

A day at the beach: Does visually perceived distance depend on the energetic cost of walking?

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It takes less effort to walk from here to the Tiki Hut on the brick walkway than on the sandy beach. Does that influence how far away the Tiki Hut looks? The energetic cost of walking on dry sand is twice that of walking on firm ground (Lejeune et al., 1998). If perceived distance depends on the energetic cost or anticipated effort of walking (Proffitt, 2006), then the distance of a target viewed over sand should appear much greater than one viewed over brick. If perceived distance is specified by optical information (e.g., declination angle from the horizon; Ooi et al., 2001), then the distances should appear similar. Participants ($N = 13$) viewed a target at a distance of 5, 7, 9, or 11 m over sand or brick and then blind-walked an equivalent distance on the same or different terrain. First, we observed no main effect of walked terrain; walked distances on sand and brick were the same ($p = 0.46$), indicating that locomotion was calibrated to each substrate. Second, responses were actually greater after viewing over brick than over sand ($p < 0.001$), opposite to the prediction of the energetic hypothesis. This unexpected overshooting can be explained by the slight incline of the brick walkway, which partially raises the visually perceived eye level (VPEL) and increases the target distance specified by the declination angle. The result is thus consistent with the information hypothesis. We conclude that visually perceived egocentric distance depends on optical information and not on the anticipated energetic cost of walking.

After a brief review of egocentric distance perception, we consider the information-based account, in which perceived distance depends on visual information alone, and the embodied account, in which it also depends on the anticipated effort of walking. We then report an experiment designed to test whether visually perceived distance over different types of terrain is influenced by the energetic cost of walking on the substrate.

There is considerable evidence that egocentric distance is reliably perceived. Magnitude estimation of egocentric distance in the open field is generally linear, although underestimated by 20% to 30% (Foley, Ribeiro-Filho, & Da Silva, 2004; Knapp & Loomis, 2004; Loomis & Philbeck, 2008). A more intuitive, action-based measure is the blind-walking task, in which the observer views a target and then attempts to walk an equivalent distance with their eyes closed. Blind walking responses on firm ground are linear and quite accurate over target distances ranging from 2 to 26 m (Bodenheimer et al., 2007; Da Silva, 1985; Elliott, 1987; Knapp & Loomis, 2004; Loomis & Knapp, 2003; Loomis, Da Silva, Fujita, & Fukusima, 1992; Rieser, Ashmead, Talor, & Youngquist, 1990; Steenhuis & Goodale, 1988; Thomson, 1983). Although blind walking is thought to be a direct report of visually perceived distance (Philbeck & Loomis, 1997), the walked or “locomotor” distance during the response must also be measured by the human odometer.

The *information-based* view claims that perceived distance is based on visual information that specifies distance under natural conditions (Gibson, 2015). Consider the monocular information for egocentric distance available in the open field. The location of an object on the ground plane is specified by its point of optical contact with the ground surface (Gibson, 1950; Epstein, 1966), and its distance is specified by the declination of that point from the horizon (Sedgwick, 1973; Sedgwick, 1986). In particular, the angular declination from the horizon (α) to the contact point

Introduction

In a complex world, all distances are not created equal. A walk on the beach is not a stroll in the park. The same physical distance on two different surfaces can differ widely in the energetic cost or number of steps needed to walk that distance. It is generally assumed that the visual perception of egocentric distance is independent of the consequences of action, but in recent years that assumption has been questioned.

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specifies the egocentric distance (Z) of the object in units of eye height (E):

$$\frac{Z}{E} = \frac{1}{\tan\alpha} \quad (1)$$

Indeed, the evidence indicates that perceived distance varies systematically when the visual horizon or the declination angle is manipulated (Messing & Durgin, 2005; Ooi, Wu, & He, 2001; Wallach & O’Leary, 1982; Williams & Durgin, 2015), demonstrating that declination provides effective information for egocentric distance. Moreover, when the visual continuity of the ground surface is disrupted, egocentric distance is underestimated (Feria, Braunstein, & Andersen, 2003; Sinai, Ooi, & He, 1998; Wu, He, & Ooi, 2007).

To guide behavior such as blind walking, the information-based view proposes that optical information about distance is mapped to the control of action; this yields task-specific mappings for different classes of actions (e.g., walking, throwing, verbal estimates) (Rieser, Pick, Ashmead, & Garing, 1995; Warren, 1998; Warren, 2020). During everyday walking, for example, the optically specified distance to an object systematically covaries with the walked locomotor distance to reach that object, enabling the calibration of a mapping between declination angle and locomotor distance. This visual–locomotor mapping underlies blind-walking responses. How locomotor distance is measured by the human odometer on the basis of idiothetic information is not well understood, however (Chrastil & Warren, 2014; Turvey, Romaniak-Gross, Isenhower, Arzamarski, Harrison, & Carello, 2009; White, Shockley, & Riley, 2013). It is possible that the distance metric is independent of the terrain, as in a stride integrator (Wittlinger, Wehner, & Wolf, 2007), so blind-walked distances remain accurate on different substrates. Alternatively, the visual–locomotor mapping might be separately calibrated to each type of terrain. The information-based view thus holds that distance estimates are based on visual information (e.g., declination angle), and blind-walking responses are based on a visual–locomotor mapping.

The *embodied* view claims that perceived distance is based not solely on optical information but also on the energetic cost associated with walking. In particular, Proffitt and colleagues (Proffitt, 2006; Witt, Proffitt, & Epstein, 2004) proposed that visual perception relates the geometry of spatial layout to the anticipated effort of action. Because wearing a heavy backpack increases the anticipated effort of walking, the distance to a target on level ground appears greater when wearing a backpack; similarly, the slope of a hill appears steeper (Bhalla & Proffitt, 1999; Proffitt et al., 2003). Although the optical information remains the same when one dons the backpack, perceived distance or

perceived slope is the product of the information and the anticipated cost of walking. Because this does not affect the mapping from perceived distance to action, however, blind walking is still an accurate measure of perceived distance (Proffitt, Stefanucci, Banton, & Epstein, 2003; Witt et al., 2004).

The embodied view acknowledges a debt to Gibson’s (2015) concept of affordances (see Proffitt, 2006; Proffitt & Linkenauger, 2013). Gibson described affordances as properties of environmental surfaces taken with reference to the action capabilities of an animal. Because it is more energetically expensive to walk on some ground surfaces than others, their affordances for walking may differ, although the optical information for target distance over those surfaces is the same (e.g., declination angle). Energetic cost may thus influence affordance perception (Warren, 1984) and action decisions (Hayhoe, 2017), without affecting distance perception. Consequently, the information-based account predicts that, whereas affordance judgments should depend on energetic cost, distance judgments should not (Warren, 2020). In contrast, the embodied account conflates the perception of surface layout with perception of what the layout affords for action (e.g., Proffitt, 2009; Proffitt et al., 2003). Specifically, it proposes that distance judgments be treated as affordance judgments, and predicts that they both depend on optical information and anticipated cost (Proffitt, 2006; Proffitt et al., 2003).

The embodied account has been supported by findings of a main effect of anticipated effort on perceived layout in a wide variety of tasks (Bhalla & Proffitt, 1999; Lessard, Linkenauger, & Proffitt, 2009; Proffitt et al., 2003; Witt et al., 2004). If the energetic cost of performing an action influences the perception of the spatial layout, one would also expect that increasing the effort should increase the slope of the psychophysical distance function. However, on the occasions when distance perception has been tested at multiple target distances, the authors have not reported a significant interaction of effort and distance (Proffitt et al., 2003; Witt et al., 2004). Here, we leverage the large energetic difference between walking on sand and firm ground with a range of target distances to investigate the effect of anticipated cost on the slope of the psychophysical distance function.

Dry sand is a familiar example of an energetically expensive surface for human walking. On a firm, non-slippery substrate, the inverted pendular gait is highly conservative, requiring minimal muscular work (Cavagna, Thys, & Zamboni, 1976; Kuo, 2007). In contrast, a soft, granular substrate such as sand is displaced during push-off and heel strike, absorbing energy and increasing the cost of transport. The mechanical work and metabolic cost of walking on dry sand is 2.1 to 2.7 times greater than walking on a firm surface at the same speed (Supplementary Table S1)

(Davies & Mackinnon, 2006; Lejeune, Willems, & Heglund, 1998; Zamparo, Perini, Orizio, Sacher, & Ferretti, 1992). Consequently, if distance is perceived in units of energy expenditure, distance on a sandy beach should appear to be twice the same distance on firm ground. Critically, this means not only that there should be a main effect of terrain but also that this effect should increase proportionally with distance, yielding an interaction between terrain and distance.

The present study

In the present study, we used the blind walking task to test whether the energetic cost of walking influences visually perceived distance. The experiment was conducted at the TradeWinds Resort during the Annual Meeting of the Vision Science Society (VSS 2019), where we could find a sandy beach adjacent to a brick walkway (see Figure 1). Participants viewed a target over brick or over sand (i.e., viewed terrain), then turned and blind-walked an equivalent distance on the same or the other substrate (i.e., walked terrain). This crossed design yielded four view-walk conditions.

We expected that when viewing and walking on firm ground (firm-firm condition), participants

would accurately match the distance, as previously reported (summarized in Loomis & Knapp, 2003). If a higher anticipated effort caused the target to appear farther away, then after viewing over sand (sand-firm condition), participants should walk a significantly greater distance than after viewing over firm ground. In addition, because energetic cost increases proportional to distance, the difference between viewing over sand and firm ground should grow with target distance (i.e., an interaction between viewed terrain and target distance). On the other hand, if the response is based on the optical information for distance (e.g., declination angle), then walked distance should be similar when viewing over sand and firm ground, with no interaction between viewed terrain and target distance. Thus, the energetic hypothesis predicts that blind-walking responses should be greater after viewing over sand than over brick, whereas the information hypothesis predicts no difference between these conditions.

We tested both walked terrain conditions (sand and firm) for three reasons. First, a crossed design provided an internal replication of the effect of viewed terrain (firm-sand vs. sand-sand). Second, it allowed us to test whether locomotor distances on different substrates are equivalent. Specifically, given the intention to walk a given distance, is the executed distance the same on sand and firm ground? Finally, by randomly varying

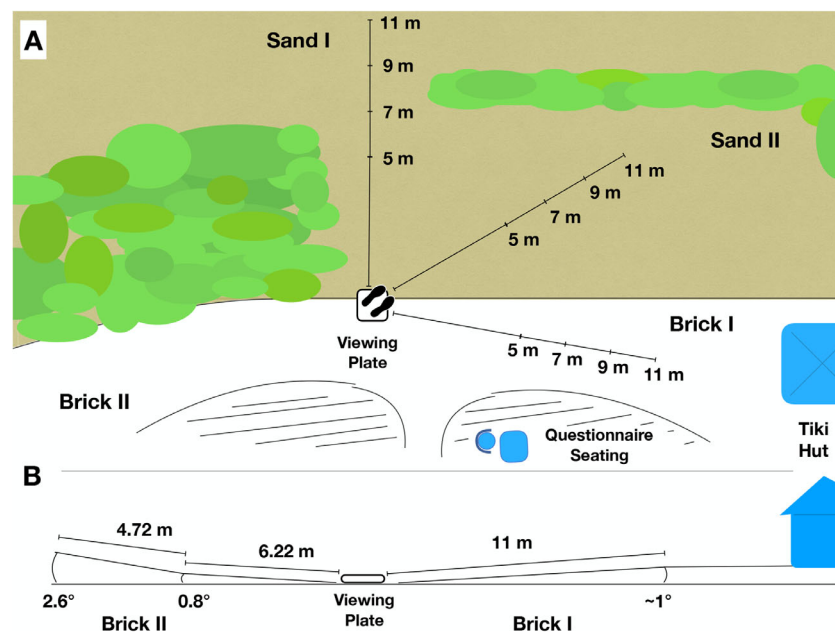


Figure 1. Set-up of the experiment. (A) Schematic of the testing area. The target cone was viewed at one of four distances (5, 7, 9, or 11 m) over firm ground (Brick I) or over sand (Sand I or Sand II). The participant made a blind-walking response on either the congruent or incongruent terrain (Brick II, Sand I, or Sand II). (B) Elevation schematic of the brick walkway. Brick II had an initially shallow segment (0.8°) followed by a steeper incline (2.6°); this surface was used for the blind-walking response. Brick I had a slope between the steep and shallow segments of Brick II, closer to the latter (estimated at about 1.0°). Due to COVID-19, we were unable to return and make exact slope measurements.

the walked terrain *after* blindfolding, we encouraged participants to match the perceived target distance and discouraged compensatory cognitive strategies during target viewing.

The viewed terrain manipulation thus allowed us to dissociate the predictions of the information-based account from those of the embodied account. We found no evidence that a greater energetic cost of walking increased perceived distance, contrary to the embodied hypothesis.

Methods

Participants

Thirteen adults (five females, eight males; 25.8 ± 3.6 years old) were recruited through posted flyers in the lobby area of the TradeWinds Resort, St. Pete Beach, FL. None reported having any visual or motor impairment, and they were paid for their participation. The protocol was approved by Brown University's Institutional Review Board, in accordance with the tenets of the Declaration of Helsinki. Permission to conduct the study was obtained from the VSS Board of Directors and the TradeWinds Resort management.

Apparatus and stimuli

The experiment was performed outdoors, where a brick walkway ran adjacent to a flat, sandy area (Figure 1A). The participant viewed a target while standing on a white, rubber base plate (0.5 cm thick) placed on the brick walkway. The target was a small (0.23 m tall) orange plastic traffic cone, placed on the ground. Target locations were marked by tan golf tees in the sand and red and black chalk marks on the brick, visible only to the experimenters. These markers were placed at four distances (5, 7, 9, and 11 m) from the base plate.

Two sand paths and two brick paths were used in the experiment (Figure 1A). Both Sand I and Sand II were level and used for target viewing and blind-walking responses. The Brick I walkway had a slight uphill grade in one direction ($\sim 1.0^\circ$), and Brick II began with a shallow incline for 6.22 m (0.8°) followed by a steeper grade for 4.72 m (2.6°) (Figure 1B). To minimize the influence of the ground slope on visually perceived distance, the shallower walkway (Brick I) was used for target viewing and the steeper walkway (Brick II) for blind-walking responses. Participants wore safety goggles lined with white paper to occlude their view of the surroundings without blocking the daylight, to prevent dark adaptation.

We attempted to measure the slope of the brick walkway using a laser rangefinder with a built-in level (BLAZE Pro 165 Foot Laser Measure, GLM165-40; Bosch, Gerlingen, Germany) by holding the rangefinder on a monopod at the base plate, aiming the leveled beam at a vertical white board on the walkway and measuring the height of the beam above the ground. The monopod made it difficult to maintain a level beam, and the bright sunlight made it difficult to measure the beam height reliably. Consequently, we used the Bubble Level application (Lemondo Ltd., Tbilisi, Georgia) on an iPhone 6 (Apple Corporation, Cupertino, CA) to measure the local slope of Brick II at regular intervals, but neglected to do so for Brick I. Brick I was clearly shallower than the steep incline of Brick II and closer to its minor incline (Figure 1B); we thus estimated the slope of Brick I to be about 1.0° . We planned to return with better instruments to VSS 2020, but were thwarted by the COVID-19 pandemic.

The distance walked by the participant was measured with the laser rangefinder from the front edge of the viewing base plate to a vertical white board (0.9 m by 0.6 m) placed at the participant's final position. Upon completion of the walking trials the participant was seated and answered a post-experiment questionnaire on an Apple iPad (7th generation).

Design

There were two viewed terrain conditions and two walked terrain conditions: the target was placed on the sand or on the brick walkway (viewed terrain), and the participant made a blind-walking response on either the congruent or incongruent terrain (walked terrain). This yielded four view-walk terrain combinations: sand-sand, sand-firm, firm-firm, and firm-sand. In each combination, the target was positioned at the same four distances, resulting in blocks of 16 trials. Viewing and walking were counterbalanced on the Sand I and Sand II paths; viewing occurred on the Brick I path, and walking on Brick II.

Procedure

Participants were instructed to view the target, note how far from them it looked, and then walk the same distance in a different direction while blindfolded. On each trial, the participant stood on the base plate, viewed the target, and placed the goggles over their eyes when they were ready to respond. Experimenter 1 then rotated the participant on the spot, gently by the shoulders, to face a new direction to walk. Participants were instructed to "walk quickly and decisively in that direction until you have covered the same distance that the target looked to be from

you.” The participant then began walking forward, accompanied by Experimenter 2. While the participant was blind-walking, Experimenter 3 moved the target cone to a new location for the next trial; the location was indicated by Experimenter 1 to Experimenter 3 with hand gestures to keep the participant naïve to the next condition.

Experimenter 2 intervened to stop the participant if a collision with other pedestrians or obstacles (e.g., a trash can) was imminent. If the participant walked too close to the edge of a path, slight pressure was applied to the participant’s elbow so they turned slightly while continuing to walk forward. To prevent experimenter bias or cuing, Experimenter 2 was instructed to attend only to the safety of the participant and had no knowledge of the tested distances or the location or appearance of the distance markers.

The participant stopped walking when they judged they had walked a distance equal to the target distance. Experimenter 2 then placed the white board at the participant’s heels, and Experimenter 1 recorded the laser rangefinder reading. Experimenter 2 then turned the participant and led them back to the base plate. About one step from the plate, the participant was instructed to lift the goggles, step onto the plate, and turn to view the next target. All experimenters stood behind the participant out of sight during the target viewing.

Each participant completed as many trials as possible in a test session lasting 1 hour, 15 minutes. Trial order was randomized within blocks. If a trial was interrupted by beachgoers, then the trial was redone at the end of the block, up to a maximum of four trials; after that, the trial was appended to the next block.

The post-experiment questionnaire asked about the participant’s beach experience and any conscious strategies used to match the target distance (see Supplementary Material). A session took approximately 1.5 hours to complete, including informed consent, test trials (with water breaks), and questionnaire. All sessions took place between 8:00 a.m. and 12:30 p.m.

Data analysis

The number of trials per subject varied due to individual differences in blind-walking speed. On average, each participant completed 51 trials (± 13 *SD*), slightly more than three trials per condition. Of the 662 total trials, 37 trials (5.6%) were interrupted and redone at the end of a trial block. Equipment malfunction due to temperature resulted in the loss of two post-experiment questionnaires.

We performed a linear mixed-effects regression analysis, which analyzes nested dependencies within datasets and copes well with missing data. The

dependent variable was walked distance (m). The fixed effects were target distance (5, 7, 9, and 11 m; centered continuous variable), viewed terrain (sand or firm), walked terrain (sand or firm), and their possible interactions. We used a maximal random-effects structure with a by-subject intercept, as well as by-subject random slopes for the effects and the interactions of viewed terrain, walked terrain, and target distance. The analysis was performed in MATLAB R2019a (MathWorks, Natick, MA) using the fitlme function (maximum likelihood approximation). *P* values were obtained by likelihood ratio tests of the full model with the effect in question against the model without the effect in question.

Results

Overall, participants walked an average of 1.1 times farther than the target; the mean and slope of this function were unaffected by the walked terrain but depended significantly on the viewed terrain. Specifically, viewing the target over sand yielded accurate responses on both sand and brick (Figure 2A, lower lines), but, unexpectedly, viewing over brick yielded overshooting on both terrains (Figure 2A, upper lines). This difference became more pronounced as the target distance increased (i.e., there was an interaction effect of target distance by viewed terrain).

Regression results for fixed effects are summarized in Supplementary Table S2. Means and slopes of the blind-walking responses did not depend on the walked terrain. The mean distance walked on brick (8.42 m) was not statistically different from that walked on sand (8.18 m), $\chi^2(1) = 0.550$ and $p = 0.458$, and the slopes were nearly equal, $\chi^2(1) = 0.044$ and $p = 0.834$ (Figure 2). This was the case whether the target was viewed over sand or brick. Specifically, as shown in Figure 2A, responses in the sand–firm and sand–sand conditions were nearly equal (two lower lines), and responses in the firm–firm and sand–firm conditions were, as well (two upper lines). Thus, there was no viewed by walked terrain interaction, $\chi^2(1) = 0.718$ and $p = 0.397$, or a three-way interaction, $\chi^2(1) = 0.343$ and $p = 0.558$. These results indicate that locomotor distances were equivalent on both types of terrain, and that responses were unaffected by the slight grade of the Brick II path.

Critically, we tested the embodied hypothesis that perceived target distance would be greater when viewed over sand than over firm ground. However, the results were in the opposite direction: on average, participants walked $0.68 \text{ m} \pm 0.16$ (*SE*) farther when viewing over firm ground than when viewing over sand, $\chi^2(1) = 10.818$ and $p = 0.001$ (Figure 2). In addition, the slope of the function was greater when viewing over firm

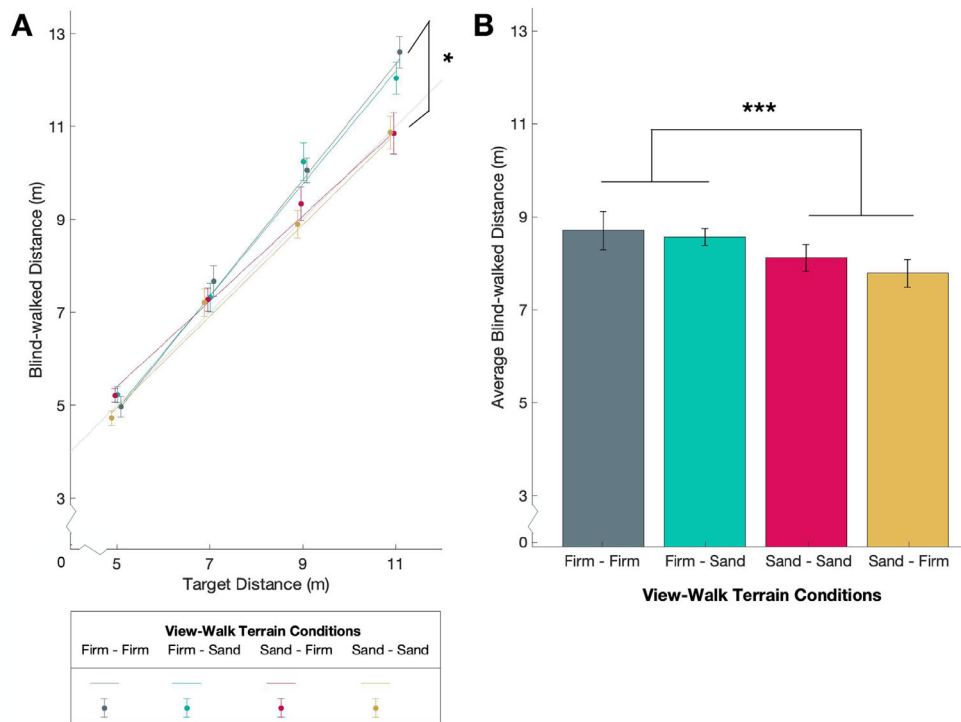


Figure 2. (A) The blind-walked distance (m) as a function of target distance (m). Mean responses ($\pm SE$) are plotted for each target distance (5, 7, 9, and 11 m) in each view–walk condition. Solid lines are the marginal regression model predictions in each condition. Means and predictions are slightly jittered horizontally for visibility. (B) Regression predictions of the marginal mean ($\pm SE$) blind-walked distances for the average target distance (8 m) in each view–walk condition. *Significant interaction of viewed terrain and target distance ($p < 0.05$). ***Significant effect of viewed terrain ($p < 0.001$).

ground than over sand, as indicated by a significant viewed terrain by target distance interaction, $\chi^2(1) = 5.978$ and $p = 0.014$. These results indicate that perceived distance was greater over the brick walkway than the sand beach and increased proportional to target distance. In sum, there was a significant effect of the viewed terrain, but in the direction opposite to the embodied hypothesis.

Accounting for the slope of the brick walkway

What might explain the unexpected overshooting when the target was viewed over firm ground compared with accurate blind-walking when it was viewed over sand? The viewed brick surface (Brick I) had a slight uphill slope, whereas the sand beach was level. Responses were quite accurate in both the sand–firm and sand–sand conditions (Figure 2A, lower lines), implying that the uphill slope of the response surface (Brick II) did not affect the walked distance. In contrast, responses overshoot the target distance in both the firm–firm and firm–sand conditions (Figure 2A, upper lines). We suggest that perceived distance was greater over firm ground than over sand due to the slight incline of the Brick I walkway.

As reviewed in the introduction, the declination angle from the horizon provides effective information for the distance of a target on the ground. When the ground is level, the visually perceived eye level (VPEL) coincides with the true horizon or inertial horizontal (IH) at 0° and with the geographical horizontal (GH) which is parallel to the ground plane (Figure 3A). However, if the ground surface is sloped, VPEL lies midway between the IH and the GH (Stoper & Cohen, 1989). When viewing outdoor scenes, VPEL shifts about 40% of the way to the GH over the range of slopes from -7° to 7° and saturates at about 4° when viewing uphill (O’Shea & Ross, 2007). For example, when looking up a 5° incline, the VPEL is 2° above the IH, and 3° below the GH. This partial shift in VPEL reduces the declination angle to targets on the inclined ground surface, producing corresponding increases in perceived distance (Messing & Durgin, 2005; Ooi et al., 2001; Wu, He, & Ooi, 2005), as well as perceived size (Matin & Fox, 1989; Stoper & Bautista, 1992). The increase in perceived distance on an uphill slope can explain the overshooting we observed when the target was viewed over Brick I.

Figure 3 illustrates how the perceived distance of the target would increase on a slight uphill slope compared with flat sand and consequently predict a

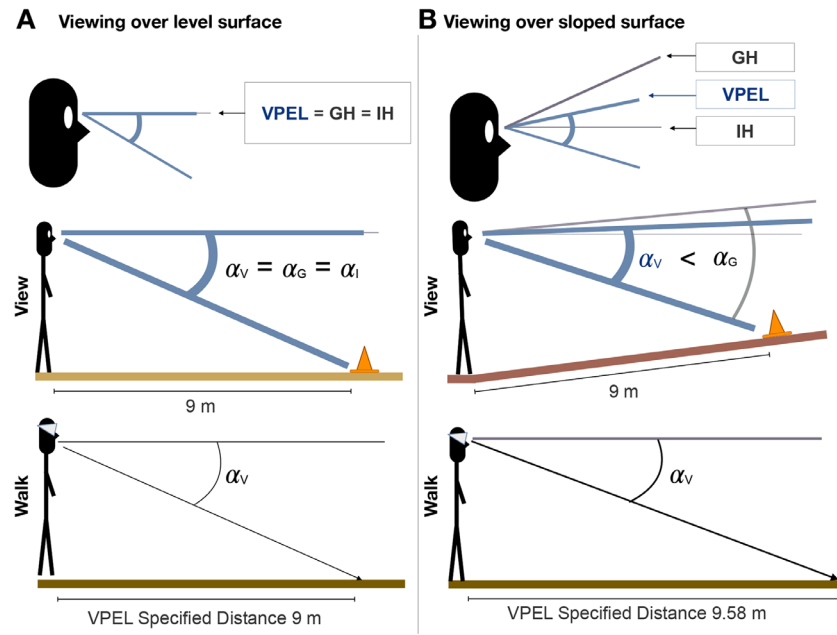


Figure 3. Visual distance specified by declination angle depends on ground slope. (A) When viewing a 9-m target on level sand, the VPEL is parallel to both the GH and the IH or horizon (top). Thus, the declination angles from all three are equivalent (middle). The predicted blind-walking distance is 9 m, based on an assumed eye height of 1.6 m, and the declination angle from the VPEL (10.08°) (bottom). (B) When viewing a 9-m target on an uphill slope of 1.0° , VPEL is now 0.4° above the IH and 0.6° below the GH (top). The declination of the target from VPEL (9.48°) is thus smaller than in (A), corresponding to a perceived distance 0.58 m farther away (middle). For a blindfolded participant (bottom), VPEL corresponds to the IH (0°), so the declination angle from the VPEL predicts a walked distance of 9.58 m. Note that if VPEL were completely captured by the sloping ground, so it was parallel to the GH, the declination angle (α_v) would be equal to α_G and the response distance would be 9 m in both (A) and (B).

greater blind-walking response. First, assuming an average eye height of 1.6 m, each target position on level ground projected a corresponding declination angle from the VPEL (Figure 3A, middle). Second, when viewing a 1° incline (Brick I), the VPEL increased by 40% of that value, shifting it 0.4° above the IH and 0.6° below the GH (Figure 3B, top and middle). Critically, this reduced the declination angle from VPEL to each target position by 0.6° compared with viewing over level ground (Figure 3, middle). Thus, by Equation 1, the VPEL-specified distance of each target increased proportionally. The reduced declination angle maps to a correspondingly greater blind-walking response (Figure 3, bottom). In sum, when a target is viewed over the slight incline of the brick walkway (Figure 3B), its declination angle intersects the ground at a greater distance than when viewed on the level sand (Figure 3A), predicting the observed effect of viewed terrain.

We corrected the target distances when viewed over Brick I (view firm) in this manner and then repeated the previous regression analysis. Specifically, we substituted the VPEL-specified distance in place of the physical target distance and predicted the blind-walked distance as before. This effectively expanded the x -axis for the

view firm data (cf. Figure 2A, Figure 4A), reducing the slopes of the two upper lines. As fixed effects, we entered viewed terrain (sand or firm), walked terrain (sand or firm), and the VPEL-specified target distance (centered on 8 m) into the model, with a maximal random-effects structure. Regression results for fixed effects are summarized in Supplementary Table S3.

When response distance was plotted as a function of the VPEL-specified target distance, the means and the slopes in each view-walk condition were not significantly different (Figure 4). All slopes were close to the diagonal ($1.03 \pm 0.05 SE$), with no effect of viewed terrain or walked terrain, nor any interactions. Critically, correcting for the shift in VPEL eliminated the previous effect of viewed terrain. The mean distance walked after viewing the target over Brick I (8.10 m) was no different from that when viewing over sand (7.96 m), $\chi^2(1) = 0.911$ and $p = 0.340$, and the slopes were nearly equal, eliminating the viewed terrain by target distance interaction, $\chi^2(1) = 2.484$ and $p = 0.115$. These results indicate that the unusual overshooting after viewing on firm ground can be explained as a visual effect of the slight incline of Brick I.

Mean blind-walking responses were still unaffected by the walked terrain. The mean distance walked

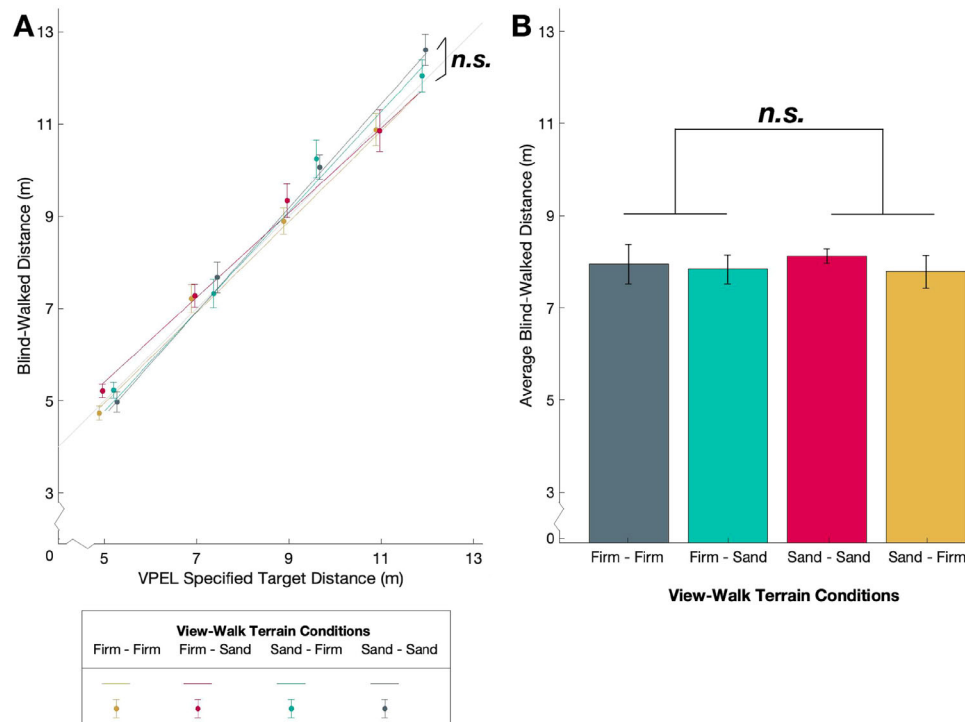


Figure 4. The declination angle from VPEL is calculated for viewing the target over the level sand surface and the sloped (1°) brick walkway. This eliminated the difference between the intercepts and slopes of the viewed terrain conditions (i.e., no main effect of viewed terrain or interaction with VPEL-specified target distance; not significant). (A) The blind-walked distance (m) plotted as a function of the VPEL-specified target distance (m). For targets viewed on the sand (warm tones), the VPEL-specified target distances coincide with the actual distances (5, 7, 9, and 11 m). However, when viewing the target over the sloped, firm walkway (cool tones), the VPEL-specified distances were 5.19, 7.35, 9.58, and 11.87 m. Solid lines are the marginal regression model predictions. (B) Regression predictions of the marginal means (\pm SE) blind-walked distance for the each view-walk terrain pair at a target distance of 8 m.

on Brick II (8.14 m) was no different from that for walking on sand (7.91 m), $\chi^2(1) = 0.585$ and $p = 0.444$, and their slopes are nearly equal, $\chi^2(1) = 0.035$ and $p = 0.851$ (Figure 4). These results confirm that locomotor distance was equivalent on both types of terrain and was unaffected by the slight grade of Brick II.

In sum, perceived target distance is specified by the declination angle from VPEL, independent of the energetic cost of the terrain. To what extent does this conclusion depend on our estimate of the Brick I incline (about 1°)? A steeper estimate might not merely eliminate the effect of viewed terrain but could actually reverse it: As the grade increases so does the VPEL-specified target distance, up to an incline of about 7° (O'Shea & Ross, 2007). This would effectively expand the x -axis for the view firm conditions further than in Figure 4A, resulting in a shallower slope than in the view sand conditions. The results would then appear to be consistent with the energetic prediction. In short, we could potentially explain away findings that are opposite to or consistent with the energetic hypothesis by assuming an appropriate grade for the Brick I walkway.

To evaluate this possibility given our data, we computed the VPEL-specified target distances for Brick I inclines ranging from 0° to 5° , in 0.1° increments, and repeated the regression analysis. The results appear in Figure 5, which plots the significance of the likelihood ratio tests (p value) for the main effect of viewed terrain (purple diamonds) and its interaction with VPEL-specified target distance (magenta circles), as a function of the Brick I incline, where the horizontal red line represents the $p < 0.05$ cutoff.

Inclines from 0.0° to 0.7° yielded significant main effects and interactions similar to our original analysis of the raw data (Figure 2). The regression slopes are steeper in the view firm than view sand conditions. Inclines between 0.8° and 1.7° , however, yielded no main effect of viewed terrain, and those between 0.8° and 3.7° yielded no interaction. These effects did not significantly reverse until the incline reached 3.8° , at which point the regression slopes are shallower for the view firm condition than the view sand condition; both the main effect of viewed terrain and the interaction of VPEL-specified distance by viewed terrain become significant. We are confident that the incline of Brick I

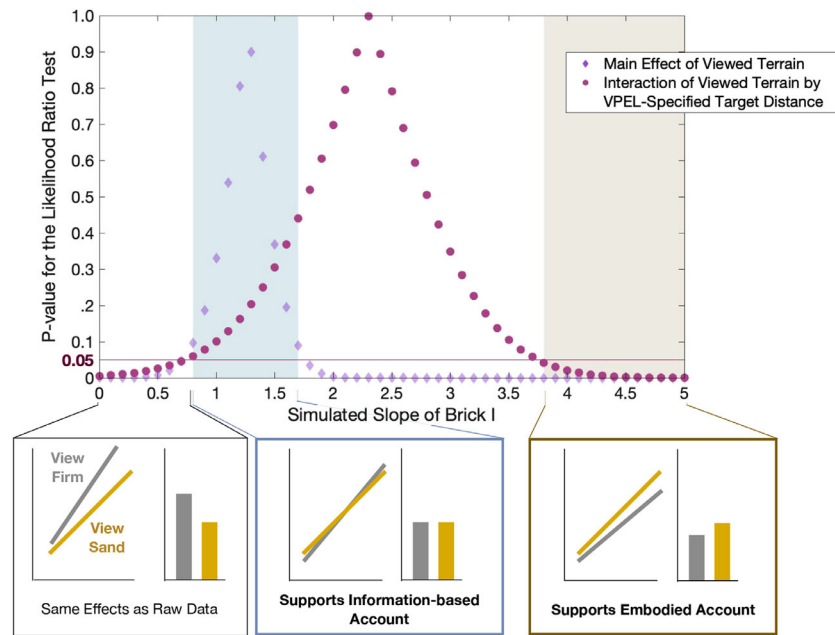


Figure 5. Likelihood ratio tests of regressions models with VPEL target distance, correcting for ground slope from 0° to 5° . Figure shows the p value of the main effect of viewed terrain and the interaction between viewed terrain and target distance, as a function of the ground slope. The original significant main effect of viewed terrain and its interaction with target distance, falling below the dark red line ($p < 0.05$), occurs for a ground slope up to 0.7° . All effects are non-significant for ground slopes between 0.8° and 1.7° (blue shaded area), supporting the information-based account. The significant main and interaction effects of viewed terrain to the right support the embodied account ($>3.7^\circ$; dark yellow shaded area). General trends representing viewed terrain regression slopes and marginal means (i.e., interaction with VPEL-specified target distance and main effect) are illustrated below each range of note. Additionally, all ground slopes result in non-significant effects of walked terrain.

was well below the measured 2.6° incline of Brick II, within the 0.8° to 1.7° range.

In sum, the unusual overestimation of distance when viewing over firm ground can be attributed to the slight uphill grade of the brick walkway, which increased the perceived target distance specified by the declination angle from VPEL. When this slight incline is taken into account, there are no significant effects of viewed terrain. We thus take the results to indicate that perceived target distance is based on visual information and is independent of the anticipated cost of walking on the terrain. These results support the information-based account and do not support the embodied account.

Post-experiment questionnaire

To analyze the results of the post-experiment questionnaire, we performed linear regressions on blind-walked distance including explicit strategies and days spent at the beach as predictors, in addition to previous factors (viewed terrain, walked terrain, and target distance). The queried explicit strategies included consciously adjusting for the relative number

of steps or the relative effort required to walk on sand versus firm ground (adjust steps and adjust effort; see Supplementary Table S4) and visualization of the target location or the surroundings during blind walking (visualize target and visualize surround; see Supplementary Table S5). Days spent at the beach were estimated by the participant for the past year and their lifetime.

Mean blind-walked distance remained unaffected by the walked terrain. Including explicit terrain-based strategies into the regression did not account for the ability of the participants to walk the same distance on sand as they did on firm ground. The mean distance walked on the brick walkway (8.63 m) was no different from that for walking on sand (8.29 m), $\chi^2(1) = 0.749$ and $p = 0.387$, and including the interactions with adjust steps and adjust effort did not significantly influence the response (Supplementary Table S4). These results indicate that locomotor distance was equivalent on both types of terrain, and these explicit strategies did not significantly affect the response.

Visualizing the surroundings predicted participants undershooting the target distance by 0.68 m on average, $\chi^2(1) = 4.929$ and $p = 0.026$, whereas visualizing the

target location had no effect on the response nor did the interaction between visualizing the surroundings and the target significantly affect walked distance, $\chi^2(3) = 6.916$ and $p = 0.075$. This suggests that visualizing the passing surroundings may have increased the estimate of traveled distance or walking speed. Visualization did not interact with walked terrain, $\chi^2(1) = 0.348$ and $p = 0.555$, as the mean walked distances on sand and on firm ground were the same. These results indicate that locomotor distance was equivalent on both types of terrain, and visualization did not significantly change the walked terrain response.

We constantly walk across firm surfaces in daily life, but how many days at the beach are required to calibrate walked distances on sand? The median number of days at the beach in the past year was 6 days ($Q_1 = 2.75$, $Q_3 = 8.75$), whereas the recalled number of beach days over the lifetime had a median of 50 days ($Q_1 = 21$, $Q_3 = 95$). As predictors of walked distance, days at the beach over the lifetime and in the past year did not interact with walked terrain, $\chi^2(1) = 1.644$ and $p = 0.200$, and the effect of walked terrain remained null, $\chi^2(1) = 0.438$ and $p = 0.508$. The ability to blind-walk the same distance on sand and firm ground thus did not appear to depend on the number of previous days at the beach, at least over the range of 10 to 700 days. This suggests either that the distance metric of the odometer is invariant across firm ground and soft sand or that a visual-locomotor calibration for new terrain can be established in a few days.

Unexpectedly, we did find a significant interaction between the number of days at the beach in the past year and over the lifetime, $\chi^2(1) = 3.964$ and $p = 0.046$. This effect appears to be driven by an outlier, as one participant had spent 700 days at the beach! Removing the outlier did not impact the regression estimates; the outlier was not an influential point. Although the regression coefficients remained the same (Supplementary Table S6), however, the effect of days at the beach become non-significant. This suggests that the number of days spent at the beach, at a scale of the past year or lifetime, does not impact blind-walking performance.

In sum, the inclusion of explicit strategies in the regression analysis, such as adjusting for the effort of walking or visualization, did not alter the main findings illustrated in [Figure 2](#). Viewed terrain and its interaction with target distance remained significant predictors of the response, whereas walked terrain still had no effect. The mean distance walked on brick was no different from that for walking on sand, indicating that walking was unaffected by conscious strategy use and by the number of days spent at the beach. Either the visual-locomotor mapping can be calibrated to a new terrain with a few days of experience or the

odometer distance metric is invariant across different substrates.

Discussion

To investigate whether the energetic cost of walking influences the perception of egocentric distance, we manipulated the terrain over which a target was viewed and on which a blind-walking response was made (firm brick or soft sand). We found no overall effect of walked terrain, indicating that locomotor distance was equivalent on both sand and firm ground. We did, however, observe an unexpected effect of viewed terrain, as responses were accurate for targets viewed over sand but overshot targets viewed over brick, increasingly so as a function of target distance. This result was the opposite of the embodied prediction but can be explained by the visual information at the test site.

According to the embodied view, the perception of egocentric distance is a product of optical information and the anticipated effort of the intended action ([Proffitt et al., 2003](#); [Witt et al., 2004](#)). This hypothesis predicts that viewing a target over sand with the intention to walk that distance should increase the perceived distance of the target compared with the same target viewed over firm ground. Even if both targets have the same declination angle, the greater energetic cost associated with walking on sand would yield a larger perceived distance and produce a greater blind-walking response. The embodied hypothesis thus predicts a significant effect of viewed terrain and an interaction with target distance, proportionally overshooting target distances viewed over sand compared with firm ground. Contrary to this hypothesis, however, we observed the opposite effect and interaction, with proportional overshooting of targets viewed over firm ground compared with sand.

According to the information-based view, egocentric distance perception depends on the available visual information for target distance; in the open field, the declination angle from the perceived horizontal (VPEL) provides effective information. This hypothesis predicts accurate blind-walking responses, assuming that walked distances are equivalent on the two types of terrain. Indeed, blind-walking to targets on firm ground has repeatedly been found to be accurate or to slightly undershoot the target (see [Loomis & Knapp, 2003](#)). Thus, the present finding of overshooting targets viewed over firm ground was initially puzzling; however, when the topography of the test site was taken into account, this overshooting could be explained by the shallow uphill slope of the viewed brick walkway.

The viewed walkway (Brick I in [Figure 1](#)) had a slight incline of approximately 1.0° , which has been shown to

partially shift the VPEL by 40%, to 0.6° below the GH parallel to the incline. Consequently, the declination angle of a target from the VPEL was smaller on the brick walkway than on level sand, specifying a greater target distance (mean of 8.71 m on brick vs. 8.0 m on sand) (Figure 3). The mapping from declination angle to walked distance thus yielded a larger response. After correcting the VPEL, we found that the blind-walked distance was close to the VPEL-specified distance in all conditions, eliminating the viewed terrain effect and interaction (Figure 4). It is important to note that our ability to determine the true geographical slant of Brick I was limited, and the participants did not make explicit judgments of VPEL. However, Figure 5 simulates a large range of ground slopes adjusting for a shift in VPEL based on the empirical findings of O’Shea and Ross (2007), and our approximate slope of 1.0° coincidentally accounts for the overshooting after viewing a target over brick. Our results can thus be explained by the optical information present at the test site, consistent with the information-based hypothesis. Contrary to the embodied hypothesis, we conclude that perceived egocentric distance does not depend on the anticipated effort of walking on the viewed substrate.

The present experiment joins a number of other studies that have failed to find “action-specific” effects on the visual perception of spatial layout that are predicted by the embodied view. They include studies of perceived distance (Durgin, DeWald, Lechich, Li, & Ontiveros, 2011; Hutchison & Loomis, 2006; Woods, Philbeck, & Danoff, 2009), perceived slant (Durgin, Baird, Greenburg, Russell, Shaughnessy, & Waymouth, 2009; Durgin, Klein, Spiegel, Strawser, & Williams, 2012), and perceived size (Firestone & Scholl, 2014). Various alternative explanations have been offered for action-specific findings, including the demand characteristics of the experiment, cognitive intrusions on perceptual judgments, or a response bias to judge affordances rather than spatial properties. The present results confirm that, in a task that emphasizes how the layout *looks*, responses are driven by optical information. Ironically, this conclusion is reinforced by our finding that an accidental property of the test site produced a visual effect of viewed terrain in the direction opposite to the energetic prediction.

We hasten to point out that, even if the energetic cost of action does not influence perceived spatial layout, it is known to affect affordance perception and action selection. For example, Warren (1984) found that the energetic cost of climbing stairs with different riser heights predicted affordance judgments of the preferred stairway to climb. Decisions about gait selection and reach trajectories are also based on the energy expenditure of the associated actions (Long & Srinivasan, 2013; Shadmehr, Huang, & Ahmed, 2016). Energetic cost thus influences behavioral decisions, if not the perceived layout per se.

Finally, to explain blind-walking performance, some account of how the human odometer measures walked distance is needed. Our finding that the blind-walked distance was the same on brick and sand, with no effect of walked terrain, indicates that a given intended distance is carried out equivalently on two very different substrates. This result implies either separate calibrations of the visual–locomotor mapping to soft sand and firm ground or a locomotor distance metric that is invariant across substrates.

The number of steps and energetic cost required to walk a given distance on sand are both greater than on firm ground (Lejeune et al., 1998) (Supplementary Table S1). The higher energetic cost of sand is due, in part, to an increase in work done by the foot, a decrease in muscle–tendon efficiency, and an increase in limb movement (Lejeune et al., 1998). Although step frequency and step length do not differ between sand and firm ground when walking at the same speed, a slower preferred walking speed is adopted on sand (Leicht & Crowther, 2007; Zamparo et al., 1992). This results in a lower step frequency, smaller step length, and 5% more steps to walk the same distance on sand. If blind-walking were guided by a fixed visual–locomotor mapping in which the measure of walked distance is expended energy or number of steps, then participants would have stopped short when walking on sand compared with firm ground. Our finding that walked distance was the same on both substrates implies either that the mapping is calibrated to the substrate-specific biomechanical cost or that the locomotor distance metric is independent of biomechanical cost. An example of the latter would be a stride integrator based on some idiothetic information (Chrastil & Warren, 2014; Turvey et al., 2009; Wittlinger et al., 2007).

Although participants were instructed to blind-walk quickly and decisively to match the target distance, conscious strategies may have been employed to compensate for the difficulty of walking on the terrain. A skeptic might argue that participants consciously compensated for sand being more difficult to walk on by deliberately overshooting the felt target distance, thus *appearing* to be calibrated to soft sand as well as firm ground. Indeed, nearly half of the participants reported consciously adjusting their steps and/or the effort of walking to match the visually perceived target distance. However, the regression analysis showed that such conscious strategies did not significantly contribute to the walking response.

Conclusion

The present experiment tested the embodied hypothesis that visually perceived distance is influenced by the energetic cost of walking, using a blind-walking

task. Although we observed a significant effect of the viewed terrain, it was in a direction opposite to the energetic prediction and can be attributed to the slight incline of the viewed brick walkway. The results can be explained by the optical information for target distance (declination angle from VPEL) in all conditions. The present findings thus support the hypothesis that the visual perception of egocentric distance is based on optical information and does not depend on the anticipated effort of walking.

Keywords: distance perception, embodied perception, visual perception, locomotion, ecological optics

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