orientations of near, reachable surfaces whereas gesturing with a free hand is fairly accurate. Experiment 2 shows that palm board estimates are much lower than free hand estimates for an outdoor hill as well. Experiments 4 shows that wrist flexion is biased and noisy compared to elbow flexion, while Experiment 5 shows that small changes in palm board height produce large changes in palm board estimates. Together, these studies suggest that palm boards are biased and insensitive measures. The existing literature arguing that there are two systems in the perception of geographical slant is re-evaluated, and a new theoretical framework is proposed in which a single exaggerated representation of ground-surface orientation guides both action and perception.

1. Introduction

Does accurate action require accurate (unbiased) perceptual representations? If by accurate action, one means effective action, then the answer is no. Action can be guided by completely biased perceptual experience, so long as that experience is predictable and stable (Durgin, 2009). Consider the actions of a watchmaker looking through a magnifying lens. The sizes of the parts of the watch are clearly distorted by the lens, but *perceived* actions are distorted in the same way. The watchmaker can become quite deft in the use of the magnifier. For a more ballistic action, consider the spear fisherman who must cope with refractive distortions of position at the water–air boundary.

The conscious perception of hills overestimates their slopes (geographical slant) substantially (Gibson & Cornsweet, 1952; Kammann, 1967; Proffitt, Bhalla, Gossweiler, & Midgett, 1995; Ross, 1974). Proffitt et al. considered whether successful action with respect to hills depended merely on calibrated action (like the watchmaker; see also Philbeck, Loomis, and Beall (1997)), or on a separate perceptual representation that supported action (Bridgeman, Lewis, Heit, & Nagle, 1979; Milner & Goodale, 1995). They argued that experimentally induced dissociations between haptic measures and verbal reports, such as in response to fatigue, supported the idea that there were two separate perceptual representations for geographical slant, only one of which was available to conscious inspection. This claim was further developed in two studies that argued for the existence of a separate accurate motor representation of hills (Bhalla & Proffitt, 1999; Creem & Proffitt, 1998) used to guide motor actions (Creem & Proffitt, 2001; Proffitt, 2006, 2009). In this paper we will argue that the principal evidence that has been taken to support this view has been misinterpreted. We suggest, instead, that hill misperception may be a kind of magnification for action.

There are many means of asking research participants to evaluate a surface's geographical slope (orientation relative to the horizontal planes defined by the normal vector of gravity). One particular method has played a central role in the theoretical development of a two-systems approach to geographical slope perception. In a section heading entitled "Visually guided actions show little or no evidence of the phenomenal overestimation of geographical slant", Proffitt et al. (1995, p. 425) wrote "Our haptic measure of pitch showed very little evidence of slant overestimation." By "haptic measure", they refer to adjusting an unseen *palm board* to match the orientation of the hill. Generically, a palm board is a flat surface that can be rotated by hand about a horizontal axis

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so as to represent, non-visually, the slant of another surface (such as a visually observed hill). The style of palm board that we address in this article is shown in Fig. 1, redrawn from Proffitt (2006). Note that the palm board is positioned near waist level and the arm is extended down to meet it. Proffitt and associates (e.g., Proffitt, 2009) consistently describe the task of adjusting a palm board as a "visually guided action" (such as reaching, catching or grasping).

Whereas verbal and other "conscious" reports are said to reflect a phenomenal overestimation of geographical slant, the palm board has been presented as a sort of direct measure of the dorsal unconscious (Creem & Proffitt, 1998, 2001). In many published reports, the palm board has been described as an accurate reflection of true motor geography untainted by the vagaries of misperception that mar (and are said to guide) the conscious experience of geographical slope (Bhalla & Proffitt, 1999; Creem & Proffitt, 1998; Feresin & Agostini, 2007; Proffitt, 2006; Proffitt et al., 1995; Stefanucci, Proffitt, Clore, & Parekh, 2008; Witt & Proffitt, 2007). Our first objective is to thoroughly evaluate the palm board measure.

We specifically seek to test the following theoretical and empirical claim:

Adjusting a palm board is a *visually guided action* (Proffitt, 2009; Proffitt et al., 1995).

This claim has three corollaries that we will evaluate.

(1) Palm boards are impressively accurate measures of geographical slant (Proffitt, 2006; Proffitt et al., 1995).
(2) Null results found with palm boards are informative when compared with positive effects on verbal measures because they can demonstrate a dissociation between phenomenal experience and perception-for-action with respect to hills (e.g., Bhalla & Proffitt, 1999; Proffitt, 2006, 2009; Proffitt et al., 1995; Witt & Proffitt, 2007).
(3) Positive differences found with palm boards when contrasting memory and perception demonstrate a dissociation between perception-for-action and memory (Creem & Proffitt, 1998) and demonstrate that palm boards are sensitive measures (Proffitt, 2009).

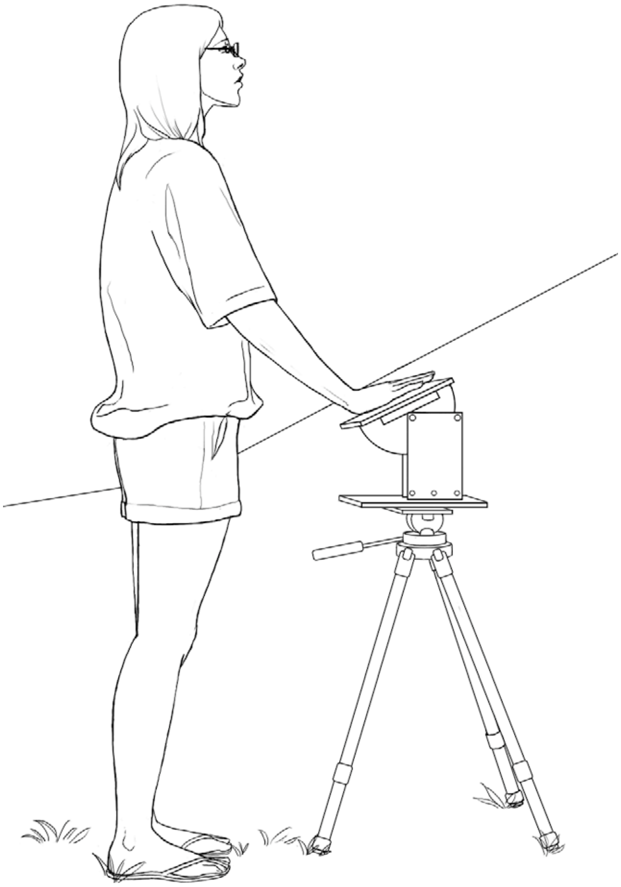

Fig. 1. Using a palm board according to the method of Proffitt et al. (1995). Redrawn from Proffitt (2006).

We will argue instead, on both empirical and conceptual grounds, that adjusting a palm board is not a visually guided action and that palm boards that primarily depend on wrist flexion are biased and insensitive measures. The bias of palm board measures is theoretically significant because the two-systems theory of slant perception has depended exclusively on the use of palm boards to provide evidence for accurate motor representations. The insensitivity of palm board measures is theoretically significant because palm board measures often "find" null effects. We will show that, proportional to their average gain, their between-participant variability is quite high. Invalidating the palm board as an "action" measure allows us to advance the alternative theory that the misperception of geographical surface orientation may be a functional adaptation, like a magnifying lens, intended to guide precise action (Hajnal, Abdul-Malak, & Durgin, in press; Li & Durgin, 2009).

1.1. A poor candidate for a visually guided action

Conceptually, palm board adjustment does not appear to resemble true visually guided actions. The task of adjusting a palm board involves comparing conscious haptic perception with conscious visual perception (He, Hong, & Ooi, 2007). In this sense it is entirely unlike catching a ball (McBeath, Shaffer, & Kaiser, 1995) or reaching out to pick up a disk (Aglioti, DeSouza, & Goodale, 1995), which do not entail conscious decisions about haptic variables. Instead, adjusting a palm board resembles a pantomime action, such as holding one's fingers apart to represent the size of a disk (Haffenden & Goodale, 1998). True visually guided actions are enacted with respect to the object in question (Milner & Goodale, 1995).

The hallmark of visually guided action is that it is usually followed by verifiable and immediate consequences, such as an expected contact with a surface. In contrast, palm board adjustments are the examples of haptic perception, usually not accompanied by perceptuomotor feedback. The patient DF, for example (a visual agnosic) could accurately post a card through a variably oriented slot, but was unable to accurately hold the card parallel to the orientation of the slot (Goodale, Milner, Jakobson, & Carey, 1991). Goodale and Humphrey (1998) argued that posting the card was a visually guided action, but that merely holding it parallel was a kind of pantomime reflecting conscious perception of orientation (absent in DF). We contend that the action of setting a palm board parallel to an observed hill is more clearly analogous to consciously trying to match the card to the orientation of a slot rather than to actually posting the card through the slot.

1.2. Overview of current studies

The argument of the empirical section of our study will be that the apparent accuracy of palm board measurements in the geographical slant literature is a measurement artifact. In Section 7 we will critically evaluate some of the evidence that has suggested that the perceived slope of hills is affected by behavioral potential (Bhalla & Proffitt, 1999). We will show that the existing evidence is surprisingly weak and sometimes contradicts the claims it is intended to support. We propose an alternative view that stable and systematic exaggeration in the perception of ground-surface orientation, like the watchmaker's magnifying lens, provides a basis for more effective immediate action.

1.2.1. Overview of experiments

In a series of five studies we will show that "wrist-flexion" palm boards are biased and insensitive measures that can mask real perceptual differences and can seem to reveal false ones. Experiments 1 and 3 will show that palm boards underestimate the orientations of surfaces in reach – whereas reaching and even pantomiming with an unconstrained hand/arm (free hand) are both fairly accurate for surfaces in reach. This falsifies corollary 1 (see above). Experiment 2 demonstrates that palm board estimates deviate from free-hand measures for an outdoor hill as well. Because manipulating a palm board of this type requires that the wrist joint be the primary source of biomechanical rotation, in Experiment 4, we will show that proprioception of wrist flexion in the absence of a palm board is exaggerated (i.e., perceived flexion of the wrist is biased) in a manner that quantitatively predicts palm board bias and accounts for observed palm board insensitivity. In conjunction with Experiments 1–3, this falsifies corollary 2. Finally, in Experiment 5 we will show that small changes in posture (raising the palm board by about 10 cm) can produce large shifts in palm board estimates, suggesting that published reports of palm board accuracy and sensitivity may be artifacts. This falsifies corollary 3.

2. Experiment 1: a demonstration of palm board bias

To directly address the question of whether palm boards are visually guided action measures, we asked people to adjust a palm board to match a small physical slope within reach. If palm board measurements, as characterized by Proffitt et al. (1995; Bhalla & Proffitt, 1999; Creem & Proffitt, 1998; Proffitt, 2006, 2009; Witt & Proffitt, 2007) are visually guided actions, they ought to be particularly accurate for matching near surfaces (i.e., surfaces with which the hand could reasonably be expected to interact). In contrast, if palm board measures have seemed to be accurate in prior studies because the haptically perceived orientation of a palm board was overestimated (i.e., with about the same gain as the overestimation of hills), then the palm board itself will likely be set too low for a surface within reach. We contrasted palm board settings with a simple proprioceptive measure (holding one's unseen hand parallel to the slope). Bridgeman and Hoover (2008) have recently reported that a similar proprioceptive measure involving forearm orientation was not particularly accurate for large-scale hills.

2.1. Methods

2.1.1. Participants

Twenty-five undergraduate students at Swarthmore College, naïve to the hypotheses, participated as part of a class laboratory. Experimental procedures in this and all the subsequent experiments reported in the paper were approved by the local research ethics committee, participant visual acuity was normal or corrected to normal and all participants signed an informed consent form agreeing to participate.

2.1.2. Equipment

The visual stimulus was a wooden surface (30 cm wide × 45 cm), slanted at 30 deg. The slope was placed on a desk facing the subject who stood about 70 cm from it as shown in Fig. 2. Hand orientation was monitored at 60 Hz with a Vicon optical motion capture system (Oxford, UK). A barrier at their right prevented participants from seeing their hand. The palm board consisted of a plastic surface mounted on a tripod that tilted easily (but not without friction) from a stop at 0 to 75 deg and was set at a height of 90 cm from the ground. The palm board was near, but above the waist for all participants, as illustrated in Fig. 2, approximating the posture used by Proffitt et al. (1995).

2.1.3. Procedure

Students were instructed to place their right hand on the flat palm board and to stand so that their hand was hidden from view. While facing the wooden sloped surface they performed two tasks. One task was to set the palm board parallel with the wooden slope.

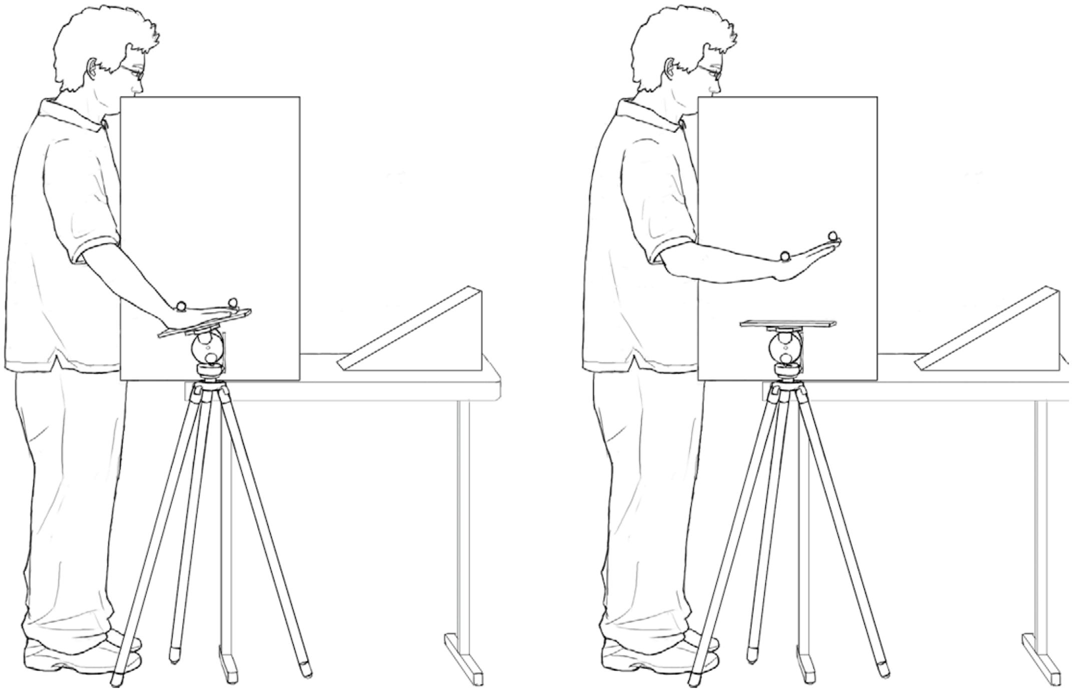

Fig. 2. Experimental setup in Experiment 1. Participants were asked to set the palm board (left) or their freely moving palm (right) to an orientation that felt parallel with the 30 deg slope on the table. The palm board was typically set about 10 deg too low.

Once they had adjusted it they were to keep it stationary for 2 s and then rotate it back to the horizontal orientation. The other task was to lift their hand off the palm board and hold it in the air so that the palm of their hand felt like it was parallel with the wooden slope. They were free to orient the hand using their shoulder, elbow and/or wrist. Again, they were asked to hold it in position for a couple of seconds before returning it to the horizontal palm board. Task order was varied between subjects (12 participants started by adjusting the palm board).

2.1.4. Analysis

Palm orientation was estimated from the changes in the orientation of the back of the hand compared to the horizontal position, based on 1000 ms of data starting 1500 ms before the start of the return to the base position.

2.2. Results

When the hand was held freely in the air, the mean palm-of-hand orientation was 32.7 deg ($SD = 8.92$). This did not differ reliably from the actual slope of 30 deg, $t(24) = 1.50$, $p = .147$. In contrast, the mean palm board setting (19.4 deg, $SD = 8.50$) was reliably less than the actual slope of 30 deg, $t(24) = 6.22$, $p < .0001$, and reliably less than the free-hand setting, $t(24) = 6.26$, $p < .0001$. The discrepancy between attempts to match the slope with the free hand and with the palm board suggests that the haptic perception of the slope of the palm board itself is exaggerated, causing participants to set the palm board too low. The free-hand measure was far more accurate.

2.3. Discussion

Whereas the free-hand proprioceptive measure employed here was fairly accurate for a sloped surface within reach, the palm board measure was not. Proffitt (2006) has suggested that palm board measurements of outdoor geographical slopes are more accurate than verbal judgments because they are visually guided actions. The present result suggests instead that palm board responses may be accidentally accurate in some contexts because of haptic misperception of the slope of the palm board.

We should emphasize that Proffitt et al. (1995) and Bhalla and Proffitt (1999) published what they called “haptic” measurements in which participants were asked to set the palm board to various verbally specified inclinations by touch. Consistent with our view, people set the palm board too low. Bhalla and Proffitt (1999) argued that these low setting reflected learned calibrations between visual perception (exaggerated slope perception of hills) and motor experience with hills. However, the palm is not normally used to interact with hills. The alternative possibility that errors in haptic perception were simply intrinsic to the type of measure was not considered, perhaps because errors in haptic perception seem surprising.

Our experiment shows that a proprioceptive (free hand) measure that allowed participants to orient their hand using all the degrees of freedom normally available (i.e., not requiring that the wrist joint be used primarily to orient the hand) produced a very accurate representation of a near surface slope – which differed from palm board measures. Bridgeman and Hoover (2008) used a similar proprioceptive measure outdoors with hills and found that it overestimated geographical slant. We therefore suggest that the apparent accuracy of palm boards for outdoor hills may be accidental: The orientation of the palm board and the orientation of the hill are misperceived in similar ways. The fact that verbal judgments of slopes, much lower palm board estimates of slopes, and very low palm board matches to verbal judgments are generally inter-consistent (Bhalla & Proffitt, 1999; Proffitt et al., 1995) can be interpreted as evidence that palm-board orientation is systematically misperceived – whether while judging hills or judging small, near surfaces.

Our tentative conclusion is that neither the palm board nor the free-hand measure is a visually guided action. The free-hand measure seems to more faithfully reflect the true surface orientation. However, we are not suggesting that the free hand is a direct measure of perception. Our emphasis is only that it appears to be well calibrated for near surfaces. The palm board does not.

3. Experiment 2: replication with an outdoor hill

In this experiment we had new participants use the same two measures we used in Experiment 1 (frictional palm board and free hand) for two different parts of a steep outdoor slope. Bridgeman and Hoover (2008) have reported that farther portions of outdoor slopes appear steeper than nearer portions using an 11-deg hill. They asked participants to orient their forearm to represent the slope and they also collected verbal reports. Both measures showed overestimation of surface orientation that increased with viewing distance. Feresin and Agostini (2007), using a reduced-friction ergonomic palm board, also reported that, for hills from 4 to 16 deg, nearer portions of the hills (4 m) were judged to be shallower than farther portions (6 m).

We replicated aspects of Bridgeman and Hoover’s experiments, but had our participants stand on the flat ground in front of the hill and used a frictional palm board near waist level (like Proffitt et al. (1995)). Like Bridgeman and Hoover (2008), we used a digital camera to record our free-hand measure, but we used the orientation of the hand (specifically the palm) as in Experiment 1 rather than the forearm. We collected palm board measurements using the same photographic technique.

Based on the results of Experiment 1, we expected that palm board setting would continue to be lower than the free-hand matches, but we expected that both measures would be sensitive to the perceptual difference obvious to casual inspection: standing near its base, the lower portion of the hill seemed much shallower than the portion at eye-level.

3.1. Method

3.1.1. Participants

Fifteen undergraduates from Swarthmore College participated as part of a laboratory exercise in a psychology course. All of them were naïve to the purpose of the study and had normal or corrected-to-normal vision.

3.1.2. Equipment

The palm board and occluding surface were the same as those used in Experiment 1. Two small spherical markers were placed on each subject’s right hand, one near the wrist, the other one on the right index fingernail. A digital camera was placed on a tripod two meters away level with the palm board, parallel with the axis of palm rotation. On each trial five digital photographs were taken of the hand position – one for the palm board estimate and one for the proprioceptive estimate for each of two viewing directions. An image taken of each participant’s hand resting on the horizontal palm board served as a baseline.

The hill was a grassy slope that was not near a path. The vertical height of the hill was 1.8 m, exceeding the eye height of all the participants. The base of the hill met with a level grass area. The hill’s right and left edges extended far beyond the view provided to the participants. The actual physical slant of the hill was measured at two intervals. The first meter of the slope had a measured incline of 23.5 deg. The meter of surface surrounding an elevation of

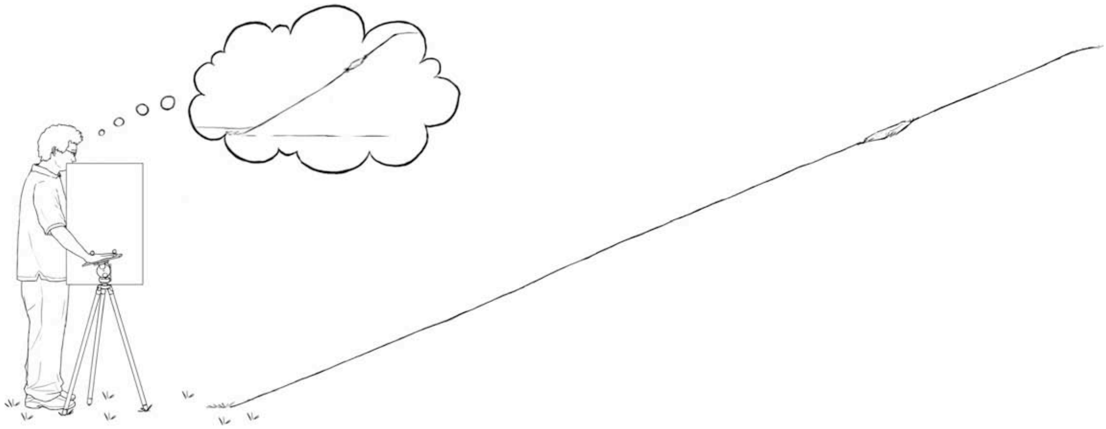

Fig. 3. Experimental setup in Experiment 2. Participants stood in front of an outdoor hill and set an unseen palm board (shown) or their free hand parallel with the hill, while looking forward or down. Verbal and proprioceptive measures suggested the hill appeared steeper than it was (the thought bubble is based on verbal estimates and seems a good representation of the appearance of the hill to us as well), and that estimates were closer to accurate with downward gaze. The palm board settings were too low and did not measure any effect of gaze orientation.

approximately eye-level (1.5 m) was slanted at 24.5 deg. The slope was covered with grass, without any conspicuous bumps or holes in it apart from a rock a little above eye-level that we used as a reference point ("the area just below that rock") when describing the portion of the hill we wanted the participants to judge. See Fig. 3.

3.1.3. Procedure and design

Participants were led to the base of the hill, and asked to make a series of four non-verbal judgments about its slope. They were instructed either to look down close to the base of the hill or straight ahead at the hill, and use their unseen free hand and the palm board to make estimates of its slope. They then repeated the two judgments with the alternative gaze orientation. The order of first gaze orientation (forward or down) was crossed with first measure (palm board or free hand). After all four non-verbal judgments were completed, verbal judgments of slope were solicited for each gaze orientation. Participants could not see their right hand during the experiment and received no feedback about the accuracy of their judgments.

3.1.4. Data extraction

The angle formed by the direction of the markers and the palm board surface in the baseline photograph ($M = -13.5$ deg) was subtracted from the angle calculated from the marker positions on each trial. This represented the angle formed by the palm's surface and the horizontal direction for both the free hand gesture and the palm board responses. The angles were calculated from the rectangular horizontal and vertical distance between the two markers in pixel units. Angular errors stemming from projective image distortion were determined to be negligible.

3.2. Results

Fig. 4 presents the average results by gaze direction and response type. When participants observed the space near the bottom of the hill (downward gaze direction) and responded with their hand held freely in the air, the mean palm-of-hand orientation was 31.5 deg ($SD = 9.37$), which was reliably less than the 36.1 deg ($SD = 11.0$) palm orientation while looking straight ahead, as expected, $t(15) = 1.89$, $p = .0394$, one-tailed. This extends the result of Bridgeman and Hoover (2008) to a case where observers stand on level ground. In contrast, when participants used a palm board the average produced angles were 18.5 deg ($SD = 7.68$) and 18.1 deg ($SD = 6.97$) for looking down and forward, respectively. These did not differ from each other, $t(15) = 0.202$, $p = .842$, but in both cases palm board estimates were reliably lower than the true slopes of 23.5 deg ($t(14) = 2.61$, $p = .0207$) and 24.5 deg ($t(14) = 3.65$, $p = .0026$). (Palm board underestimation is typical for steep hills in the data of Proffitt et al. (1995).) Thus, the palm board was not sensitive to the perceptual difference reported by Bridgeman and Hoover (2008) and Feresin and Agostini (2007) and replicated here with the free-hand measure on level ground.

Consistent with the proprioceptive measure, verbal reports indicated that the hill looked significantly steeper at eye-level ($M = 44.3$ deg, $SD = 10.7$) than near the bottom ($M = 34.1$ deg, $SD = 10.8$), $t(15) = 4.44$, $p = .0005$. Fig. 3 depicts the physical geometry of the hill along with the perceived geometry deduced from the verbal data, which roughly agrees with our own subjective experience.

In Experiment 1, palm board estimates were smaller than free-hand measures by a factor of 0.60. Based on the 4.5-deg difference in the free-hand measure for gaze forward vs. gaze down, we might therefore expect to see a 2–3 deg difference in the palm board measure. The 95% confidence interval of palm board differences in the present experiment includes 3 deg. The null palm board effect of the present experiment does not show that there is no effect on the palm board measure, only that we failed to detect one.

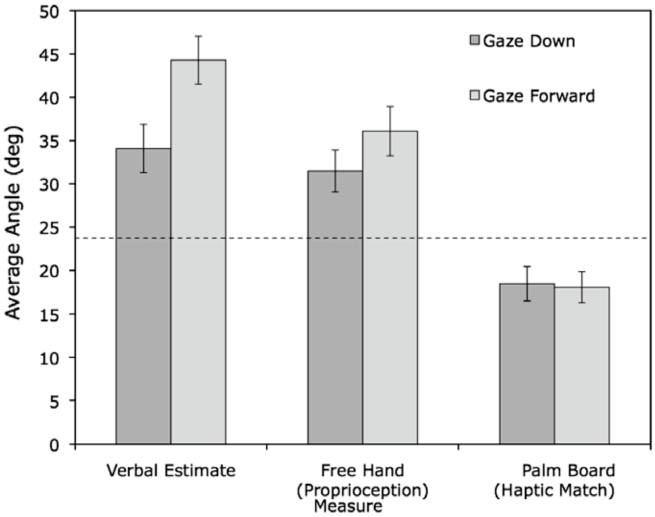

Fig. 4. Mean results of outdoor slope estimates in Experiment 2 by response type and gaze orientation. Actual slope is represented by the horizontal line. Error bars represent ±1 standard error.

3.3. Analysis of variability for Experiments 1 and 2

When a null effect is found with a palm board, it seems important to ask whether there is greater proportional variability in the measure. If one measure has a lower gain than another, it must have correspondingly lower variability to remain as sensitive. We therefore computed the coefficients of variation (*CV*s) for each measure by the technique of computing the standard deviation of the logarithms: $CV = e^{(stdev(ln(x)))} - 1$, where x is a slope response in deg given by a participant. Logarithms are used to capture proportional variability. Squaring the *CV* gives an estimate of the normalized variance, and the ratios of the normalized variances constitute an *F*-ratio (with $N - 1$ degrees of freedom in the numerator and in the denominator), allowing us to compare the normalized variances of these two measures (e.g., Durgin, Akagi, Gallistel, & Haiken, 2008). Note that the assumptions underlying this approach will be supported by Experiments 3 and 4 to follow.

In the indoor task of Experiment 1, the proportional variability in the palm board measure ($CV = 0.535$) was reliably greater than that of the free-hand proprioceptive measure ($CV = 0.331$), $F(24, 24) = 2.61$, $p = .0111$. We might expect to see greater variability in both measures for the outdoor task because of greater uncertainty about the visual slope. More importantly, however, in Experiment 2 the variance in the palm board measure of settings averaged over the two gaze directions ($CV = 0.756$) was again significantly greater than that in the free-hand measure ($CV = 0.454$), $F(14, 14) = 2.77$, $p = .0333$. The palm board *CV* was also reliably larger than that for the verbal measure ($CV = 0.306$), $F(14, 14) = 6.11$, $p = .0009$.

3.4. Discussion

As in Experiment 1, there was a marked divergence in Experiment 2 between the palm board and the free-hand proprioceptive measure. For this outdoor surface beyond reach, the free-hand measure was less accurate than in Experiment 1 (revealed overestimation consistent with verbal measures), but the palm board continued to underestimate the surface orientation. The relative gain between the palm board and the free-hand measure remained similar overall, but the free hand was, proportionally, a more sensitive measure.

Does the null result of the palm board show that it is based on a different representation, unaffected by direction of gaze? We think not. Effects of direction of gaze have been reported in previous studies using frictionless palm boards (Feresin & Agostini, 2007) as well as studies using verbal and non-verbal measures (Bridgeman & Hoover, 2008). Our verbal and free hand findings of reduced slope when looking down at the near portion of the hill are thus consistent with these previous findings, whereas the null result with the palm board is simply an indeterminate result. It is important that scientists distinguish between evidence that a measure did not find an effect (i.e., of gaze direction) and evidence that there is no effect. We have shown that the data we collected are statistically consistent with a 3-deg effect on the palm board. We therefore conclude that the null result found with the frictional palm board (which was modeled in most respects on the ones used by Proffitt and his colleagues) is simply uninformative.

4. Experiment 3: palm boards provide low slant estimates of reachable surfaces

The use of palm boards is deeply ingrained. Although Experiments 1 and 2 seemed to demonstrate that palm boards are not particularly well calibrated, a variety of objections might be raised about the specific stimulus tested or the specific palm board used. We had adopted a frictional palm board, like the one used by Proffitt et al. (1995). Should ours have had less friction than it did? Was there something unusual about the specific stimuli we used?

For Experiment 3 we developed a means of presenting stimuli so that we could measure reaching behavior as well as measuring matching by a free hand and by a palm board. The stimuli were irregularly shaped wooden boards that were suspended from below in near visual space. We carefully removed horizontal references from view and tested a wide range of angles. In addition to using palm board and free-hand matching tasks, we tested conditions in which people reached their hand out to place it on the surfaces so that we could observe actual visually guided actions (reaching) with respect to the target surfaces and confirm that such actions were accurate.

4.1. General methods for Experiments 3A and 3B

4.1.1. Participants

Twenty-one Swarthmore College students participated. Twelve performed the palm board and free-hand tasks. The other nine performed the reaching task.

4.1.2. Apparatus

The main slope-presentation device was crafted from aluminum and steel and set on a tripod (see Li and Durgin (2009)). It allowed a mounting surface to be quickly and accurately set to any one of a number of pre-selected angles. A large number of irregularly shaped wooden surfaces were manufactured as well. Each wooden surface could be placed securely onto the mounting surface. These wooden surfaces were about 40 cm across with a smooth, but irregular perimeters. A different surface was used for each trial.

The slopes were presented within a hemispheric enclosure of black felt (about 2 m in diameter) and viewed through a restricting goggle so that the inclined surfaces were isolated from any visual reference frame that included a horizontal plane. They were lit from the sides.

Participants stood in front of the surfaces about 0.5 m from the center. The surfaces were presented just below chest level. A flap was brought down over the restricting goggle between trials so that the participant could not observe the experimenter preparing the next slope.

A Vicon tracking system was used to record angle measurements of the right palm based on four markers placed on the back of the hand. Between trials, the right hand rested on a horizontal surface that was either the palm board or an alternate surface.

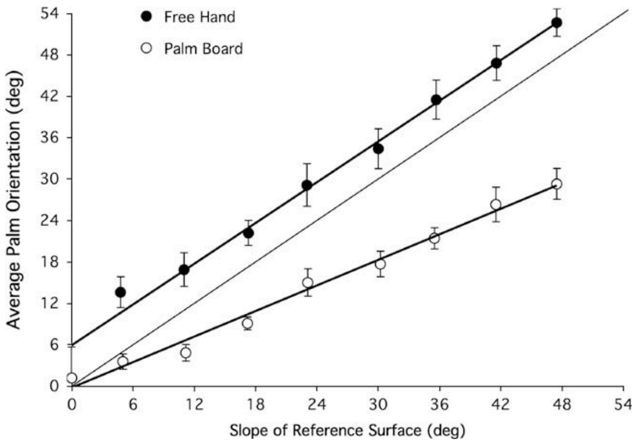

Fig. 5. Results of Experiment 3A. Mean orientation of palm board and of free hand as a function of visual surface orientation. Error bars represent ±1 standard error.

For the palm board condition a low-friction palm board was developed. It consisted of a panel of wood (26.5 cm long × 19.5 cm wide with 1.9 cm thick) that was suspended on an axis through the center of mass of the panel and that was nearly frictionless so that the weight of two US pennies (i.e., 5 g) was sufficient to cause it to rotate. It was fitted with a stop at horizontal and was placed just above waist level according to the method of Proffitt (2006; Proffitt et al., 1995).

4.2. Experiment 3A: free hand and palm board slant estimates for reachable surfaces

We again compared free hand estimates with palm board estimates.

The participants were 12 Swarthmore College undergraduates who had not participated in any of our other studies on slope perception. Task was manipulated within subjects, but blocked. Half were assigned first to the free-hand task; the others were assigned to the palm board first.

For each task, each of nine slopes from 0 to 48 deg (increments of 6 deg) was presented once in a random order. In the free-hand task, participants were asked to hold their unseen hand out in a position that was parallel with the viewed surface and indicate verbally when ready. The experimenter recorded hand orientation for about a second and then ended the trial. Hand orientation was also recorded during the period when the hand was resting on the horizontal rest in order to establish a baseline. A similar procedure was used with the palm board, with the exception that the

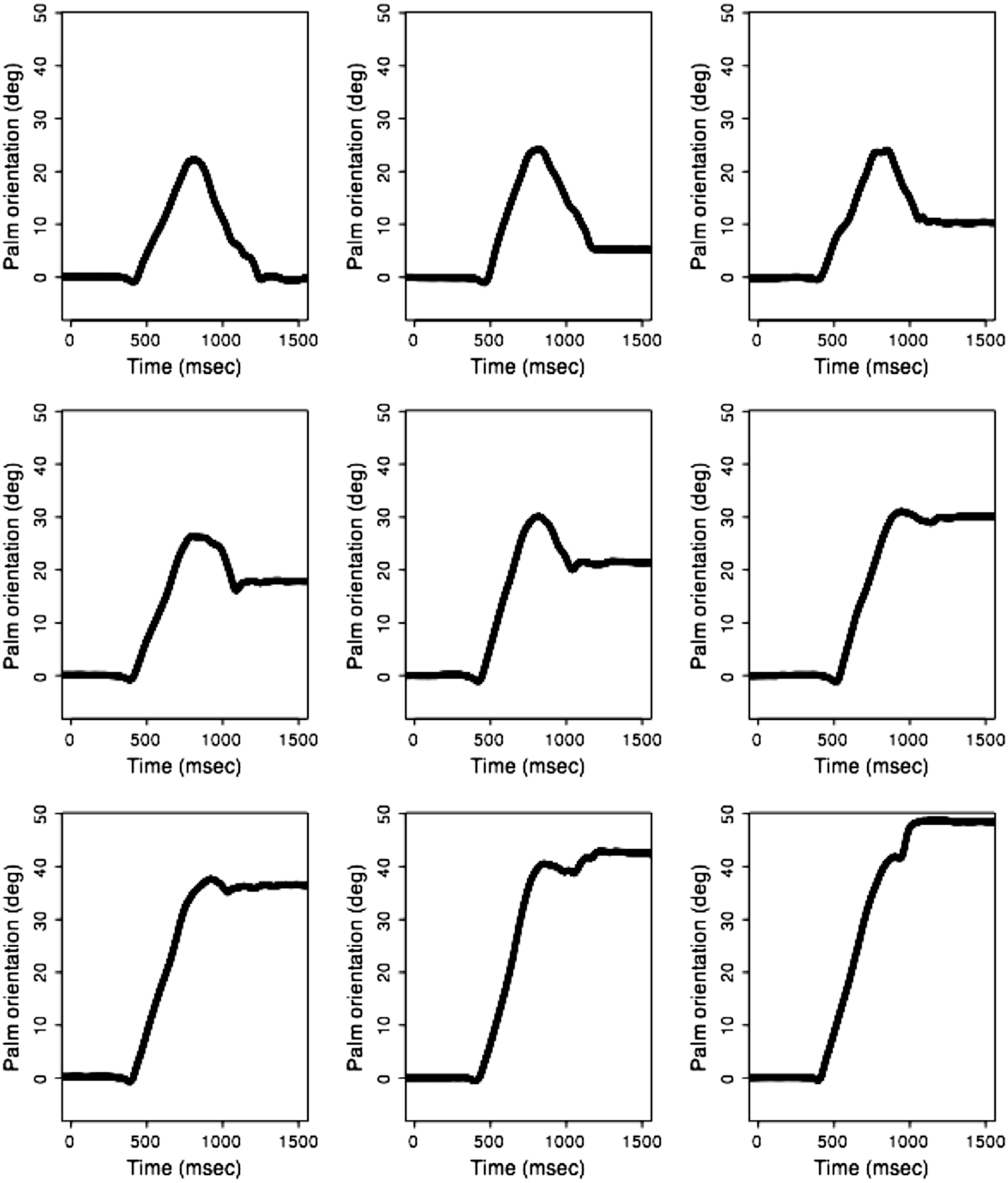

Fig. 6. Orientation of the palm during reaching to sloped surfaces from one participant in Experiment 3B. Smooth bell functions represent free movement through the air. Final plateaus represent the hand at rest on the surface.

instruction was to set the palm board parallel with the visible surface; the participants were required to return the palm board to horizontal (where it met a stop) between trials.

Mean palm orientation of the hand is plotted as a function of surface orientation in Fig. 5 for each measure. It is evident that both measures produce good linear representations of the surface orientation, but that the gain for the palm board is quite low. A regression line for the palm board judgments had a slope of 0.61 and an intercept of 0 (consistent with the fact that the zero inclination was met with a stop). The regression line for the free hand had a slope of 0.98 and an intercept of 6 deg. The average gain of the free-hand measure did not differ from 1, and was reliably greater than the average gain of the palm board measure, $t(11) = 5.98$, $p < .0001$. It is worth noting that the 6-deg intercept represents about half the angle between the palm and the back of the hand; if participants experience their hand as a uniformly-thick surface, the 6-deg intercept may indicate that participants were inadvertently matching the orientation with the major axis of their hand rather than the palm.

The gain measured for the palm board is consistent with the palm board data in Experiment 1, where the mean palm board estimate was 60% of the true slope. It also corresponds well to the haptic production task of Proffitt et al. (1995), which had a gain of 0.57.

4.3. Experiment 3B: reaching task

Reaching out and touching a visible surface is, without controversy, a visually guided action. To ensure that participants could reach accurately to the surfaces in Experiment 3A, we conducted a study of reaching.

The participants were nine Swarthmore College undergraduates who had not participated in any of our prior studies on slope perception.

We used the Vicon system to record the orientation of the palm at 200 Hz as participants lifted their hand from a horizontal surface at their side and reached out to place it on a sloped one. The participants completed two practice reaches (to slopes of 12 and 30 deg), and then reached to nine surfaces (6-deg increments) from 0 to 48 deg in a random order. They were instructed to reach out rapidly without risking injury and place their hand flat on the surface. They were instructed to keep their hand rigid throughout. Because of the restricting goggle, the participant's hand was not visible to the participant in its initial position, but it came into the visual field as it approached the surface.

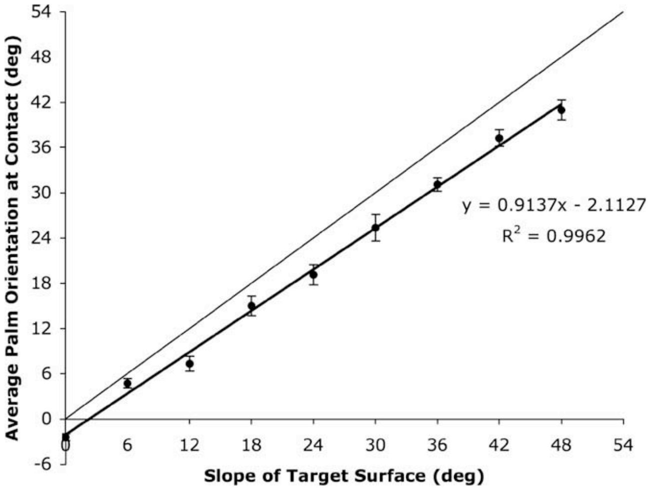

Fig. 7. Results of Experiment 3B. Mean orientation of hand at first contact with surface as a function of visual surface orientation. Error bars represent ±1 standard error.

A typical set of traces of hand orientation over time is shown in Fig. 6. The pattern we observed across all nine participants was that the basic motor action of lifting up the hand (to reach out to the sloped surface) was relatively independent of the slope of the surface, even though reaches were quite accurate. For example, the peak angular velocity was essentially constant across all reaches for any given participant. Nonetheless, the orientation of the hand smoothly transitioned from the initial position to the sloped surface quite accurately suggesting that visually guided action toward the surfaces was planned based on a precise spatial representation.

The small errors in hand orientation at the point of contact show up in the traces as initial points of fluctuation in the orientation plots during the phase just prior to the final plateau of extended contact with the surface. Orientations just prior to these fluctuation points were used as estimates of palm orientation at first contact. Average palm orientation at first contact for each slope is plotted in Fig. 7. The linear regression line through these points has a slope of 0.91 and intercept of -2.0 deg. The fact that the slope is not 1 may merely reflect that the task does not require full adjustment of the hand prior to contact. This relatively high gain does show that reaching was guided by the orientation of the surface. The practice trials did not differ from the main trials. These data indicate that our participants can reach out and touch our surfaces easily and accurately. Note that, because hand orientation can be self-correcting once in contact with the surface, reaching does not require precision for this task. The data display reasonably good precision nonetheless.

Although reaching is a visually guided action, we do not conclude from our study that our free-hand measure is a visually guided action. Because it is not an action directed at the distal surface, we believe that it, too, is a pantomime action. Our conclusion is that adjusting a palm board is neither a visually guided action nor a calibrated action, whereas the free hand appears to be calibrated for near surfaces. The fact that reaching is successful shows that the strong bias found for the palm board cannot be attributed to a failure of dorsal perception. Rather, the palm board is set too low because it feels steeper than it is.

5. Experiment 4: proprioception of wrist flexion is similarly biased

In Experiments 1 and 3, we have seen that free-hand measures of the slant of near surfaces can be fairly accurate (calibrated for near surfaces), while palm boards (frictional or low-friction) are quite inaccurate. The fact that the axis of rotation of a palm board is necessarily near the wrist requires the wrist joint to be the primary source of manual rotation for this kind of measure. This is because rotations of the arm about the shoulder joint or forearm about the elbow joint will tend to separate the hand from the palm board, as indicated in Fig. 8. In contrast, the use of a free hand can employ any of these joints, or several in combination because the vertical location of the hand is unconstrained. It thus seems likely that proprioception of wrist flexion is scaled differently than proprioception of the arm and hand assembly. On the one hand, this might be due to the limited range of flexion of the wrist on its own. On the other hand, poor calibration might also reflect the fact that visual observation of pure wrist flexion is rare, so there is little basis for proper calibration to vision (Hajnal et al., in press). In Experiment 4 we measured proprioceptive scaling of wrist flexion in the absence of the palm board. To show that our task was not intrinsically biasing, we compared wrist-flexion proprioception with elbow-flexion proprioception for both bias and sensitivity.

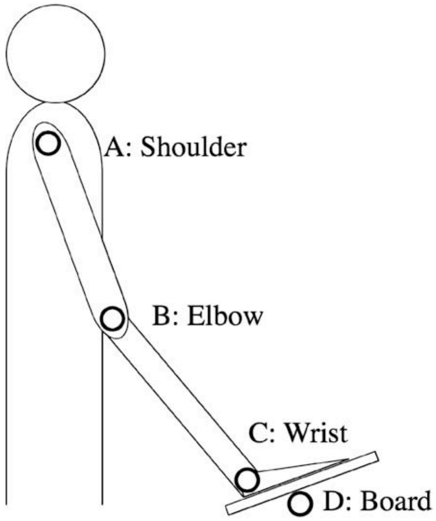

Fig. 8. Illustration of rotational axes of arm (A–C) and palm board (D). Assuming that the *location* of the palm board axis (D) is fixed, and that the *location* of the shoulder is also fairly stable, large rotations about either the shoulder (A) or the elbow (B) will lift the hand away from the palm board. Thus, palm board rotation must be governed primarily by rotation of the hand about axis C (the wrist joint). In contrast, with a free-hand measure (where the location of the hand in space is unconstrained), large rotations of all three joints may be used to orient the hand.

5.1. Method

The participants were 25 undergraduate students recruited in exchange for a candy bar. The data of one student were eliminated for failing to follow instructions.

5.1.1. Design

Production of angles by wrist and by hand was measured within subjects in a blocked design in which six visually presented angles (5, 10, 20, 30, 45 and 60) were presented in a random order in each block, and the joint used for each block was varied in order between subjects.

5.1.2. Equipment

Markers placed on the back of the hand were photographed against a grid from 2 m away to minimize projective distortions, as shown in Fig. 9. The visual stimulus was a smooth white line presented against a circular black background to represent a 2D orientation. This 2D representation was used to minimize any ambiguity about the size of the angle to be produced. A horizontal board supported the arm. The forearm remained in contact with the board during wrist flexion trials. The elbow remained in contact during elbow-flexion trials.

5.1.3. Procedure

On each trial a 2D line orientation stimulus was presented. When participants indicated that they had oriented their unseen hand to the angle indicated by the line, using the appropriate joint, a photo was taken. Then the screen was blanked, and a new stimulus was presented 1 s later. The hand was returned to the horizontal between each trial. Photos were normally taken of the hand resting horizontally at the beginning and end of the 12 trials.

5.2. Results

Angles were extracted manually from the photos using specialized software that measured line orientations between selected marker points in the images. A correction for baseline orientation was applied. Average palm orientation as a function of requested angle is plotted in Fig. 10 by joint used.

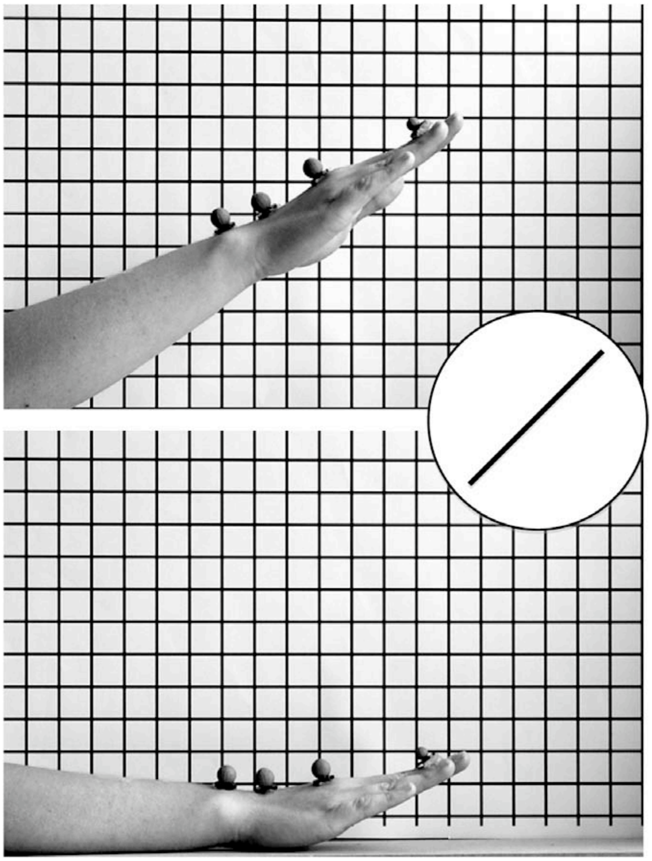

Fig. 9. Experimental task for Experiment 4. Images are shown of attempts to match a visually displayed 2D 45-deg line with the unseen palm of the hand using the elbow joint (top) or the wrist joint (bottom). The 45-deg line is shown here schematically, for illustration. The actual stimulus was white on black.

5.2.1. Bias

For each participant we computed the gain for each joint by a linear least-squares fit. The average gain for the wrist joint (0.53) was reliably less than the gain for the elbow joint (0.79), $t(24) = 6.48$, $p < .0001$.

5.2.2. Sensitivity

The standard deviations of hand orientations at each angle were divided by the gain for the relevant joint and squared. Like the *CV*s computed earlier, this provides an estimate of the between-subject variability of the measure normalized relative to the scale of the measure. The ratio between these normalized variances for the wrist and the elbow joint was computed at each angle and averaged. The resulting *F*-ratio indicated that wrist settings had greater proportional variability than elbow settings, $F(24, 24) = 2.79$, $p = .0074$. This means that a small change in the stimulus (or in the perception of the stimulus) can be detected more reliably using the elbow than the wrist, much as we have shown, using *CV*s, that the free-hand measure is more sensitive than the palm board.

5.3. Discussion

Using a 2D visual angle representation to reduce visual uncertainty, we have found that direct comparison of the proprioception of wrist flexion and elbow flexion indicates that the proprioception of hand orientation based on flexion of the wrist is both more

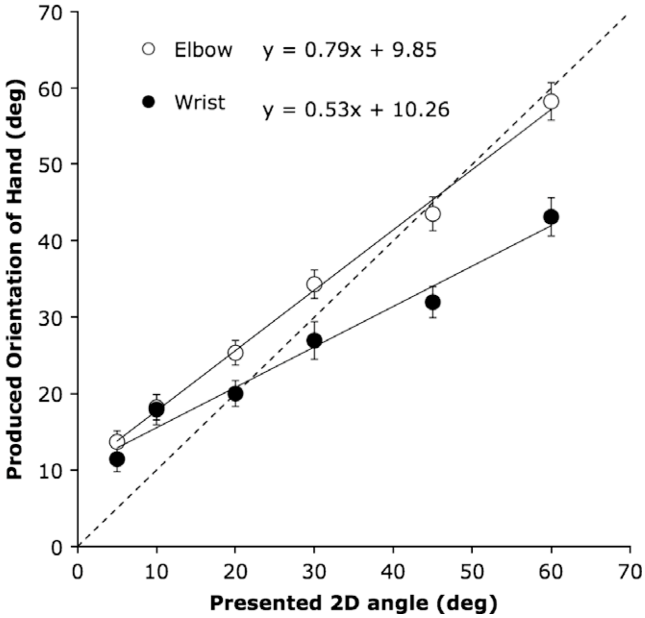

Fig. 10. Results of Experiment 4. Mean orientation of hand as a function of 2D visual orientation to be matched and joint used. Error bars represent ±1 standard error.

biased and less sensitive as a measure of perceived orientation (proportionally more variable) than that based on flexion of the elbow. Wrist flexion is more limited by biomechanical constraints and is also unlikely to be independently calibrated because it is rarely used independently of the rest of the arm. Errors in wrist proprioception appear to be sufficient to account for the measured behavior of palm board adjustment in the posture recommended by Proffitt (2006; Proffitt et al., 1995). Prior studies of limb orientation proprioception suggest that people are sensitive to world-orientation of limbs (Soechting, 1982; Worringham, Stelmach, & Martin, 1987), though body-centered frames of reference may dominate when the two compete (Darling & Miller, 1995; Kappers, 1999, 2003, 2004; Kappers, Postma, & Viergever, 2008). These studies do not, however, usually examine such constrained postures as we have used in this experiment, and as would be required when setting a palm board.

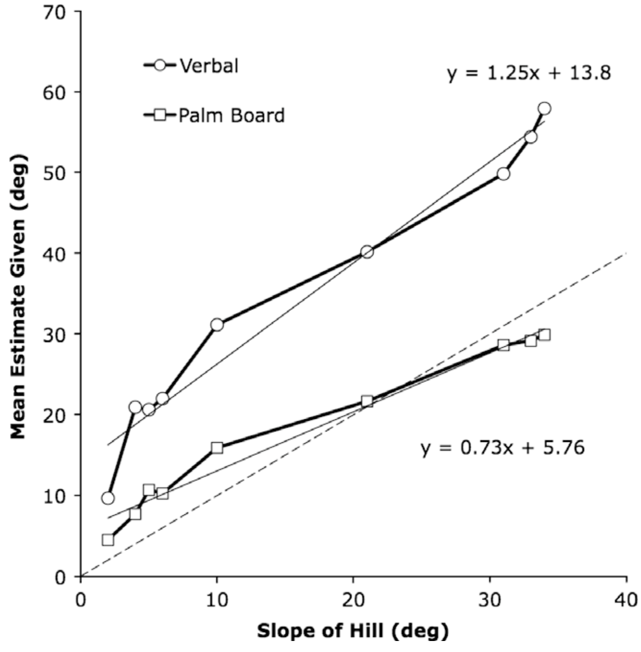

Fig. 11. "Normative" verbal and palm board data for outdoor hills (from Proffitt et al. (1995)) plotted from Table 2 of Bhalla and Proffitt (1999). Relative gains of palm board and verbal measures (0.73/1.25 = 0.58) closely corresponds to gain of wrist flexion (Fig. 10; 0.53) and to the gain of palm board estimates for near surfaces (Fig. 5; 0.61).

Whereas Proffitt et al. (1995) interpreted the relative accuracy of their palm board measurements as evidence of the calibration of the action system, the present data suggest that their palm board measurements were accidentally accurate. In Fig. 11 we have replotted the data collected by Proffitt et al. Although a more complex function may apply to the perception (e.g., a power function), linear fits capture the first order differences between the two measures. The difference in magnitude between palm board estimates of hills and verbal estimates in Fig. 11 could be explained by the distorted proprioceptive gain of wrist flexion. Comparison of our Experiments 1 and 2 suggests that outdoor hills of the same slant seem steeper than surfaces in reach. This may be at least in part because farther surfaces seem steeper (Bridgeman & Hoover, 2008). It also suggests, however, that the accuracy attributed to palm boards (for outdoor hills) is accidental rather than theoretically significant.

6. Experiment 5: effects of arm posture on palm board estimates from memory

We have focused in the foregoing experiments on showing that the wrist-flexion palm board is a biased and insensitive measure and shown that it depends on using a joint (the wrist) that is not particularly flexible or well calibrated. In part, we have been setting the stage for a discussion of the many null effects that have been used to argue for a dissociation between perception and action (e.g., Bhalla & Proffitt, 1999). However, Proffitt (2009) has recently anticipated our concerns and argued "It is important to note that, in cases in which we predict an influence on the palm board, such as adjustments made from memory, the palm board adjustments are affected (Creem & Proffitt, 1998). This shows that the null effect on the palm board is not just due to a lack of statistical power." (p. 571).

We therefore think it important to briefly review the findings of Creem and Proffitt (1998) here and point out a possible artifact of their reported method. In their first study, Creem and Proffitt (1998) found no effect of having participants close their eyes or turn their back on the hill before making a palm board adjustment (they compared their data to perceptual data collected by Proffitt et al. (1995)). Because participants were not warned that they would be asked to adjust a palm board, this first experiment shows that the palm board could be operated off a short-term representation that was not simply a prepared, calibrated motor action. In two non-experimental studies of long-term memory (Experiments 2 and 3) Creem and Proffitt reported that palm board estimates of slope in long-term memory were elevated (relative to data from Proffitt et al. (1995)). However, in both these experiments they confounded memory with posture. That is, whereas the perceptual judgments from Proffitt et al. (1995) were collected using a posture like that shown in Fig. 1, Creem and Proffitt (1998) state that they had their participants sit while making slope judgments from memory. (In the fourth experiment of their paper, where a standing posture was used, apparently positive results appear to have been limited to a single hill among three tested.)

We suspect that postural factors may explain most of their findings, because He et al. (2007) have reported that when a palm board is placed at shoulder level, the resulting estimates are higher than those given at waist level. Creem and Proffitt (1998) did not show the posture used in their study, but only indicate that participants were seated and that the palm board was "placed at their side" (p. 28). No indication of the vertical height of the palm board was given.

We found that our (standard) tripod made it difficult to set our palm board lower than about the navel when seated. For most people, navel height when seated is essentially the same as "waist-height" when seated, but both are actually slightly closer to the shoulder than is "waist-height" while standing. We therefore sought to test whether a small change in posture from the one depicted in Fig. 1 to one in which the palm board was just above the level of the navel would affect judgments of slope from memory. To clarify that the issue was arm posture rather than standing or sitting, per se, we also included a standing control condition in which the palm board was again placed slightly above the navel.

6.1. Methods

6.1.1. Participants

Thirty-six undergraduates (18 male) participated.

6.1.2. Design

Posture was manipulated between participants. Twelve participants were tested with the classic posture shown in Fig. 1. The other 24 were tested with the palm board set just above their navel (12 seated, 12 standing). Because this experiment involved between-subject comparisons, sex was balanced in all conditions.

6.1.3. Materials

The low-friction palm board with a stop at zero was used. Three well-known campus paths were selected. A verbal description, a campus map and a satellite photo with the relevant portion of the path indicated were used to indicate the locations of the slopes to be recalled.

6.1.4. Procedure

The order of hill presentation was randomized. Participants were provided with information specifying the identity of each of the three slopes in turn and asked to close their eyes while adjusting the palm board to match their memory of the uphill slope of the path. Ratings of familiarity were also collected. Two judgments were excluded from analysis because specific participants rated the associated hills as highly unfamiliar to them.

6.2. Results and discussion

The average palm board estimates of the remembered slopes of the three paths are shown in Fig. 12. As anticipated, a small change in the posture of the arm produced a sizeable change in these palm board settings from memory. This is consistent with the effect of posture reported by He et al. (2007) in a study of perception, though our change in posture was much more subtle. A mixed-effects model (Bates, 2005; R Development Core Team, 2007) was used to analyze the data including sex, body posture (standing or sitting), and arm posture (classic position or "navel" position) as possible factors and hill and subjects as random factors. Including sex and body posture did not improve the fit of the model, but models that included arm posture as a factor provided reliably better fits to the data than models that did not, $X^2(1) = 4.31$, $p = .038$. The model estimate of the effect was 4.4 deg (95% CI: 0.2–8.2 deg).

He et al. (2007) reported a manipulation of arm posture that produced large shifts in the intercept, but not the gain of the palm board. Our data reflect the same kind of shift, as does the data of Creem and Proffitt (1998). Note that because the axis of rotation of the palm board is in a fixed position, even a palm board at shoulder height, but positioned forward, must be rotated primarily by flexion of the wrist, so the results of Experiment 4 apply to both postures. It now appears possible that the effects that Creem and Proffitt attributed to memory were due to subtle changes in the arm posture.

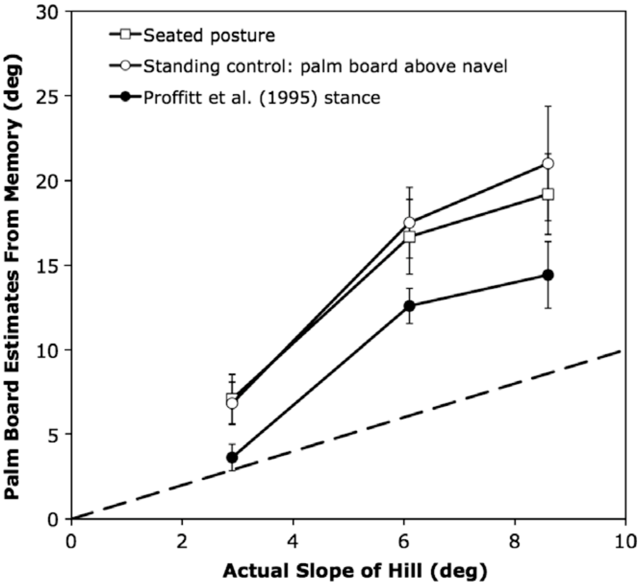

Fig. 12. Results of Experiment 5. Mean palm board estimates from memory for campus hills as a function of posture. Small changes in palm board height produce large changes in palm board setting. Error bars represent ±1 standard error.

More importantly, the fact that subtle changes in posture can produce measurable shifts in palm board estimates underscores the fact that palm board estimates are sensitive to the wrong kinds of information. The fact that small changes in posture can produce large shifts in palm board estimates may help explain why some labs (e.g., Witt & Proffitt, 2007) are able to present data showing excellent palm board matches to one or two presented slopes: during pilot testing, researchers may inadvertently develop a palm board setup that provides the impression of accuracy for their specific stimulus arrangement.

7. General discussion

We have shown that (1) palm board estimates of surfaces in reach are set too low, and that this is probably because (2) proprioceptively perceived flexion of the wrist is exaggerated. We have also shown that (3) small changes in the position of the palm board can produce large changes in palm board outputs, whereas (4) palm boards appear to be relatively insensitive measures (have greater variability proportional to their gain). All of these findings suggest that the existing data from palm boards are difficult to interpret, and that evidence of accurate settings for outdoor hills may be due to measurement artifacts.

Palm boards were originally developed by Gibson (1950; Gibson & Cornsweet, 1952) as a non-verbal means of assessing surface orientation. But the palm board used by Gibson was positioned vertically and was manipulated by an upheld arm. Gibson (1979) wrote, "the slant ... could be judged by putting the palm of the hand at the same inclination from the frontal plane and recording it with an adjustable 'palm board'" (p. 165). Our investigations have not been extended to such postures, but modern technologies offer improved methods of registering the orientation of a free hand. Free-hand measures ought to be better calibrated than palm boards because they allow full use of the calibrated actions of the hand-arm assembly. Free-hand measures are not visually guided actions in the way that reaching to a surface is, but they are useful non-verbal means of measuring differences in perceived surface orientation (e.g., Experiment 2).

7.1. What is the evidence for a dissociation in the perception of geographical slant?

In the geographical slant literature, most of the evidence taken to support a dissociation between the representation guiding "motor" (i.e., palm board) measures and "conscious" measures has consisted of null effects for palm boards paired with positive effects for other measures. For example, Proffitt et al. (1995) reported that verbal estimates of slopes were more elevated after a fatiguing run, but that palm board estimates were unaffected. They interpreted this as evidence that the conscious system reflected "behavioral potential" relevant for planning, while the haptic system reflected motor accuracy. The alternative possibility, that palm boards were less sensitive measures, was not investigated. When Proffitt et al. also found that palm board estimates for steep downhill slopes were steeper than for uphill slopes, they, themselves suggested that there was likely a biomechanical constraint in the uphill estimates; a conjecture with which we agree. However, the same argument could explain why Bhalla and Proffitt (1999) never found elevated palm board estimates for steep hills in their many studies.

In their nearly identical studies of fatigue, Proffitt et al. (1995) and Bhalla and Proffitt (1999) each tested two hills, one steep (31) and one shallow (5 deg). Following Proffitt et al.'s discussion of downhill vs. uphill estimates, we assume that their uphill palm board estimates of the steep hill may have been limited by biomechanical constraints. So, was there any evidence of an effect of fatigue on palm board estimates of the shallow hill? For the 5-deg hill, Proffitt et al. found a small increase in the palm board estimates, but it was only marginally reliable ("$p < .07$", p. 424), and it was interpreted as a null effect providing evidence of a dissociation between explicit estimates (where there was a reliable increase) and the palm board measure. When Bhalla and Proffitt replicated this fatigue study, they again found a small increase in palm board estimates of the low hill, but this time the effect was even noisier ("$p = .18$", p. 1084). However, they did not note that the *conjoint probability* of these two findings was now sufficient to reject the null hypothesis ($p < .05$). Instead, the new result was treated as a replication of a null finding for palm boards. We think this case well illustrates the risk of arguing for a dissociation based on null effects obtained with a noisy measure.

Bhalla and Proffitt (1999) presented three other studies by which they sought to demonstrate not only that palm boards were accurate, but that they were dissociated from verbal measures. In each study, Bhalla and Proffitt considered whether a variable that affected or reflected behavioral potential (burden, fatigue, fitness and age/health) would affect conscious judgments of slope while leaving palm board estimates unaffected. In other words, they consistently sought to demonstrate null results on palm boards, and treated such results as positive evidence of a representational dissociation. However, null results of this sort ought to be of limited scientific interest because they are difficult to interpret.

7.2. A new look at old data

Whereas we are questioning the validity of the palm board measure, the interpretation of the positive results of their studies has also proven controversial. For example, Durgin et al. (2009) replicated the result that wearing a heavy backpack increased verbal judgments of slope, but found that the effect was eliminated when a convincing explanation for wearing the backpack was provided (see also Russell and Durgin (2008)). Indeed, in the absence of a convincing cover story, the effect was found to be due to a subset of compliant participants who could not only articulate the experimental hypothesis in a post-experimental survey, but also indicated that they thought they had been affected by the backpack (i.e., they cooperated with the experimental demand).

Why did not demand characteristics affect palm board estimates? In Bhalla and Proffitt's (1999) backpack study (again using the 5 and 31 deg hills), they found no effect of a backpack on palm board estimates, but we are hesitant to accept their conclusion that this is evidence of a separate motor representation. Given the relative gains of palm boards (e.g., 0.73) and verbal responses (1.25) in Proffitt et al.'s normative hill data, we suggest that researchers resist the temptation to interpret "dissociations" between these measures that include a null effect on palm boards – especially for steep hills where palm boards used at waist level are likely affected by biomechanical constraints on wrist flexion (when the forearm is lowered at a 60 deg angle, the wrist must flex by 90 deg to produce a 30-deg inclination of the palm board).

Another of the studies that Bhalla and Proffitt (1999) reported seems particularly worthy of reconsideration. The theory behind the study was that being elderly and infirm would make hills appear steeper, but not affect palm board estimates. The results of the study have long been interpreted as supporting this hypothesis, but the pattern of data actually found strikes us as less clarifying than originally characterized. We have plotted the data from that study in Figs. 13 and 14, using the tables of means and standard errors provided by Bhalla and Proffitt (1999, p. 1082).

First, let us consider the palm board settings made for verbal angles. Fig. 13 shows the palm board angles produced by their 32 elderly participants (Bhalla & Proffitt, 1999), and by "normative" participants (Proffitt et al., 1995) when asked to set the palm board to various angles. The normative data (gain of 0.57) closely resemble the wrist flexion data we collected in Experiment 4 (gain of 0.53), whereas the elderly show a much lower gain (0.35). It seems likely that reduced joint flexibility among the elderly might be responsible for this low gain (Holland, Tanaka, Shigematsu, &

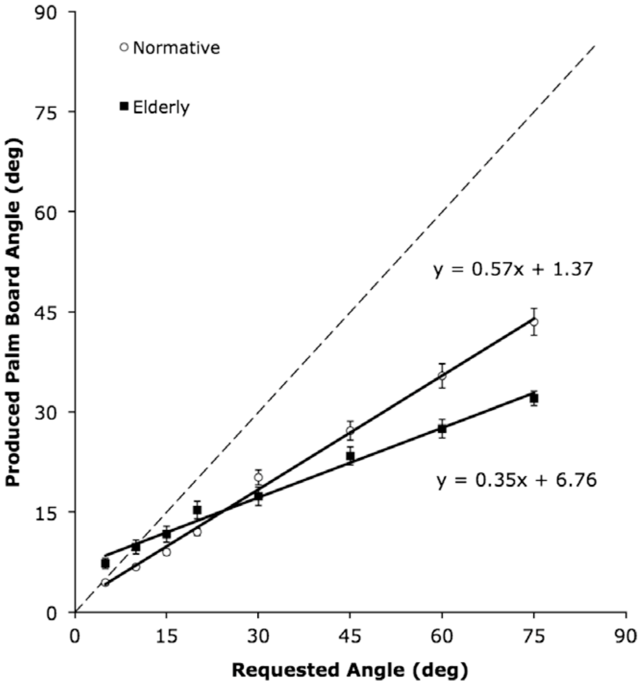

Fig. 13. Palm board angles produced in response to verbal angles for normative (Proffitt et al., 1995) and elderly participants (Bhalla & Proffitt, 1999). Means and standard errors obtained from Table 2 of Bhalla and Proffitt (1999). Best fit lines are shown.

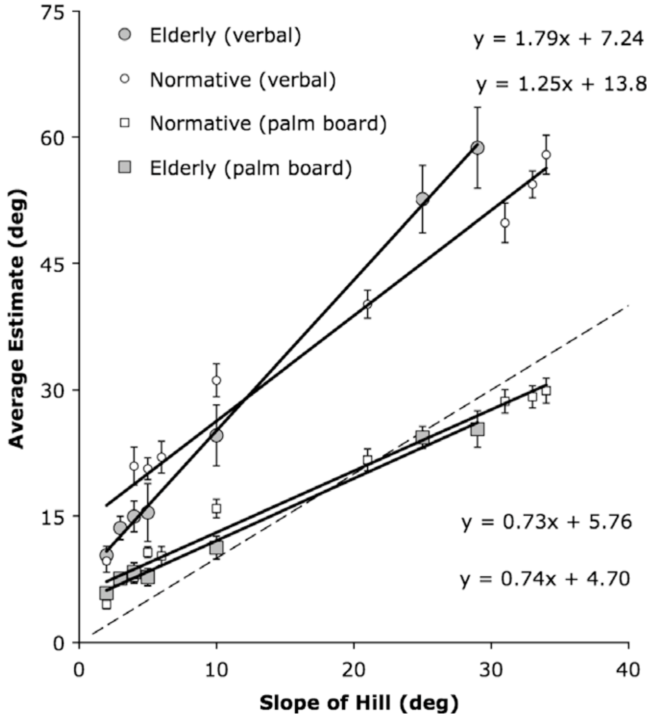

Fig. 14. "Normative" (Proffitt et al., 1995) and elderly (Bhalla & Proffitt, 1999), verbal and palm board estimates for outdoor hills plotted from Table 2 of Bhalla and Proffitt (1999). The verbal data for low slopes seems to contradict the conclusions of Bhalla and Proffitt (1999). Best fit lines are shown.

Nakagaichi, 2002), though other possibilities exist as well. Bhalla and Proffitt argued that this lower gain was due to calibration between the exaggerated conscious perception of hills among the elderly and their accurate motor representation required for interacting with hills. Bhalla and Proffitt reported statistics showing that for the upper range of angles (60 and 75 deg) palm board settings were lower among the elderly than among the normative participants, consistent with their view. However, they declined to report statistics regarding the lower end of the range, stating only that they were not *individually* reliable. This conclusion strikes us as surprising given the size of the standard errors they reported, which we have reproduced in our figure. These low-angle data appear to contradict the predictions of their model.

Now consider the verbal hill estimates of the elderly reported by Bhalla and Proffitt (1999), as shown in Fig. 14. These also reflect a rather surprising pattern: The data of the elderly appear to be *lower* for low slopes than the normative data, contrary to the behavioral potential hypothesis favored by Bhalla and Proffitt. In this case, Bhalla and Proffitt reported that estimates for the low slopes, *analyzed as a group*, were not different for the elderly than the normative, but that the estimates for the high slopes were higher among the elderly. We are unable to determine the exact analysis performed based on their report, and Bhalla has informed us that the electronic records of the original data are no longer available. Considering the small size of the standard errors, it appears reasonable to believe that if the anomalous 2-deg slopes were excluded from the analysis the data would actually support the conclusion that the elderly gave *lower* estimates of low hills (4, 5, and 10 deg) than did the normative participants. In other words, Bhalla and Proffitt seem to have published, without calling attention to it, data that strongly contradict their favored hypothesis.

In defense of Bhalla and Proffitt (1999), we should note that one of their main arguments was that *within* the group of elderly they tested, self-reports of health were correlated with some of the verbal hill estimates. Unfortunately, this finding may have been due to a biasing aspect of their procedure: prior to making judgments about each hill, elderly participants were "asked questions related to the walkability of the hills *for a person their age*" (Bhalla & Proffitt, 1999, p. 1088, emphasis added). Calling attention to behavioral potential and age in this explicit way just before collecting slope estimates, may have encouraged less mobile/healthy participants to adjust their verbal judgments for steep hills accordingly, (e.g., in accord with stereotype threat, Hess, Auman, Colcombe, & Rahhal, 2003; Steele & Aronson, 1995, or experimental demand, Durgin et al., 2009; Orne, 1962).

An additional difference between the procedures used for the elderly and for the "normative" participants, was that each elderly participant was asked to judge four hills (the range was 2–25 deg for one group of elderly participants and 3–29 deg for another), rather than only one. This is an understandable design decision, but it may have contributed to the exaggeration of judged relative differences between hills resulting in the gain of 1.79 found for the elderly verbal reports, compared to the 1.25 gain for verbal reports in the normative data. Pagano and Isenhower (2008) have recently demonstrated effects of expected range on verbal judgments of distance.

We must acknowledge that it is rather surprising that the palm board estimates given by the elderly do so closely correspond to those given by normative participants (see Fig. 14), but based on our investigation of palm boards, this close correspondence does not necessarily support the view that Bhalla and Proffitt espoused. After all, the gain of the palm board estimates is still quite low (i.e., less then 1) and the scaling of the elderly estimates may have been affected by exposure to the range of slopes shown to them. In support of the latter view, we note that the maximum average palm board estimates for the two subsets of elderly participants are within 1 deg of one another even though the steepest slopes for the two groups differed by 4 deg.

Overall, we think the data collected by Bhalla and Proffitt do not clearly show that hills are *perceived* as geometrically steeper by the elderly. The elevated estimates for steep hills may be an artifact of experimental demands or of the repeated measures design. The reduced estimates for low hills support the latter hypothesis and seem to strongly contradict the behavioral potential hypothesis.

7.3. No evidence for effects of behavioral potential on perception?

Perception for action should be fairly stable. Proffitt (2006, 2009) has emphasized that the effects of behavioral potential on conscious perception ought not to affect the representations used to control motor actions, and it is for this reason that the imputed dissociation between conscious reports and palm board estimates has such theoretical significance. Our critique of the palm board as a measure does not rule out the possibility that there exists an unbiased motor representation of the sort Proffitt advocates and has been suggested by others for near space (e.g., Milner & Goodale, 1995), nor does it prove that the conscious perception of geographical slant is stable, as we suspect may be true. However, we think there are significant methodological problems with all four of the studies reported by Bhalla and Proffitt (1999) to demonstrate the malleability of slope perception – and in many other similar studies.

A summary of design limitations in the four studies of Bhalla and Proffitt (1999) is shown in Table 1; a related summary of concerns regarding the analyses is shown in Table 2. The only study we have not already discussed concerned effects of fitness. Proffitt (2009) has rightly argued that the problem of experimental demand was less a concern for this study, because the measures of fitness were kept separate from the hill judgments. But even with-

Table 1
Design limitations of the four studies of Bhalla and Proffitt (1999).

Study	Major design limitation	Implication
1. Backpack	Uncontrolled demand character (no compelling explanation of backpack)	Participants cooperated
2. Fatigue	Uncontrolled demand character (fatigue is explicitly part of experiment)	Participants cooperated
3. Fitness	Selection bias for male athletes Athletes: 16 M; 8 F Non-athletes: 23 M: 27 F	Fitness confounded with sex
4. Elderly	Repeated-measures compared to between (each elderly participant judged four hills; comparison group each judged only one)	Exaggerate differences
	Uncontrolled demand character (elderly asked about “walkability” for someone “their age” prior to making estimate)	Participants cooperated

Table 2
Concerns with analyses of the four studies of Bhalla and Proffitt (1999).

Study	Major analysis concern	Problem
1. Backpack	Null palm board effect interpreted	Null effect not interpretable
2. Fatigue	Two null effects interpreted	Combined analysis $p < 0.05$
3. Fitness	Effects of sex not included in analysis	Fitness confounded with sex
4. Elderly	Analysis unclear for low slopes	Data contrary to hypothesis

out this concern, their study seems to have included an unexplained selection bias. Whereas Proffitt et al. (1995) reported that women tended to provide higher estimates of slopes then did men, Bhalla and Proffitt (1999) did not control for sex in their analyses of fitness. They reported that 67% of the athletes in their study were male, whereas the majority of their non-athletes were female. Because this suggests that sex and fitness were correlated in their study, it is notable that they do not control for effects of sex in their analyses. We simply do not know whether the effects they attributed to fitness were judgmental effects related to the gender differences found in their prior reports.

Finally, whereas Bhalla and Proffitt (1999) argued that palm board settings were “recalibrated” based on fitness, the basis for this claim (their haptic-match-to-verbal-task data) is susceptible to an alternative explanation. They reported that fitter individuals set the palm board higher than less fit individuals, but only when asked to produce the highest verbal angles requested (60 and 75 deg). This finding could also be explained if the *maximum* comfortable backward flexion of the wrist were correlated with fitness, which seems quite plausible.

A number of other effects attributed to effort (e.g., Proffitt, Stefanucci, Banton, & Epstein, 2003), intent (e.g., Witt, Proffitt, & Epstein, 2004), and fear (e.g., Stefanucci et al., 2008) have been shown to be methodologically flawed (or difficult to replicate) in a manner suggesting that no actual perceptual change was present (Durgin et al., 2009; Hutchison & Loomis, 2006; Russell & Durgin, 2008; Woods, Philbeck, & Danoff, 2009). Although our criticisms have been directed at a specific methodology and form of reasoning (from null findings) regarding the perception of geographical slant, our ultimate concern is with the nature of the theoretical claims that have sought to dissociate perception and action using these methods of evidence and argument. It may yet turn out that fatigue, for example, really does affect the visual evaluation of slope. However, null effects on palm board measures are not informative, for example, about whether fatigue is also likely to make us misstep.

7.4. Proprioceptive error

Historically, the bodily senses have often been treated as infallible and as the teachers of vision stemming back to Aristotle and, later, Aquinas (Jütte, 2008). In more recent times Bayesian theorists have noted that vision and touch interact in ways reflecting their differential sensitivities (Ernst & Banks, 2002). Proffitt et al. (1995) considered that the haptic misperception of palm boards that they observed (e.g., Fig. 13) was due to calibration to action. The studies of Creem and Proffitt (1998) were clearer in staking out the claim that a separate representation was involved, by appealing to dissociations between short-term memory and long-term memory. Bhalla and Proffitt (1999) extended this view by arguing for separate, but intercalibrated motor and perceptual representation. Based on our study, we believe that proprioception of the wrist is simply not well calibrated.

As part of a study of the haptic perception of orientation, Hajnal et al. (in press) found that haptic perception of surface orientation via dynamic touch by finger tip was accurate among sighted, but somewhat exaggerated for blind participants. They suggested that cross-modal interactions between vision and touch allowed a more-nearly Euclidean calibration of the portion of haptic space shared by vision and touch.

In our investigations of palm boards we have argued that a major source of error concerning palm-board orientation is proprioceptive error with respect to the perceived flexion of the wrist (Experiment 4). It is worth noting that the hand is rarely used for visually guided actions that involve wrist flexion alone. When reaching to a surface, the orientation of the hand can be adjusted by the simultaneous actions of many joints. Evidently this leaves the wrist itself uncalibrated to vision (or calibrated with the wrong gain). Our free-hand measures, which allowed coordinated use of shoulder, elbow and wrist joints to control the hand, show good calibration with respect to reachable surfaces when the hand was moved naturally, without artificial constraint. Thus, although the calibration of the finger by vision demonstrated by Hajnal et al. (in press) does not extend to arbitrary postures of joints like the wrist, it seems to apply to the orientation of an unseen hand when moved freely.

7.5. An alternative view of slope perception

If hills look so steep (and indeed they do), how can our actions be accurate with respect to them unless our action system has access to an accurate representation? Easily. Recall the watchmaker. The idea that palm boards reflect an accurate (calibrated) unconscious perceptual system used for action, has encouraged adherence to the idea that accurate perceptual representations are required to guide accurate action. Proffitt et al. (1995) wrote “Although the planning of molar, long-term aspects of gait is facilitated by perceiving an exaggeration of slant, the local task of visually guiding one’s feet is not.” (p. 425). We disagree. Exaggerated perceptual scaling of slope, like other forms of sensory rescaling (e.g., Durgin & Gigone, 2007; Durgin, Gigone, & Scott, 2005) may represent a recoding useful for action itself. Moreover, gaze during locomotion is not toward the feet, but ahead (Patla, 1997). Much as the watchmaker's actions can be guided more precisely by using a magnifying lens, the precision of our locomotor actions with respect to surfaces may be facilitated by systematic exaggerations in the perception of surface deviations from horizontal. A similar argument has been made for self-motion perception (Durgin, 2009). If the motor system conceives itself to be acting on the same steep surface that our conscious awareness observes, then systematic errors in perception pose no problem.

If this is the case, then we should expect that the haptic perception of surface orientation by foot would be similarly exaggerated. In fact, using both verbal and free-hand measures, Hajnal et al. (in press) have shown that ramps of 4–16 deg, when stood upon, feel about twice as steep as they are. Thus, the exaggeration of slopes in vision is also present in pedal haptic perception, consistent with earlier reports of correspondence between pedal and visual perception of slope (Kinsella-Shaw, Shaw, & Turvey, 1992). Notably, Hajnal et al. found that the pedal overestimation of haptic surface orientation was present in congenitally blind participants as well, and thus was not likely a *consequence* of visual exaggeration.

We conclude that the scaling of geographical slope perception may serve a functional role in the evaluation of surface orientation for purposes of action as well as planning, but that there is no need to posit a separate, "accurate", motor representation in this case. A recent study of downhill slope perception (Li & Durgin, 2009) provides support for the scale-expansion view. Li and Durgin demonstrated that failures of slope constancy with changes in viewing position could be modeled by coding exaggerations they documented in the perception of optical slant (surface orientation relative to gaze) and in the perceived direction of gaze (see also O'Shea and Ross (2007)): the scaling of both variables was found to be exaggerated. Because geographical slant is the arithmetic difference between optical slant and gaze direction, the dual perceptual exaggerations of these two variables approximately cancel out for a level ground plane, but will tend to exaggerate deviations from horizontal. Whereas the perception of wrist orientation may have little to do with slope perception for locomotion or planning, the exaggerated perception of head orientation and gaze declination and the exaggerated haptic perception of ramps underfoot may indicate that there are indeed advantages in expanding the scaling of geographical slant for the sake of precise motor action.

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