Abstract of “Are You 'Shore' It Looks Farther Away: Does the Energetic Cost of Walking On Sand Influence Perception of the Spatial Layout or the Affordance for Action?” by Brittany A. Baxter, Ph.D., Brown University, May 2021.

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Experiments using a perceptual matching task in which standard and comparison targets appeared on sand and/or brick surfaces were conducted in virtual reality. Participants adjusted the distance of the comparison to match either the perceived energetic cost, perceived ease of walking, or perceived distance of the standard. The energetic cost and difficulty of walking on sand were judged to be significantly greater

than on firm ground. Once again, contrary to the *embodied* hypothesis, the anticipated effort of walking had no influence on perceived distance.

The present results underscore that judgements of spatial layout should not be conflated with judgments of what the layout affords for action. Perceived egocentric distance is based on visual information such as declination angle, whereas the perceived cost of walking is based upon visual information about the layout and composition of the ground surface.

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Are You 'Shore' It Looks Farther Away: Does the Energetic Cost of Walking On Sand Influence Perception of the Spatial Layout or the Affordance for Action?

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CHAPTER 1

General Introduction

I have walked from my apartment to campus on seven different routes, but which is the most efficient? I would like to believe that the route I have taken most frequently over the past year is the most efficient one, but many factors could contribute. If given a map, I could plot the shortest, most direct course. Yet, this would not guarantee an efficient route – indeed, the straightest path goes up the steepest part of College Hill and leaves the sidewalk to cut across terrain that is much more difficult to walk on. So let's do away with the map and ask, is there visual information right in front of me that would lead me down a shorter, less effortful, or more walkable path? These visual variables would need to inform me about the distance and cost of available paths, to enable me to choose the best route. The purpose of this dissertation is to investigate whether the energetic cost of walking influences the perceived distance of the path and the perceived affordances of the terrain. Locomotion provides a test case of the more general problem of action selection: when faced with multiple pathways to realize a goal, how do I select a particular course of action? The preferred solution is likely to depend on my action capabilities, the properties and layout of the environment, and the difficulty or cost of the available paths.

Route Selection in Robots and Humans

Robots and humans share similar challenges in navigating cluttered terrain. Each obstacle on the way to a goal creates a bifurcation in the tree of possible routes, such that the number of alternative paths increases geometrically. Route selection from the start position to the goal position is a problem with numerous possible solutions. In the field of robotics, the problem is defined as finding the optimal route that minimizes some objective function related to overall cost. The approaches to solving this problem are generally divided into methods that require a metric map of the environment (global path planning) and those that depend on the local information about the relative positions of obstacles and goals (local path planning).

Global path planning algorithms generally choose a route to a goal by minimizing the total path length or path curvature within the given constraints. They assume a prior map of object locations, which leads them to fail in dynamic environments or when there are irregularities between the map and the real environment (for review see Bonin-Font et al., 2008; DeSouza & Kak, 2002; Güzel, 2013). In contrast, local path planning algorithms (e.g. Sezer & Gokasan, 2012), are based on current information, and have a flexibility that is lacking in global map-based algorithms. Like humans, they take advantage of prospective information about upcoming objects to traverse cluttered, novel, or dynamic environments successfully. They generally include rules that prioritize goal directedness while minimizing changes in direction (heading) and maintaining a minimum distance from obstacles (Fox et al., 1997; Simmons, 1996; Ulrich & Borenstein, 1998). The resulting paths thus emerge from local interactions with obstacles rather than being globally pre-planned.

These local variables are weighted to yield paths that satisfice, that is to say, paths that are sub-optimal compared to the optimal path computed from a global map but better than the worst possible path. Qualitative, and quantitative, assessment of simulated paths through randomized obstacle arrays are used to select and weight parameters to achieve ‘successful’ navigation (i.e. satisficing paths). Parameter fitting is often performed using a cost function that minimizes the length, oscillations, collisions, average speed, or time to goal of the emergent paths. Goal directedness, or minimizing the deviation from the goal direction, commonly produces shorter, more direct paths through cluttered environments (Borenstein & Koren, 1991; Fox et al., 1997; Simmons, 1996; Ulrich & Borenstein, 1998). Minimizing the deviation from current heading was introduced into the Vector Field Histogram (VFH+) approach to create smoother paths of a more consistent speed (Borenstein & Koren, 1991; Ulrich & Borenstein, 1998). The minimum allowable distance from obstacle boundaries trades off with minimizing the deviation from the goal and from the current heading, which often coincide. There is a fine balance between taking a direct path to the goal and causing a collision.

Similar local strategies -- minimizing deviation from the goal and the current heading while avoiding collisions -- have been observed in human locomotion during obstacle avoidance and goal selection (Baxter & Warren, 2018, 2020; Cohen & Warren, 2007). When walking to a goal, Fajen & Warren (2003) showed that pedestrians minimize their deviation from the goal direction, in combination with steering around obstacles. When selecting between two competing goals, pedestrians choose the goal that minimizes the deviation from their current heading. Cohen and Warren (2007) manipulated the initial distance and deviation of the two goals from the initial heading, and asked participants to walk to their preferred goal. When the distances were equal, participants tended to prefer the goal with the smaller deviation angle; conversely when the deviation angles were equal, they preferred the closer goal. During barrier avoidance, all three variables play a role. Gérin-Lajoie and Warren (2008) manipulated the degree to which a barrier obstructed a participant's path to a goal and reported a preference to circumvent the barrier by walking around the end that required the least deviation from the goal direction; however, this was confounded with the other variables. In a recent revival of this line of work, I found that, when distance to each end of the barrier is varied, the smaller distance trades off with the smaller deviation from the goal in determining the preferred route around the barrier (Baxter & Warren, 2019, 2020). When all three variables are dissociated, deviation from the goal is the strongest predictor of the preferred route, while distance and deviation from current heading have weaker influences (Baxter & Warren, 2018, 2020). Current models of pedestrian behaviour also take advantage of these local variables, including the steering dynamics model (Fajen & Warren, 2003; Warren & Fajen, 2008), the Social Force model (Helbing & Molnar, 1995), and cognitive heuristics models (Dutra et al., 2017; Moussaid et al., 2011).

Importantly, these local variables are better predictors of human route selection than the global path length or path curvature (Baxter & Warren, 2018). Moreover, they also tend to reduce the overall length and energetic cost of the route, which suggests that humans take a satisficing path (Baxter & Warren, 2018, 2020; Fajen & Warren, 2010). Circumventing an obstacle requires turning away from the direction of the goal, and some available paths require larger deviations or sharper turns than others. These maneuvers impact the energetic cost of the route, which is a consequence of the total path length and the biomechanical forces required to turn, brake, and accelerate. As in robotics, minimizing deviation from the goal direction tends to produce shorter, more direct paths through cluttered environments (Fajen & Warren, 2010). Minimizing changes in heading also reduces the energetic cost of a route by reducing the lateral forces required to make a turn, as well as the longitudinal forces required to make the speed changes that accompany turning (Hicheur et al., 2007). During unobstructed straight walking, humans maintain their preferred speed but stereotypically decelerate while turning and then accelerate coming out of the turn. This preferred walking speed minimizes metabolic cost per unit distance, as measured by oxygen consumption, and pedestrians return to this speed quickly following a perturbation (Alexander, 1989; Selinger et al., 2015). A straighter path thus allows a steady-state walking speed over a shorter distance, so the trajectory to the goal is more efficient. These findings suggest that local variables account for human route selection, and result in paths that tend to be energetically efficient without requiring global optimization procedures.

Information-Based Control of Locomotion

Vision is paramount for obstacle avoidance in humans as it provides prospective, local information about the layout of the environment and about self-motion relative to surrounding objects (Patla, 1998). One's heading direction with respect to objects is specified by the optic flow pattern (J. Gibson, 1950; Warren, 2007a) and optic flow is used to make online steering adjustments during locomotion (Bruggeman et al., 2007; Cutting et al., 1995; Sherrill et al., 2015; Warren et al., 2001). Humans rely on this heading information in visually rich environments to steer toward a visible stationary goal by aligning the focus-of-expansion with the goal (Bruggeman et al., 2007; Warren et al., 2001). Moreover, Warren and colleagues (2001) found that human subjects steer to a goal in a sparse environment with no ground plane or texture by nulling the angle between the goal and the locomotor axis (the target-heading angle). In virtual reality, these two variables were segregated, but in everyday locomotion, the locomotor axis and heading coincide. It has also been shown that the change in bearing direction (Cutting et al., 1995) and time-to-contact (Lee, 1980; Tresilian, 1990) of an object are perceived; nulling the change in bearing direction can be used to intercept moving targets (Chardenon et al., 2002; Fajen & Warren, 2004, 2007; Lenoir et al., 2002). These perceptual capacities ground the local variables common to both human route selection and robot path planning, including minimizing deviation from the goal direction, minimizing deviation from the current heading, maintaining a minimum distance (or time-to-contact) from obstacles, and preferring closer goals.

The Perception of Spatial Layout

As reviewed above, walking humans tend to prefer the closer of two goals and the nearer end of a barrier, presumably because smaller distances reduce energetic cost. Similarly, robot path planning algorithms tend to minimize distance, presumably because shorter paths are more efficient. This only holds, however, as long as the alternative paths traverse the same terrain. In fact, the same physical distance on two different surfaces can differ widely in the energetic cost or number of steps needed to walk that distance. So let's reconsider the perception of distance through the lens of efficiency: it is possible that pedestrians perceive not the geometric distance of a goal, but the effort required to get there.

It is generally assumed that the visual perception of egocentric distance is independent of the energetic cost of action, but in recent years that assumption has been questioned and is now hotly debated (see Durgin, 2017; Firestone, 2013; Proffitt, 2013; Schnall, 2017). I first consider current accounts of distance perception, including the geometric and information-based views, in which perceived distance is independent of energetic cost. I then consider the embodied view, according to which perceived distance depends on the anticipated effort of walking.

Geometric view. A common view of distance perception assumes that perceived distance generally corresponds to the physical distance between locations in space, as measured in Euclidean geometry (Loomis & Beall, 2004; Loomis et al., 1992). The long history of psychophysical investigation of visual space has been conducted independently of research on the control of action because it is assumed that depth cues are used to compute an internal representation of the surrounding 3D space, and this internal model provides the basis for any action. Action does not contribute to spatial perception. According to this view, perceived space can be measured through both non-action and action-based indicator variables (e.g. verbal reports and blind-walking), because they should co-vary as the cues to distance are manipulated (Loomis & Knapp, 2003). On the geometric view, perceived distance provides a common basis for a variety of spatial responses, including actions such as walking or throwing as well as verbal estimates (Loomis & Beall, 2004).

Comparable distance estimations have been found for perceptual matching and blind-walking tasks in the real world and in virtual reality (Sinai et al., 1999; Sinai et al., 1998). When performing a perceptual matching task, the observer adjusts the position of a target (what we will term the ‘comparison’) until it perceptually matches the distance to the presented ‘standard’. The ability to freely refer to the standard while adjusting the comparison makes perceptual matching a closed-loop task. Perceptual matching is fairly accurate for full/rich cue environments in augmented or virtual reality (Sinai et al., 1999; Swan et al., 2006). Blind-walking is an action-based task, in which the observer views a target and then attempts to walk an equivalent distance with their eyes closed or blind-folded. This open-loop response is free from feedback and online error correction, and is thus believed to indicate the perceived distance (Philbeck & Loomis, 1997). Blind-walking on firm ground is quite accurate and linear over target distances ranging from 2 to 26 m (Bodenheimer et al., 2007; Da Silva, 1985; Elliott, 1987; Knapp & Loomis, 2004; Loomis et al., 1992; Loomis & Knapp, 2003; Rieser et al., 1990; Steenhuis & Goodale, 1988; Thomson, 1983).

Information-based view. The information-based view focuses on the visual information that specifies distance under natural conditions, and how this information is used to guide action (J. Gibson, 1979/2015; Warren, 1998). Like the geometric view, this approach claims that perceived distance is based on visual information, but it emphasizes how optical variables are scaled to control variables to generate successful actions (Warren, 2019).

Consider the monocular information for egocentric distance available in the open field. The angular declination from the horizon is an example of such information; the angle from the visual horizon (α) to the point where an object makes optical contact with the continuous ground plane specifies egocentric distance (*Z*) in body-scaled units of eye-height (*E*) (Sedgwick, 1986):

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

Consistent with this information, manipulations of both the magnitude of the declination angle and the height of the visual horizon yield predicted changes in perceived distance. By using a minifying lens, Wallach & O'Leary (1982), demonstrated that decreasing the declination angle produces increased perceived distance. Conversely, using a base-up wedge prism to increase the declination angle resulted in decreased perceived distance, as measured by blind-walking (Ooi et al., 2001). Lowering the visual horizon in virtual reality decreased the declination angle, also yielding increases in perceived distance (Messing & Durgin, 2005). Collectively, such behavioural evidence indicates that declination from the horizon provides effective information for egocentric distance perception (Messing & Durgin, 2005; Wallach & O'Leary, 1982; Ooi et al., 2001; Williams & Durgin, 2015).

The distance given by the declination angle of a target remains the same regardless of how difficult it is to walk on the intervening substrate: the optically specified distance is independent of how hard, soft, uneven, or slippery the terrain is. In contrast, what the terrain affords for the action of walking to the target obviously does depend on such properties. Gibson (1979/2015) described *affordances* as properties of environmental surfaces taken with reference to the action capabilities of an animal. He proposed that if the relation between environmental properties and the observer's action system can be perceived, then so too can the affordances of the environment. For example, a firm ground surface affords optimal walking for a bipedal human, a soft surface affords effortful walking, while a slippery, uneven surface may not afford walking at all (Warren, 1984). Although it is more difficult to walk on some ground surfaces than others, the optical information for target distance over those surfaces (e.g. declination angle) is the same. The information-based account thus predicts that affordance judgments should depend on such surface properties, whereas distance estimates should not; they are based on optical information (e.g. declination angle) and are not influenced by the difficulty of walking. However, action tasks, such as blind-walking to the target, require mapping the optically-specified distance to a walking response, or locomotor distance, that is appropriate for that terrain. This is known as a *visual-locomotor mapping*.

To control behaviour, the information-based view proposes that such optical information about distance is mapped to the control variables of the action system; this yields task-specific mappings for different classes of action (e.g. walking, throwing, verbal estimates) (Rieser et al., 1995; Warren, 1998, 2019). During everyday walking, for example, the visually-specified distance to an object systematically covaries with the locomotor distance to reach that object, enabling the calibration of a mapping between declination angle and locomotor distance. How locomotor distance is measured by the human odometer is not well understood (Chrastil & Warren, 2014; Turvey et al., 2009; White et al., 2013), however, it is possible that the distance metric is independent of the substrate, like a stride integrator (Wittlinger et al., 2007).

Embodied view. Recently, the embodied view has claimed that the perception of spatial layout depends not only on optical information, but also on the cost of action (Bhalla & Proffitt, 1999; White, 2012; Witt & Proffitt, 2008; Witt et al., 2004). Proffitt appeals to Gibson's (1979/2015) theory of affordances to argue that, if egocentric distance is viewed as an affordance, then perceived distance should depend on both the visually specified distance and the observer's action abilities, such as their 'physiological potential' or the 'anticipated effort' of action (Proffitt & Linkenauger, 2013; Proffitt et al., 2003). The embodied account thus conflates the perception of surface layout with perception of what the layout affords for action (e.g. Proffitt, 2006; Proffitt et al., 2003). In contrast, I will argue that it is essential to distinguish the perception of layout from the perception of affordances.

In general, Proffitt and his colleagues have reported that both perceptual and action-based tasks, including verbal reports, perceptual matching, blind-walking, and throwing to match the target distance all provide converging evidence that perceived spatial layout depends on anticipated effort (Bhalla & Proffitt, 1999; Proffitt et al., 2003; Witt et al., 2004). For example, the egocentric distance to a target appears greater when the anticipated effort of walking is increased (Bhalla & Proffitt, 1999; Proffitt et al., 2003). In one study, Proffitt et al. (2003) had two groups make verbal judgements of the egocentric distance to targets of varying distances (4 to 14 m). The control group underestimated target distance, consistent with previous verbal estimates of egocentric distance (e.g. Loomis et al., 1992). The other group viewed the targets while wearing a heavy backpack, to increase the anticipated effort of walking to the target; the estimates of egocentric distance made by the backpack group were larger than the control group's estimates. Not only does wearing a heavy backpack cause targets to appear farther away, it also causes hills to appear steeper (Bhalla & Proffitt, 1999). Wearing ankle weights increases the effort needed to jump across a gap, and consequently the other side appears farther away (Lessard et al., 2009). Walking uphill is more difficult than walking on level ground, and so a target placed uphill from the participant looks to be farther away than a target placed at the same egocentric distance on level ground (Stefanucci et al., 2005). In sum, the effect of anticipated effort on perceived spatial layout seems to be so robust that it holds across a wide variety of manipulations and dependent measures.

Critique of the Embodied View

Critics of the embodied perception research attribute the observed effects of anticipated effort on perceived distance to demand characteristics of the experiment or to post-perceptual processing (Durgin, 2017; Firestone, 2013; Hutchison & Loomis, 2006a, 2006b). A number of studies fail to find effects of anticipated effort or other ‘action-specific’ effects on the visual perception of spatial layout; they include studies of perceived distance (Durgin et al., 2011; Hutchison & Loomis, 2006a; Woods et al., 2009), perceived slope (Durgin et al., 2009; Durgin et al., 2012), and perceived size (Firestone & Scholl, 2014). Demand characteristics may lead participants to intuit the experimenter’s hypothesis and respond in a manner that complies with the experimenter’s expectations. For example, Durgin et al. (2009) found that when participants wore a heavy backpack while making ground slope judgments, and believed the purpose of the backpack was to alter slope perception (the majority of the participants), they replicated the finding that slope estimates increased. However, when they used a deception to conceal the experimental intent of the backpack, the slant estimates matched those of a no-backpack group, indicating that the weight of the backpack did not influence judgments of surface orientation. In some cases, instructions may not cue the participant to the experimenter’s hypothesis, but may implicitly encourage affordance judgements rather than judgments of spatial layout (Woods et al., 2009). While the embodied view does not make a distinction between the two, the information-based view does.

The primary evidence cited by the embodied account is a main effect of anticipated effort on the perception of spatial layout across a variety of tasks (Bhalla & Proffitt, 1999; Lessard et al., 2009; Proffitt et al., 2003; Witt et al., 2004). If the energetic cost of walking influences perceived distance, however, then wearing a heavy backpack should not increase distance judgments by a constant value — rather, the increase in perceived distance should be proportional to target distance. That is, both the mean *and the slope* of the response function should increase, yielding an interaction between anticipated effort and target distance. However, only one target distance (or ground slope) is typically tested in embodied experiments, and in the few cases in which multiple distances have been tested, the slopes and interactions were either not reported or not significant (Proffitt et al., 2003; Witt et al., 2004). By itself, a main effect is consistent with a simple response bias induced by the demand characteristics of the experiment in the 'effortful' condition.

In response, an embodied theorist may argue that the relative effort between wearing a heavy backpack and no backpack was small enough that over the tested distances, the small effect size would not result in a change in the slope of the function; or if the difference in effort is large, the perceived effort is a smaller magnitude. The embodied account, however, does not reconcile the observed effect sizes with measures of energetic cost (perceived or biomechanically determined). The anticipated effort of an action is taken for granted; it is assumed that the task is truly perceived as more effortful and the magnitude difference in perceived effort is such that the perceptual difference between the tested groups is discernible. The perceived effort of a completed task is strongly correlated with other measures such as heart rate response, muscular discomfort, and walking speed (Chung & Wang, 2010; Noble et al., 1973). It is reasonable to think that judgements of anticipated effort may be accurate, but such a claim needs to be substantiated by comparisons to predictions, or measures, of metabolic or energetic cost. Predictions of energetic cost can be made based upon a wealth of literature that fits functions to the measured energy expenditure during locomotion. The effects of carrying a load during walking, jogging, and running are well established (Soule & Goldman, 1972; Winsmann et al., 1953); thus, the metabolic cost of walking to various target distances can be estimated given the external load and the individual's body weight. It remains to be determined whether the effect of an effort manipulation, such as wearing a heavy backpack weighing one fifth the subject's bodyweight (Proffitt et al., 2003), on perceived distance corresponds to the metabolic prediction.

The Present Experiments

The purpose of the present experiments is to investigate the influence of anticipated effort on both perceived egocentric distance and the perceived affordances of the terrain for walking. The results bear on the general problem of route selection based on local perception of more or less walkable paths. To test these questions, I leverage the large difference in energetic cost of walking on sand and on firm ground, and employ multiple measures, including an action task in the real environment (blind-walking), a visual matching task, and a visual route preference task, both in a virtual environment.

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 et al., 1976; Kuo, 2007). In contrast, a soft, granular substrate like 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 an equal distance on a firm surface, at the same speed (Appendix A, Table 1) (Davies & Mackinnon, 2006; Lejeune et al., 1998; Zamparo et al., 1998). Given that preferred walking speed on sand (1.39 ± 0.14 m/sec) is somewhat slower than on firm ground (1.56 ± 0.14) (Leicht & Crowther, 2007), the metabolic cost of walking on the former is still 1.84 times that of walking on the latter, when walking at the respective preferred speeds. Consequently, if distance is perceived in units of energy expenditure, distance on a sandy beach should appear to be approximately twice the distance on firm ground.

Thus, on the embodied view, a target viewed over sand should appear significantly farther away than the same target viewed over firm ground. Critically, this predicts that not only should there be a main effect of terrain on perceived distance, but this effect should increase proportionally with target distance. That is, the slope of the response function (perceived distance as a function of target distance) should be significantly greater for sand than for firm ground, yielding an interaction between target distance and terrain. Although the optical information remains the same when one dons the heavy backpack, on the embodied account, perceived distance is the product of the optical information and the anticipated effort of walking; this does not affect the mapping from perceived distance to action, however, so blind-walking indicates perceived distance (Witt et al., 2004). Because the embodied view treats distance perception as affordance perception, it predicts that distance judgments and affordance judgments would yield the same results.

In contrast, the geometric view predicts that, regardless of the energetic cost or anticipated effort of walking on a terrain, visually perceived distance will be the same on both substrates. Thus, there should be no main effects of or interactions with terrain. Although blind-walking is thought to be a direct report of visually perceived distance, the geometric view does not include an account of how walked distance is monitored during the response, or is adapted to different substrates. Additionally, the geometric view makes no prediction as to how the energetic cost of walking on a substrate will influence perception of the affordances of the ground surface.

The information-based view similarly predicts that visually perceived distance is based on optical information, independent of the energetic cost of walking on the terrain. Rather than assuming distance is perceived in geometric units, however, it holds that optical information is scaled to action in a visual-locomotor mapping, which can account for blind-walking responses (Warren, 2019). It is possible that the distance metric is independent of the substrate, like a stride integrator (Wittlinger et al., 2007), so that blind-walking responses remain accurate on different types of terrain. Alternatively, the visual-locomotor mapping might be separately calibrated for 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 calibrated visual-locomotor mapping. In addition, it predicts that the affordances of the terrain for walking can also be perceived, based on action-scaled information. Specifically, route selection is based on the "ecological efficiency" of various paths to an intended goal (Warren, 1983, 1984), where distance and the substrate both influence the energetic cost of the path.

This dissertation research uses blind-walking and perceptual matching tasks to measure perceived egocentric distance; perceptual matching was also employed to determine relative judgements of energetic cost and ease of walking on different surfaces. In Chapter 5, I also propose using a two-alternative forced choice (2AFC) task to measure the influence of ‘walk-ability’ on route selection. Blind-walking is an open-loop action-based task, in which the observer views a target and then attempts to walk an equivalent distance with their eyes closed or while blind-folded. Perceptual matching, in contrast, allows the observer to continuously view the target they are trying to match, making it a closed-loop task. The observer adjusts the position of a target (what we will term the ‘comparison’) until it perceptually matches the presented ‘standard’. Where perceptual matching requires an explicit judgement of equivalent distance or cost of walking, the 2AFC task asks the observer to choose a preferred path, and the point of equivalence is implicitly measured. During a 2AFC task, the observer is presented with two options, the standard and the comparison, concurrently, and a choice between the two is made. The point of subjective equality can be determined using a staircase procedure to vary the relative difference between the standard and the comparison, on each trial, until the response is at chance for selecting between the two.

In Chapter 2, I begin at the beach, investigating how perceived effort of walking across different terrains (sand and firm ground) influences egocentric distance judgements and how calibration to the different surfaces bears on the blind-walking response. Chapter 3 moves the beach indoors to a virtual environment and uses a perceptual matching task. I investigate the perceived difference in energetic cost of walking across sand and firm ground, how the difference between the two surfaces scales with target distance. These prospective judgements of energetic cost are then compared to the perceived egocentric distance. Chapter 4 attempts to measure affordance judgements of walkability by having participants match the ‘ease of walking’ to two targets while varying the terrain. Chapters 3 and 4 make important comparisons between prospective judgements of perceived cost and perceived egocentric distance, and provides a basis for determining whether distance or the effort of walking is being minimized when selecting between goals. Chapter 5 proposes an 2AFC method to measure the perceived walkability of alternative paths, to test how the energetic cost of walking and the egocentric distance of the goal (ecological efficiency) influence route selection. Finally, Chapter 6 draws general conclusions about influence of anticipated effort on perceived distance and perceived affordances, and the broader implications for pedestrian models and route selection.

CHAPTER 2

A Day at the Beach: Does Visually Perceived Distance Depend on the Energetic Cost of Walking?

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 distance is independent of the consequences of action, but in recent years that assumption has been questioned. We first consider current accounts of egocentric distance perception, including the geometric and information-based views, in which perceived distance depends on visual information alone, and the embodied view, 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 substrates is influenced by the energetic cost of walking on that type of terrain.

On the *geometric view*, perceived distance is assumed to correspond to the physical distance between locations in space. It thus provides a common basis for a variety of spatial responses, including actions such as walking or throwing as well as verbal estimates (Loomis & Beall, 2004). Indeed, magnitude estimation of egocentric distance in the open field is generally linear, although underestimated by 20-30% (Foley et al., 2004; Knapp & Loomis, 2004; Loomis & Philbeck, 2008). A more intuitive, action-based measure of perceived egocentric distance is the blind-walking task, in which the observer views a target and then attempts to walk an equivalent distance with their eyes closed. This open-loop response is free from feedback and online error-correction, and is thus believed to indicate the perceived distance (Philbeck & Loomis, 1997). Blind-walking on firm ground is 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 et al., 1992; Loomis & Knapp, 2003; Rieser et al., 1990; Steenhuis & Goodale, 1988; Thomson, 1983). On the geometric view, perceived distance depends on the available information (Loomis et al., 1996; Philbeck & Loomis, 1997), and is independent of the consequences of action. Although blind-walking is thought to be a direct report of visually perceived distance, some account of how walked or 'locomotor' distance is measured during the response is also needed.

The *information-based view* focuses on the visual information that specifies distance under natural conditions, and how this information is used to guide action (J. Gibson, 1979/2015; Warren, 1998). Like the geometric view, this approach claims that perceived distance is based on optical information, independent of anticipated effort. But it questions whether distance is perceived in geometric units, arguing that optical information is scaled to action (Warren, 2019).

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 (Epstein, 1966; J. Gibson, 1950). Its distance is specified by the gradient of ground texture at that point (Purdy, 1958), and by its declination from the horizon (Sedgwick, 1973, 1986). In particular, the angular declination from the horizon (α) to the contact point specifies egocentric distance (*Z*) in units of eye-height (*E*):

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

There is considerable evidence that perceived distance varies systematically when the visual horizon or the declination angle is manipulated (Messing & Durgin, 2005; Ooi et al., 2001; Wallach & O'Leary, 1982; Williams & Durgin, 2015), demonstrating that declination provides effective information for egocentric distance. On the other hand, the ground texture becomes indistinct at large distances, and there is no evidence that the texture gradient is effective information for egocentric distance.

To guide behaviour, the information-based view proposes that such optical information about distance is mapped to the control of action; this yields task-specific mappings for different classes of responses (e.g. walking, throwing, verbal estimates) (Rieser et al., 1995; Warren, 1998, 2019). During everyday walking, for example, the optically-specified distance to an object systematically covaries with the 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 walked distance is measured by the human odometer is not well understood, however (Chrastil & Warren, 2014; Turvey et al., 2009; White et al., 2013). It is possible that the distance metric is independent of the terrain, as in a stride integrator (Wittlinger et al., 2007), so blind-walking responses remain accurate on different substrates; alternatively, the visual-locomotor mapping might be separately calibrated for 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 calibrated visual-locomotor mapping.

The *embodied view* claims that perceived distance is not based solely on optical information, but incorporates the energetic cost associated with walking. In particular, Proffitt and colleagues (Proffitt, 2006; Witt et al., 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 placed on level ground appears greater, and the slope of a hill appears steeper, when wearing the backpack (Bhalla & Proffitt, 1999; Proffitt et al., 2003). Although the optical information remains the same when one dons the backpack, perceived distance or 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 indicates perceived distance (Proffitt et al., 2003; Witt et al., 2004).

The embodied view acknowledges a debt to Gibson's (1979/2015) concept of affordances (see Proffitt, 2006; Proffitt & Linkenauger, 2013). We note, however, that the account conflates the perception of surface layout with perception of what the layout affords for action (e.g. Proffitt, 2009; Proffitt et al., 2003). 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, while the optical information for target distance over those surfaces (e.g. declination angle) remains the same. The information-based account thus predicts that, whereas affordance judgments should depend on energetic cost, distance judgments should not (Warren, 1984, 2019). In contrast, the embodied account proposes that distance judgments be treated as affordance judgments, and predicts that they depend on both the optical information and the anticipated cost (Proffitt, 2006; Proffitt et al., 2003).

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 et al., 1976; Kuo, 2007). In contrast, a soft, granular substrate like 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 (Appendix A, Table 1) (Davies & Mackinnon, 2006; Lejeune et al., 1998; Zamparo et al., 1998). 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 that not only should there be a main effect of terrain but that this effect should increase proportionally with distance, yielding an interaction between terrain and distance.

The embodied account has been supported by findings of a main effect of effort on perceived layout in a wide variety of tasks (Bhalla & Proffitt, 1999; Lessard et al., 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 (Witt et al., 2004; Proffitt et al., 2003). 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.

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), where we could find a sandy beach adjacent to a brick walkway (see Figure 1) as well as a group of willing subjects. Participants viewed a target over brick or over sand, then turned and blind-walked an equivalent distance on the same or the other terrain. This 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.

The terrain manipulation thus allowed us to dissociate the predictions of the geometric and information-based accounts 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 (5F, 8M; 25.8 ± 3.6 y.o.) were recruited through posted flyers in the lobby area of the Tradewinds Resort, St. Pete's 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 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 leading to the shoreline (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 (refer to 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 (~1.0º), while Brick II began with a shallow incline for 6.22m (0.8º) followed by a steeper grade for 4.72m (2.6º) (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 the 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' Laser Distance Measure GLM165-40, Bosch), by holding the rangefinder on a monopod at the base plate, aiming the levelled 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.) on a smart phone (iPhone 6, Apple) 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 1.0º. 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 (Appendix C) on a tablet computer (iPad 7th Generation, Apple).

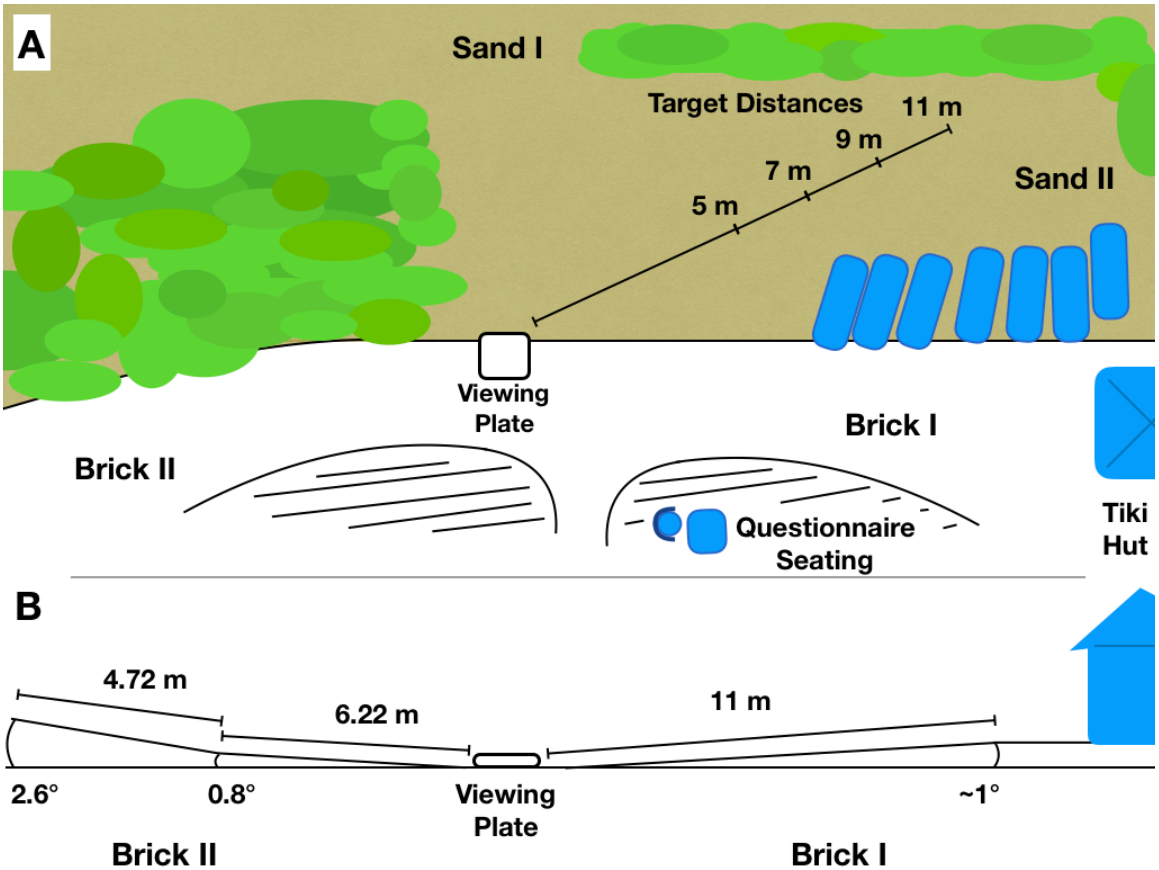

Figure 1. Set-up of the experiment. (A) Schematic of the testing area. The target cone was viewed at one of four distances, as illustrated on the Sand II area. (B) Elevation schematic of the brick walkway. Brick II had an initially shallow segment (0.8˚) followed by a steeper incline (2.6˚); this surface was used for the blind-walking response. Brick I had a slope in 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.

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 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 naive 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 1 hr 15 min test session. Trial order was randomized within blocks. If a trial was interrupted by beach-goers then the trial was redone at the end of the block, up to a maximum of 4 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 Appendix). A session took approximately 1.5 hrs to complete, including informed consent, test trials (with water breaks), and questionnaire. All sessions took place between 8:00 am and 12:30 pm.

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 data sets and copes well with missing data. The dependent variable was Walked Distance (m), with fixed effects of Target Distance (5, 7, 9, and 11 m; centered continuous variable), Viewed Terrain (sand or firm), Walked Terrain (sand or firm), and the 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) 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 (lower lines Figure 2A), but unexpectedly, viewing over brick yielded overshooting on both terrains (upper lines Figure 2A). This difference becomes more pronounced as the target distance increases (i.e. there is an interaction effect of Target Distance by Viewed Terrain).

Regression results for fixed effects are summarized in Table 2 (see Appendix B). 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) ($\chi2(1) = 0.550$, $p = 0.458$), and the slopes were nearly equal ($\chi2(1) = 0.044$, $p = 0.834$; Figure 2A, B). This was the case whether the target was viewed over sand or brick. Specifically, 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 ($\chi2(1) = 0.718$, p = 0.397) or a three-way interaction ($\chi2(1) = 0.343$, p = 0.558). These results indicate that walking was calibrated to 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 m ± 0.16 (SE) farther when viewing over Firm ground than when viewing over Sand ($\chi 2(1) = 10.818$, $p = 0.001$; Figure 2A, B). In addition, the slope of the function was greater when viewing over firm ground than over sand, as indicated by a significant Viewed Terrain by Target Distance interaction ($\chi 2(1) = 5.978$, $p = 0.014$). 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.

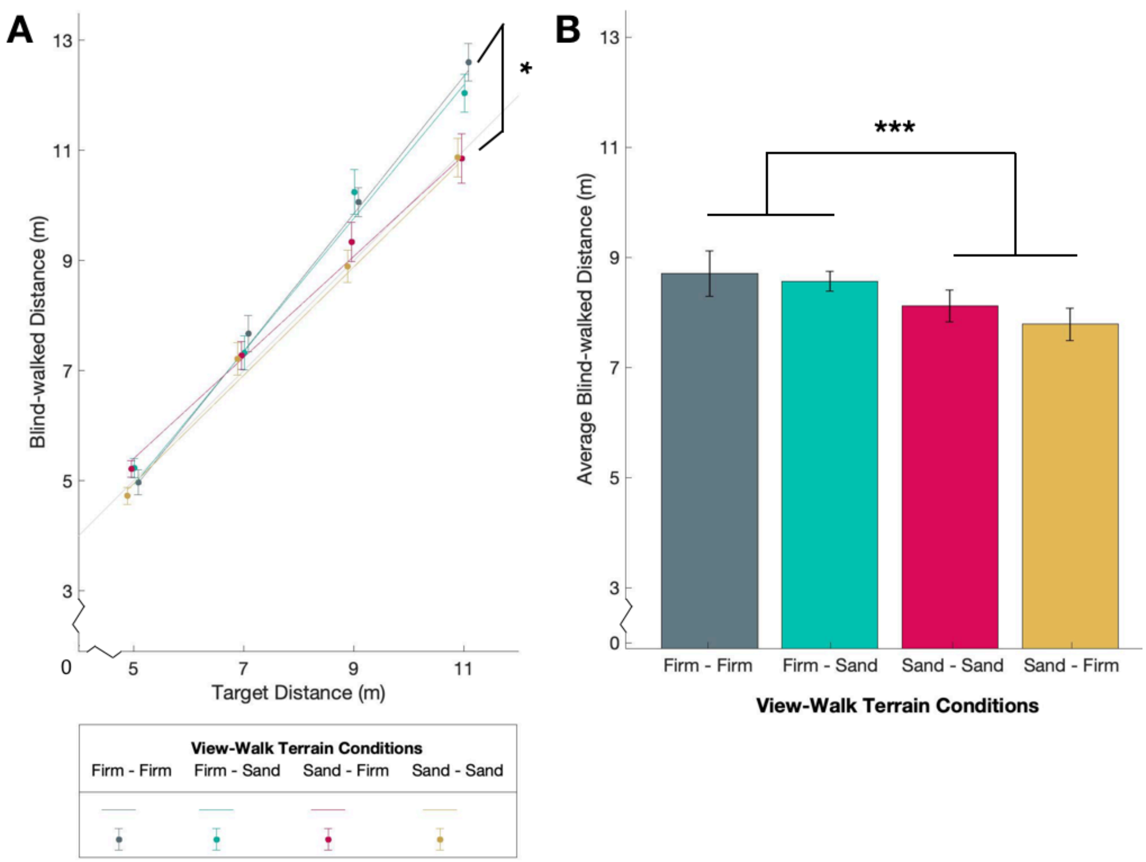

Figure 2. (A) The Blind-walked Distance (m) as a function of Target Distance (m). Mean responses (± SE) are plotted for each target distance (5, 7, 9, and 11 m) in each View-Walk condition. Solid lines are the marginal regression model predictions in each condition. Means and predictions are slightly jittered horizontally for visibility. (B) Regression predictions of the marginal mean (± 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 ($p < 0.001$).

Accounting for the slope of the brick walkway

What might explain the unexpected overshooting when the target was viewed over firm ground, compared to 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 (lower lines in Figure 2A), implying that the uphill slope of the response surface (Brick II) did not affect the walked distance. In contrast, responses overshot the target distance in both the Firm-Firm and Firm-Sand conditions (upper lines in Figure 2A). 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 the Geographical Horizontal (GH) which is parallel to the ground plane (Figure 3A). However, if the ground surface is sloped, Visually Perceived Eye Level lies mid-way between the Inertial Horizontal and the Geographical Horizontal (GH) (Stoper & Cohen, 1989). When viewing outdoor scenes, Visually Perceived Eye Level shifts about 40% of the way to the Geographical Horizontal 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 Visually Perceived Eye Level is 2° above the Inertial Horizontal, and 3° below the Geographical Horizontal. This partial shift in Visually Perceived Eye Level reduces the declination angle to targets on the visible ground surface, producing corresponding increases in perceived distance (Messing & Durgin, 2005; Ooi et al., 2001), 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.

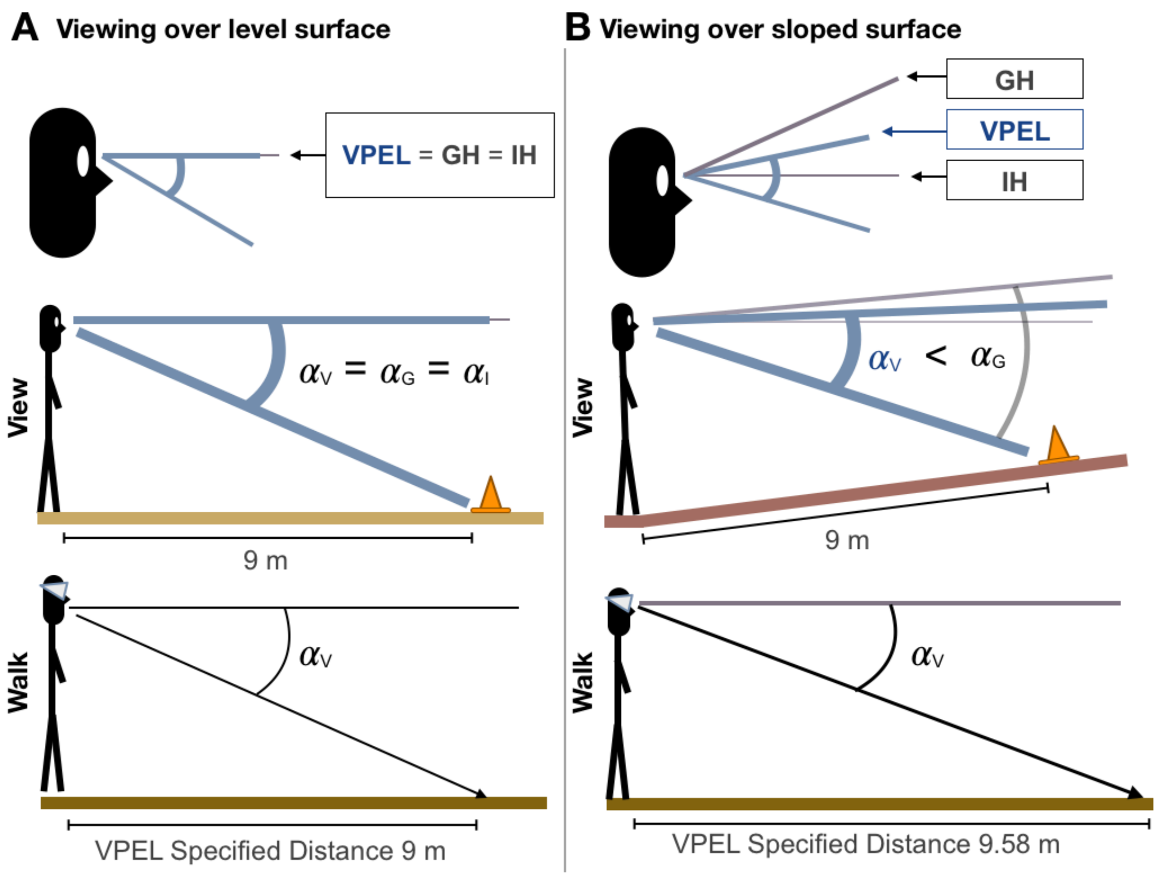

Figure 3. Visual distance specified by declination angle depends on ground slope. (A) When viewing a 9 m target on level sand, the Visually Perceived Eye Level (VPEL) is parallel to both the Geographical Horizontal (GH) and the Inertial Horizontal (IH) or horizon (top). Thus, the declination angles from all three are equivalent (middle). The predicted blind-walking distance is 9m, 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 Inertial Horizontal and 0.6° below the Geographical Horizontal (top). The target's declination from VPEL (9.48°) is thus smaller than in Panel A, corresponding to a perceived distance that is 0.58 m farther away (middle). When blindfolded (bottom), VPEL corresponds to the Inertial Horizontal (0°), so that 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 is parallel to the Geographical Horizontal, the declination angle would be equal to and the response distance would be 9m in both A and B.

Figure 3 illustrates how the perceived distance of the target would increase on a slight uphill slope compared to flat sand, and consequently predict a greater blind-walking response. First, assuming an average eye height of 1.6 m, each target position on level ground projects a corresponding declination angle from the VPEL (Panel A, middle). Second, when viewing a 1° incline (Brick I), the VPEL increases by 40% of that value, shifting it 0.4˚ above the IH and 0.6˚ below the GH (Panel B, top and middle). Critically, this reduces the declination angle from VPEL to each target position by 0.6° compared to viewing over level ground (Panels B and A, middle). Thus, by Equation 1, the VPEL-specified distance of each target increases proportionally. The reduced declination angle maps to a correspondingly greater blind-walking response (Panels A and B, 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 Table 3 (see Appendix B).

When response distance is plotted as a function of the VPEL-specified target distance, the means and the slopes in each View-Walk condition are not significantly different (Figure 4). All slopes are close to the diagonal (1.03 ± 0.05 SE), with no effect of Viewed Terrain, Walked Terrain, nor any interactions. Critically, correcting for the shift in Visually Perceived Eye Level eliminates the previous effect of Viewed Terrain. The mean distance walked after viewing the target over Brick I (8.10 m) is no different from viewing over sand (7.96 m) ($\chi 2(1) = 0.911$, $p = 0.340$), and the slopes are nearly equal, eliminating the Viewed Terrain by Target Distance interaction ($\chi 2(1) = 2.484$, $p = 0.115$). 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 are still unaffected by the Walked Terrain. The mean distance walked on Brick II (8.14 m) is no different from walking on sand (7.91 m) ($\chi 2(1) = 0.585$, $p = 0.444$), and their slopes are nearly equal ($\chi 2(1) = 0.035$, $p = 0.851$; Figure 4A, B). These results confirm that walked distance was calibrated to 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 Visually Perceived Eye Level, independent of the energetic cost of the terrain.

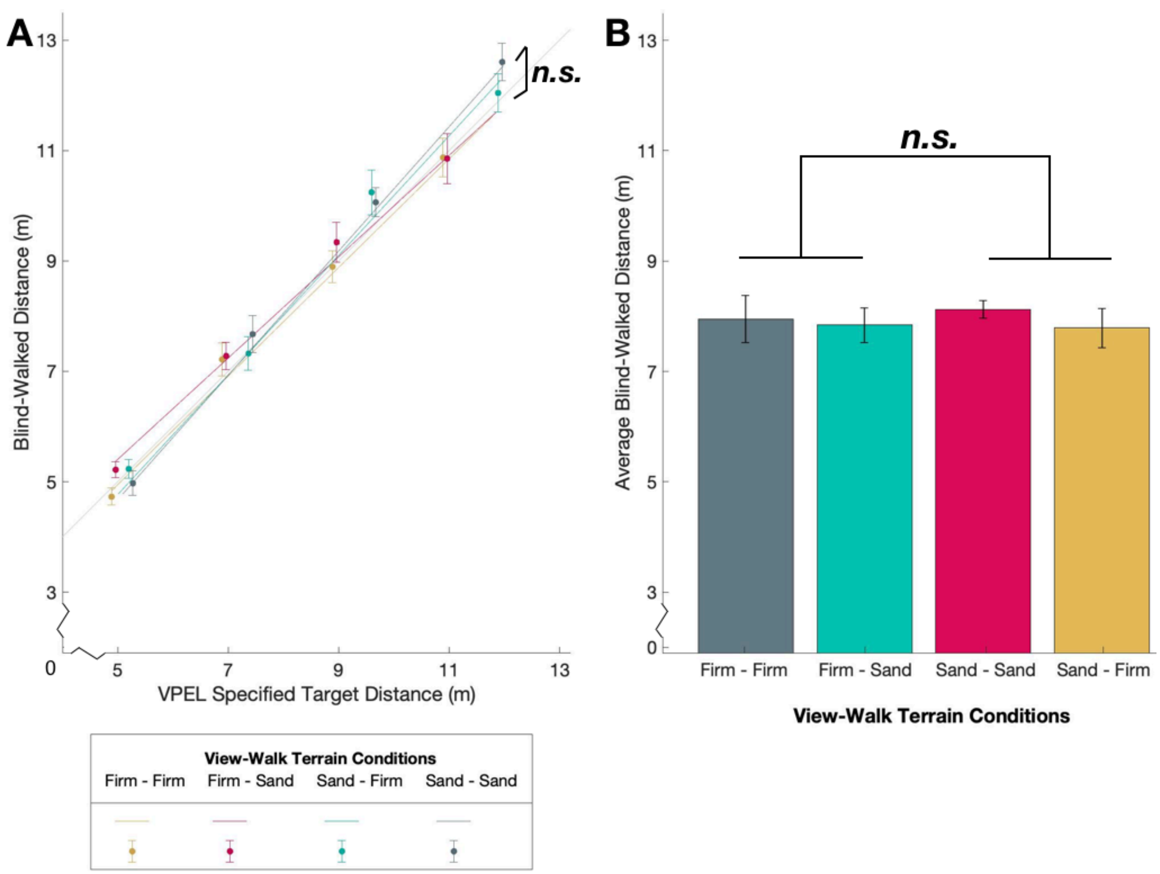

Figure 4. The declination angle from VPEL is calculated for viewing the target over the level sand surface and the sloped (1°) brick walkway. This eliminated the difference between the intercepts and slopes of the Viewed Terrain conditions (i.e. no main effect of Viewed Terrain or interaction with VPEL-specified target distance; *n.s.*). (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 coincides 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 are 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 (± SE) blind-walked distance for the each View-Walk Terrain pair at a target distance of 8 m.

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 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° yield 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, yield no main effect of Viewed Terrain, and those between 0.8° and 3.7° yield no interaction. These effects do not significantly reverse until the incline reaches 3.8°, at which point the regression slopes are shallower in the View Firm than View Sand conditions; 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 was well below the measured 2.6° incline of Brick II, within the 0.8° to 1.7° range.

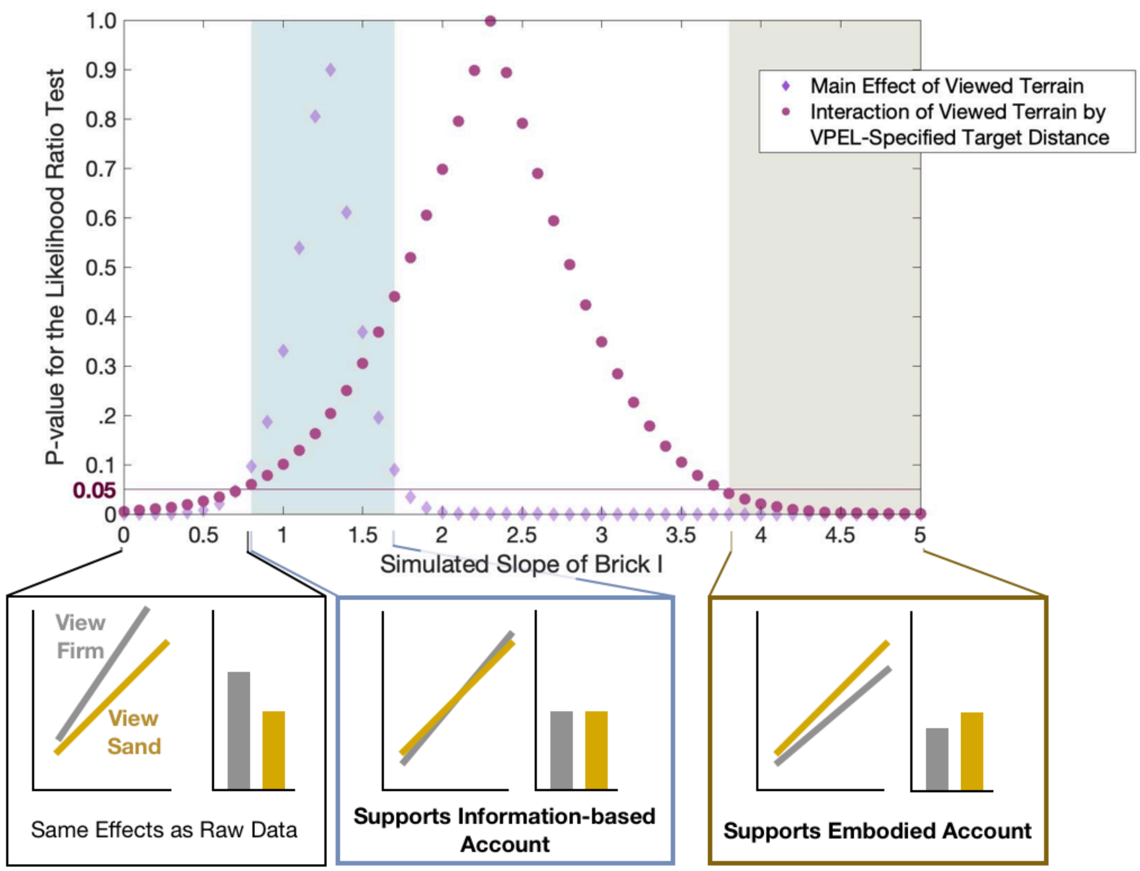

Figure 5. Likelihood ratio tests of regressions models with VPEL target distance, correcting for ground slope from 0° to 5°. The p-value of the main effect of Viewed Terrain and the interaction between Viewed Terrain and Target Distance, as a function of the ground slope. The original significant main 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°; dark yellow shaded area). General trend 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.

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 increases the perceived target distance specified by the declination angle from Visually Perceived Eye Level. Once 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 (Appendix C), 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 needed to walk on sand versus firm ground (Adjust Steps and Adjust Effort; Appendix B, Table 4), and visualization of the target location or the surroundings during blind-walking (Visualize Target and Visualize Surround; Appendix B, Table 5). 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 does 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 walking on sand (8.29 m) ($\chi2(1) = 0.749$, $p = 0.387$), and including the interactions with Adjust Steps and Adjust Effort did not significantly influence the response (see Appendix B, Table 4). These results indicate that walked distance was calibrated to 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 ($\chi2(1) = 4.929$, $p = 0.026$), 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 ($\chi2(3) = 6.916$, $p = 0.075$). This suggests that visualizing the passing surroundings may have increased the estimate of travelled distance or walking speed. Visualization did not interact with Walked Terrain ($\chi2(1) = 0.348$, $p = 0.555$), for the mean walked distance on sand and on firm ground were the same. These results indicate that walked distance was calibrated to 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 needed to be calibrated to both surfaces? The median number of days at the beach in the past year was six days (Q1 = 2.75, Q3 = 8.75), while the recalled number of beach days over the lifetime had a median of 50 days (Q1 = 21, Q3 = 95). As predictors of walked distance, days at the beach over the lifetime and in the past year did not interact with Walked Terrain ($\chi2(1) = 1.644$, $p = 0.200$), and the effect of Walked Terrain remained null ($\chi2(1) = 0.438$, $p = 0.508$). The ability to blind-walk the same distance on sand and firm ground thus does 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 ($\chi 2(1) = 3.964$, $p = 0.046$). This effect appears to be driven by an outlier — one participant had spent 700 days at the beach! Removing the outlier does not impact the regression estimates; the outlier is not an influential point. While the regression coefficients remain the same (Appendix B, Table 6), 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 remain significant predictors of the response, whereas Walked Terrain still had no effect. The mean distance walked on brick was no different from 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's 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 walked distance was calibrated to both sand and firm ground. We did, however, observe an unexpected effect of Viewed Terrain:

responses were accurate for targets viewed over sand, but overshot targets viewed over brick, increasingly so as a function of Target Distance.

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 to 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 to firm ground. Contrary to this hypothesis, however, we observed the opposite effect and interaction: proportional overshooting of targets viewed over firm ground compared to sand.

According to the geometric and information-based views, 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 walking is calibrated to the 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, but not sand, was initially puzzling. However, when the topography of the test site is taken into account, this overshooting can 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 Geographical Horizontal 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. 8.0m on sand) (Figure 3). On the geometric view, the participant then blind-walked the larger specified distance; on the information-based view, the visual-locomotor mapping from declination angle to walked distance also yielded the same 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). Our results can thus be explained by the optical information present at the test site, consistent with both the geometric and information-based hypotheses. 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 et al., 2011; Hutchison & Loomis, 2006; Woods et al., 2009), perceived slant (Durgin et al., 2009; Durgin et al., 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 the tendency 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.

Finally, according to the information-based view, blind-walking is guided by a mapping from optical information to locomotor distance, whereas on the geometric view blind-walking is a direct report of visually perceived distance. Although the present results do not directly bear on this difference, some account of how walked distance is measured during the response is necessary. Our finding that the blind-walked distance was the same on brick and sand, with no effect of Walked Terrain, indicates that a given locomotor distance is carried out equivalently on two very different substrates. This result either implies separate calibrations of the visual-locomotor mapping to soft sand and firm ground, or a distance metric that is invariant across substrates.

The number of steps and energetic cost to walk a given distance on sand are both greater than on firm ground (Appendix A, Table 1). 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 (Zamparo et al., 1992; Leicht & Crowther, 2007). 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 to 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 proprioceptive quantity (Chrastil & Warren, 2014; Turvey et al., 2009; Wittlinger et al., 2007).

While 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 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 are explained by the optical information for target distance (declination angle from Visually Perceived Eye Level) 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.

Acknowledgements

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CHAPTER 3

Rose Coloured (Sun)glasses: The Energetic Cost of Walking On Sand Does Not Affect Perceived Distance

Introduction

Picture a day at the beach, sitting on your towel by the boardwalk in the heat, one friend waves for you to join them in the water, as another calls from the Del's lemonade stand down the walk. Now my love of the waves and sugared ice being equal, I have two competing choices and need to decide. Might I pick whomever is closest? In a study of competing goals, Cohen and Warren (2007) manipulated the initial distance and heading deviation of the two goals, and asked participants to walk to their preferred goal. When the deviation angles were equal, they preferred the closer goal. The shoreline and the lemonade stand may be equal distances but it is much easier to walk on the boardwalk than on the sand.

A debate regarding whether the perception of egocentric distance is dependent or independent of anticipated effort exists in current perception-action research (see Durgin, 2017; Firestone, 2013; Proffitt, 2013; Schnall, 2017). On one side of the debate, all distances are *seen* as equal, that is to say that egocentric distance perception is independent of the consequence of action. On the other side of the debate, egocentric distance perception is determined by anticipated effort and optical variables (Bhalla & Proffitt, 1999; Proffitt et al., 2003); the distance to the shoreline *appears* to be greater the distance to the lemonade stand. We will consider each side in turn, the geometric view and information-based view that assume perception of the spatial layout to be independent of the consequence of action, and the embodied view that assumes perception of spatial layout to be a product of optical and anticipated effort. The purpose of the current study is two-fold: first, to determine the anticipated effort of walking across sand versus firm ground, second, to test whether the visually perceived distance is influenced by the anticipated effort of walking on either substrate.

The geometric view proposes that perceived distance corresponds to a representation of the spatial layout of the world around us (Loomis & Beall, 2004; Loomis et al., 1992). The long history of psychophysical investigation of visual space has been conducted independently of researching the control of action because it is assumed that depth cues combine to yield a representation of the surrounding 3D space and this internal model is the basis for any action. A further assumption is that action does not contribute to the object of spatial perception. According to this view, perceived space can be measured through both non-action and action-based indicator variables (e.g. verbal reports and blind-walking; Loomis & Knapp, 2003) because they should co-vary as the optical cues to distance are manipulated. For example, similar distance estimations have been found for perceptual matching and blind-walking tasks in the real world, and in virtual reality (Sinai et al., 1999; Sinai et al., 1998). When performing perceptual matching, the observer adjusts the position of a target (what we will term the 'comparison') until it perceptually matches the distance to the presented 'standard'. The ability to freely refer to the standard while performing the task makes perceptual matching a closed-loop task. Perceptual matching, such as the task used in the current experiment, is fairly accurate for full/rich cue environments in augmented or virtual reality (Sinai et al., 1999; Swan et al., 2006). The geometric view predicts that, regardless of the energetic cost or anticipated effort of walking on a terrain, visually perceived distance will be unchanged from one substrate to another. However, it makes no prediction as to how the energetic cost of different substrates may influence judgments of anticipated effort or the affordances of the ground surface.

The information-based view focuses on the visual information that specifies distance under natural conditions, and how this information is used to guide action (J. Gibson, 1979/2015; Warren, 1998). Like the geometric view, the information-based approach predicts that visually perceived distance is based on optical information. The layout of surfaces, as proposed by Gibson (1961, 1979/2015), is directly perceived by means of optical information detected by an active perceiver. Visual information such as ground texture gradients, optical contact, and declination from the horizon specify egocentric distance (Epstein, 1966; J. Gibson, 1950; Purdy, 1958; Sedgwick, 1973, 1986). Egocentric distance is specified by the angular declination from the horizon to an object's point of optical contact on a continuous ground plane, in units of eye-height (Sedgwick, 1986). Moreover, there is convergent behavioural evidence that manipulating the visual horizon or declination angle produces systematic changes in perceived distance (Messing & Durgin, 2005; Ooi et al., 2001; Wallach & O'Leary, 1982; Williams & Durgin, 2015). The information-based view holds that distance estimates are based on visual information and independent of action.

It is important to distinguish the perception of surface layout with perception of what the layout affords for action. Gibson (1979/2015) described *affordances* as properties of environmental surfaces taken with reference to the action capabilities of an animal. He proposed that if the relation between environmental properties and the observer's action system can be perceived, then so too can the affordances of the environment. For example, a firm ground surface affords optimal walking for a bipedal human, a soft surface affords effortful walking, while a slippery, uneven surface may not afford walking at all (Warren, 1984). Although it is more difficult to walk on some ground surfaces than others, the optical information for target distance over those surfaces (e.g. declination angle) is the same. The information-based account thus predicts that affordance judgments should depend on such surface properties, whereas distance judgments should not (Warren, 2019).

In contrast, the embodied view argues that the perception of spatial layout depends not only on optical information, but also on the consequences of action (Bhalla & Proffitt, 1999; Witt & Proffitt, 2008; Witt et al., 2004; White, 2012). Proffitt appeals to Gibson's (1979/2015) theory of affordances to argue that, if egocentric distance is viewed as an affordance, then perceived distance should depend on both the optically specified distance and the observer's action abilities, such as their 'physiological potential' or the 'anticipated effort' of action (Proffitt & Linkenauger, 2013; Proffitt et al., 2003). The embodied account thus conflates the perception of surface layout with perception of what the layout affords for action (e.g. Proffitt, 2006; Proffitt et al., 2003).

In a series of articles, Proffitt and his colleagues reported that both perceptual and action-based tasks showed that perceived spatial layout depended on expected effort, as hypothesized by the embodied view. Verbal reports, blind-walking, throwing to a target, all indicate expansion of distance as a result of manipulating the effort of the task (Bhalla & Proffitt, 1999; Witt et al., 2004). For example, Proffitt and colleagues (2003) reported that the perceived egocentric distance to a target was greater when wearing a heavy backpack, compared to not wearing a backpack, because the anticipated effort (i.e. energetic cost) of walking is greater with the backpack on. Not only does wearing a heavy backpack cause targets to appear farther away, it also causes hills to appear steeper (Bhalla & Proffitt, 1999). Wearing ankle weights increases the effort needed to jump across a gap, and consequently the other side appears farther away (Lessard et al., 2009). Walking uphill is more difficult than walking on level ground, and so a target placed uphill from the participant looks to be farther away than a target placed at the same egocentric distance on level ground (Stefanucci et al., 2005). In sum, the effect of anticipated effort seems to be so robust that holds across a variety of effort manipulations and the functionally related measures of spatial layout (e.g. the effort of walking and egocentric distance perception).

With each experiment, the converging evidence appears to mount. Yet, the effect size of anticipated effort is not compared to a measure or prediction of metabolic or energetic cost. The backpack is heavy but the specific increase in energetic output to walk each target distance is not predicted a priori. There is a large literature fitting the energetic or metabolic cost of locomotion, walking, jogging, and running, for traversing different types of terrain (Davies & Mackinnon, 2006; Kerdok et al., 2002; Lejeune et al., 1998; Voloshina et al., 2013; Zamparo et al., 1998) and while bearing external loads (e.g. Soule & Goldman, 1972; Winsmann et al., 1953) that could be used to make specific predictions of the energetic cost. The energetic cost associated with the 'effortful' condition (e.g. walking uphill versus walking over level ground) scales with distance; the embodied view should predict that as the target is farther away the difference between the control and effortful condition should become larger.

Prospective judgements of effort are missing from the embodied account because egocentric distance perception is viewed as an affordance. On the *embodied* view, the change in the perception of egocentric distance is indicative of the change in the afforded action, the 'walk-ability' to the target. In contrast, on the information-based account, reports of perceived egocentric distance are independent of reports of affordances. Surface properties such as the compliance of a terrain should not influence perceived egocentric distance, but they should affect judgements of how 'walk-able' a distance is.

In the present study, we first investigate the perceived relative energetic cost of walking over the different substrates. We use the results to evaluate the contribution of perceived energetic cost (or anticipated effort) to the perceived egocentric distance. Our control substrate, firm ground, is typically used when testing perceived egocentric distance (Knapp & Loomis, 2004; Proffitt et al., 2003; Bodenheimer et al., 2007). There is an abundance of firm, non-slippery surfaces that we walk on in our engineered, everyday environment. The inverted pendular motion of bipedal gait is highly conservative on such surfaces, requiring minimal muscular work (Cavagna et al., 1976; Kuo, 2007). We compare firm terrain to soft sand, which requires twice as much energy to walk across due to the compliance and slip of the displaced granules (Appendix A, Table 1) (Davies & Mackinnon, 2006; Lejeune et al., 1998; Zamparo et al., 1998).

Thus, in the first experiment, we establish the perceived energetic cost of walking across sand and firm ground and compare the results to measured values of energetic cost based on metabolic expenditure (see Appendix A Table 1). If distance is perceived in units of energy expenditure -- as the embodied view predicts -- distance on a sandy beach should appear to be greater than the same distance on firm ground.

In the present study we use a perceptual matching task to investigate whether the perceived energetic cost of walking affects visually perceived distance, or whether distance perception is independent of perceived effort. Participants viewed the 'standard' target over sand or firm ground, then viewing the 'comparison' target over the same or other terrain, they adjusted the distance to match the standard. This design yielded four standard-comparison terrain conditions.

We asked one group of participants to adjust the distance of a comparison target so that the energetic cost of walking to it would match that of walking to the standard target. We expected that when viewing the standard target and comparison target over congruent terrain (Firm-Firm and Sand-Sand), participants would accurately match the energetic cost, because the cost per meter is equal when the terrains are the same. Given that participants were familiarized with walking on sand, we expected responses for incongruent conditions to reflect the directional difference (if not the magnitude) between the ease of walking on firm ground and the difficulty of walking on sand. After viewing the standard over sand, participants should adjust the comparison, on the firm ground, to a distance greater than the standard. Conversely, viewing the standard on firm ground and adjusting the comparison on sand should yield a distance that is less than the distance of the standard.

Accurate magnitude judgements would place a target viewed over firm ground at twice the distance as a target viewed over sand because sand is twice as energetically costly to walk on (Figure 7A, dashed lines; Appendix A, Table 1). Thus, matching energetic cost when the standard is on firm ground and the comparison is on sand should yield a setting that is half the distance of the standard; conversely, when the standard is on sand and the comparison is on firm ground, the setting should be twice the distance of the standard. This predicts that the slope of the response function should be 0.5 in the Firm-Sand condition and 2.0 in the Sand-Firm condition.

We asked a second group to adjust the comparison target until it looked to be the same distance from them as the standard target. If a higher energetic cost or anticipated effort caused an increase in the perceived distance over sand -- if perceived distance is a product of optical information and the consequence of action -- then the incongruent conditions should significantly differ from the congruent conditions. When matching a target viewed over sand ground, a target viewed over firm ground would be set farther away (and vice versa). On the other hand, if perceived distance is specific to the visual information for distance (e.g. declination angle), then the distance of the comparison target should be similar to the distance of the standard for all four terrain combinations. To dissociate the geometric and information-based views from the embodied view, critical comparisons are made between instruction groups (match energetic cost or distance) for the incongruent conditions. If perceived effort influence distance perception we would expect differences between the congruent and incongruent conditions for the distance and that the prospective judgements of effort should be similar. We found no evidence that a greater energetic cost of walking increased perceived distance, contrary to the embodied hypothesis.

Methods

Participants

Volunteers were randomly assigned to the energy matching group (6 adults; 3F, 3M) or the distance matching group (7 adults; 5F, 2M). 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, and was in accordance with the Declaration of Helsinki.

Apparatus

The research was conducted in the Perception and Action Lab at Brown University. The participant stood on a wooden platform (6.5m wide x 2.5m long x 0.15m high) which contained a sandbox (1.5m wide x 2.5m long) in the middle, so that the sand was flush with the plywood surface on either side (Figure 6A). A square viewing plate (rubber first-base; 0.3m x 0.3m, 0.005m thick) was positioned on the plywood to the left or right of the sand, from which the participant viewed a virtual environment in a head-mounted display (HMD; Samsung Odyssey+, Irvine CA; 110° diagonal field of view; 1440 x 1600 pixels per eye). Stereoscopic images of a virtual environment were generated in Vizard (WorldViz, Santa Monica CA). Head position was tracked using the Odyssey's built-in cameras and inertial motion unit and used to update the visual display at a frame rate of 90 Hz, with a total latency of approximately 11ms. Responses were made with a wireless controller (Samsung Odyssey+) held in the right hand. The comparison target could be moved slowly or quickly (1.8m/sec or 3.6m/sec in depth) depending on the deflection of the controller's trackpad.

Displays

The two groups viewed the same virtual environments: an orientation environment that contained a small box with a viewing box placed on top and a test environment that displayed sand and concrete ground surfaces. In the orientation environment, the sky was blue and the ground plane was textured with a purple-grey marble pattern. A small burgundy box (0.58 m wide x 0.35 m deep x 0.15 m high) appeared on the ground a couple of steps in front of the participant, with the white viewing box placed on top (0.3 m wide x 0.3 m deep x 1.3 m high). The virtual ground plane was matched to the physical floor of the lab, the burgundy box to the front edge and height of the plywood platform, and the viewing box to the position of the base plate.

The test environment had a blue sky and a ground plane composed of two adjacent surfaces: a greyscale random noise texture and a photorealistic sand texture. The location of the boundary between them corresponded to a boundary between the plywood platform and the sandbox in the testing room. A red pole (0.35 m radius, 1.3 m tall) and two rectangular boxes (the 'standard' and 'comparison' targets) rested on the ground plane (refer to Figure 6). The two targets had a green or yellow granite texture (counterbalanced between participants) and various 3D sizes; the texture map was constant and did not scale with the simulated box size.

During *controller practice* trials, only the comparison target (0.9 m wide x 0.15 m deep x 0.8 m high) was presented, at a distance of 2 m from the centre of the base plate on the sand or firm surface, for a duration of 10 seconds. The participant used the controller to vary the distance of the comparison (within the bounds of 1.5 m to 24 m). During *matching practice* trials, both the standard and comparison targets (of the same size) were presented, and the participant adjusted the distance of the comparison to match the standard. The standard target appeared 6, 8, 10, or 12 m from the base plate and the comparison target appeared at a random initial distance (1.5 to 24 m) along two of the four possible target axes (Figure 6C). During *experimental* trials, the standard and comparison targets each had four possible sizes (0.5 to 0.86 m wide, 1.0 to 1.75 m high, 0.15 m deep; see Appendix D, Table 7), and on each trial their sizes were randomly selected from the 12 possible non-identical pairs. The standard appeared 5, 7, 9, or 11 m from the base plate and the comparison at a random initial distance (3 to 13 m). On all matching trials, the comparison appeared 90° to the left or right of the standard, on the same or different terrain (Figure 1C). To ensure that the two boxes were never visible together within the field of view, their opacities were determined by the direction the participant was facing. When the HMD was oriented to the left or right of a box by more than 40°, it was rendered as transparent (alpha = 0), and it faded into view as the participant turned toward it, reaching 100% opacity at 10° away.

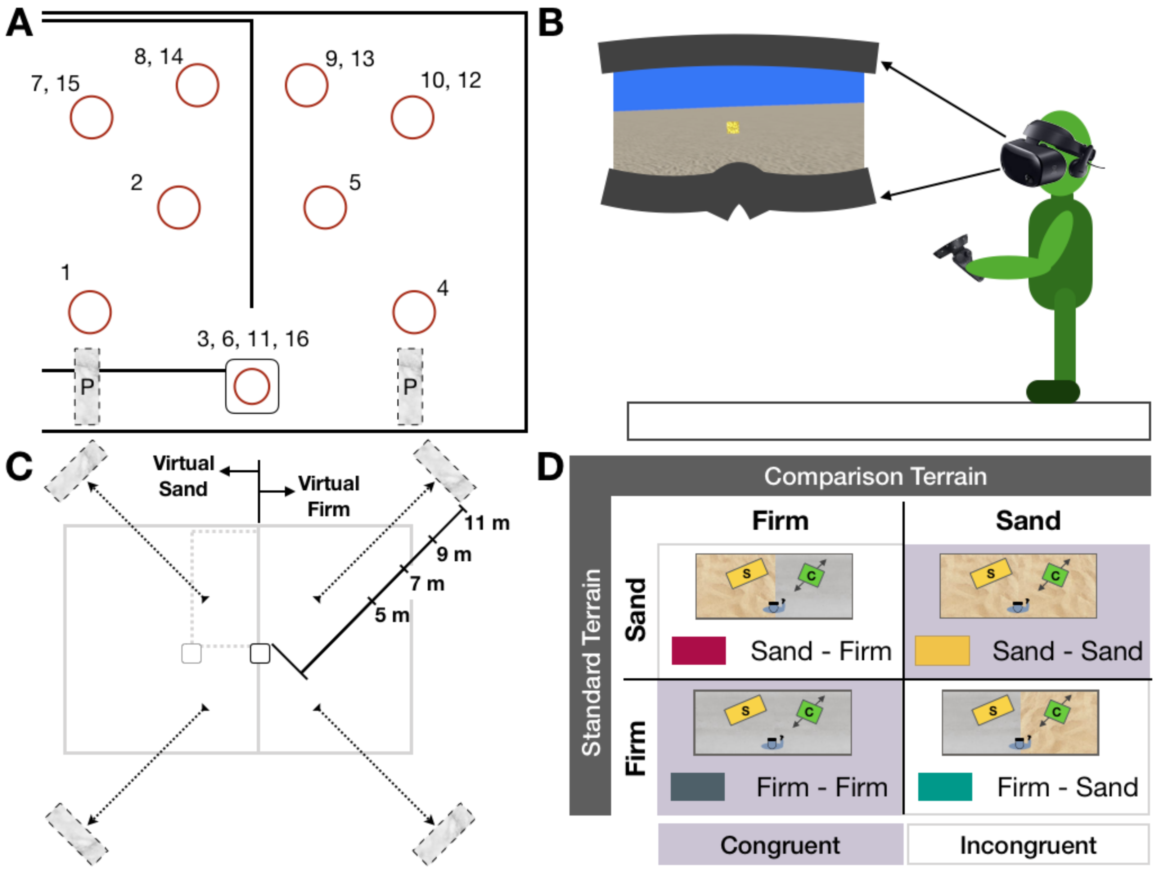

Figure 6. Experimental set-up. (A) Illustration of comparison position for controller practice (P) and exploration pole positions (red circles). Pole positions are numbered for starting the exploration on sand. Numbers are mirrored when starting on the firm platform. (B) Participant perspective of the virtual sand overlaying the physical platform and sandbox while using the controller to move the comparison (yellow box). (C) The four possible axes that the standard and comparison appear on. The standard was viewed at one of four distances, as illustrated in the (virtual) firm ground area. The comparison appears at a random distance between 3 m (the start of the dashed, arrowed line) and 13 m. The controller is used to move the comparison along the dashed axis. (D) Standard-Comparison terrain pair combinations. The terrain that the standard appeared on is the Standard Terrain and the terrain that the participant moved the comparison across, when making their distance judgement, is the Comparison Terrain.

Design

For each group, there were two Standard Terrain and two Comparison Terrain conditions: the standard target was placed on the virtual sand or firm surface (Standard Terrain), and the participant adjusted the distance of the comparison target, which was likewise placed on the sand or the firm surface (Comparison Terrain). This yielded four

Terrain Conditions: Sand-Sand, Sand-Firm, Firm-Firm, and Firm-Sand. In each condition, the standard was presented at the four target distances (5, 7, 9, 11 m), with eight repetitions, half with the standard on the left and half on the right. This yielded a total of 128 trials (4 terrain conditions x 4 standard distances x 8 repetitions), presented in a randomized order.

Procedure

When the participant entered the testing room, the wooden platform and sandbox was hidden behind a black theatre curtain. The participant put on the HMD and adjusted the interocular distance of the lenses to make the scene as sharp as possible. The experimenter then pulled back the curtain and pre-recorded instructions played through the HMD's headphones. The participant was instructed to step up onto the burgundy box (corresponding to the platform), stand within the white viewing box (corresponding to the base plate), and look up at the horizon, triggering the appearance of the sand and firm ground surfaces. The participant was asked to note the appearance of the soft sandy surface and the solid, firm surface on either side. They then completed controller practice, exploration, and matching practice phases, before moving onto the test phase.

Controller practice phase. Participants first practiced using the hand-held controller to move the comparison target in depth at the fast and slow speed. The comparison appeared at 3 m on either the sand or on the firm terrain; the terrain was counterbalanced across subjects. The participants listened to audio instructions (13 seconds) on how to use the touchpad on the controller to move the comparison target, during which they could practice with an additional 7 seconds following the recording.

Exploration phase. Participants next explored the environment by walking to a series of red target poles. They were instructed to walk across the platform or the sand to reach a pole, which triggered the appearance of the next pole. The participant walked across the two surfaces circling back to the base plate four times, totalling 16 exploration pole positions (Figure 6A). The first loop involved walking to two poles on one surface (sand or platform) and returning to the base plate. The next loop was on the other surface. On the last two loops, the participant crossed from one surface to the other in one direction and then in reverse (e.g. Figure 6A, pole 8 to 9 and then pole 13 to 14). The pole positions were different from the standard and comparison target positions in the other phases. Arriving at the final pole position on the base plate triggered an audio recording that made the connection between the real and virtual environments explicit ("as you have experienced, the sand you see is really sand and the firm ground is truly solid").

Matching practice phase. Participants were then familiarized with the matching task (energy or distance matching) in four practice trials. The participant stood on the base plate and turned on the spot until they could see the standard and comparison targets. The energy group was instructed to "Adjust the [green/yellow] box until it looks like it would take the same amount of energy to walk to as the [yellow/green] box". The distance group was instructed to "Adjust the [green/yellow] box until it looks to be the same distance from you as the [yellow/green] box," (see Appendix E, Audio Instructions). Each of the four Terrain conditions was presented once.

Test phase. Before the test trials began, the relevant instructions were played again. On all matching trials, the participant was free to look back and forth between the standard and comparison, but the comparison target had to be within ±10° of the center of the field of view in order to adjust its position (Figure 6B). When the adjustment was completed, the participant pulled the trigger on the controller to record their decision and initiate the next trial. An experimental session lasted about an hour.

Data Analysis

Due to time constraints, one of the distance matching participants only completed 71 of the 128 trials. An average of 5.5% of trials were missing due to an error with the controller's trigger; 4.5% for the matching distance Group and 6.5% for the matching energy group, within the instruction groups, the missing data are evenly distributed amongst the four terrain combinations.

We performed a linear mixed-effects regression analysis, which analyzes nested dependencies within data sets and copes well with missing data. The dependent variable was the adjusted distance (m) of the comparison target. As fixed effects, we entered the distance of the standard target (5, 7, 9, and 11 m; centered continuous variable), the instruction group (Energy or Distance matching), the Standard Terrain (sand or firm), the Comparison Terrain (sand or firm), and the possible interactions. As random effects, we had by-subject intercepts and uncorrelated slopes, for the effect of instruction group. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. The data was analyzed in *Matlab* using the *fitlme* function (Maximum likelihood approximation; R2020a). P-values were obtained by likelihood ratio tests of the full model against the reduced model without the effect in question.

Contrasts comparing the congruent terrain conditions were performed on the mean settings and slopes; Sand-Sand and Firm-Firm were expected to be no different from each other. To test the embodied view's predictions, contrasts between conditions that share the same standard terrain but differ in their comparison terrain were performed for both the mean comparison settings and the slopes (e.g. Sand-Firm compared to Sand-Sand). Incongruent terrain slopes were also contrasted with the energetic cost predictions (Sand-Firm = 2, Firm-Sand = 0.5). F-ratios are reported and Satterthwaite approximation was used to adjust the denominator degrees of freedom.

Results

The mean comparison settings are plotted as a function of the standard distance for the energy matching group in Figure 7, and the distance matching group in Figure 8. When participants match the energetic cost of walking to the target, the comparison on firm ground is adjusted to be farther away than the standard on sand, and vice versa. This pattern implies that the sand is judged to be more energetically expensive than the firm ground. However, when distance is matched, all four conditions lie close to the diagonal, with no effect of terrain (Figure 8). These results indicate that perceived distance is unaffected by the viewed terrain. The group matching energy significantly differs from the group matching distance when the standard and comparison are on incongruent terrains. Thus, even though the energetic cost of walking was judged to be higher on sand than concrete, this perceived cost did not influence perceived distance.

We first report the analysis of the embodied view-based contrasts for each group, and then compare the results across groups. Regression results for fixed effects are summarized in Appendix E Table 8.

Matching Energetic Cost

The energy group was instructed to adjust the comparison target to match the energetic cost of walking to the standard target. When the targets appeared on congruent surfaces (Firm-Firm and Sand-Sand conditions), the comparison adjustments were fairly accurate, slightly undershooting the mean standard distance of 8.0m by 0.18 m (Figure 7A, yellow and grey solid lines). The mean comparison setting in the Firm-Firm condition (7.81 m ± 0.11 SE) was no different from that in the Sand-Sand condition (7.82 m ± 0.12 SE) ($F(1, 1509.3) = 0.013$, $p = 0.909$). Moreover, their regression slopes were close to 1.0 and nearly identical (0.92 in the Firm-Firm condition, 0.94 in the Sand-Sand condition) ($F(1, 1509.3) = 0.392$, $p = 0.532$). These results indicate that participants perceive the energetic cost of walking on the same type of terrain as quite similar.

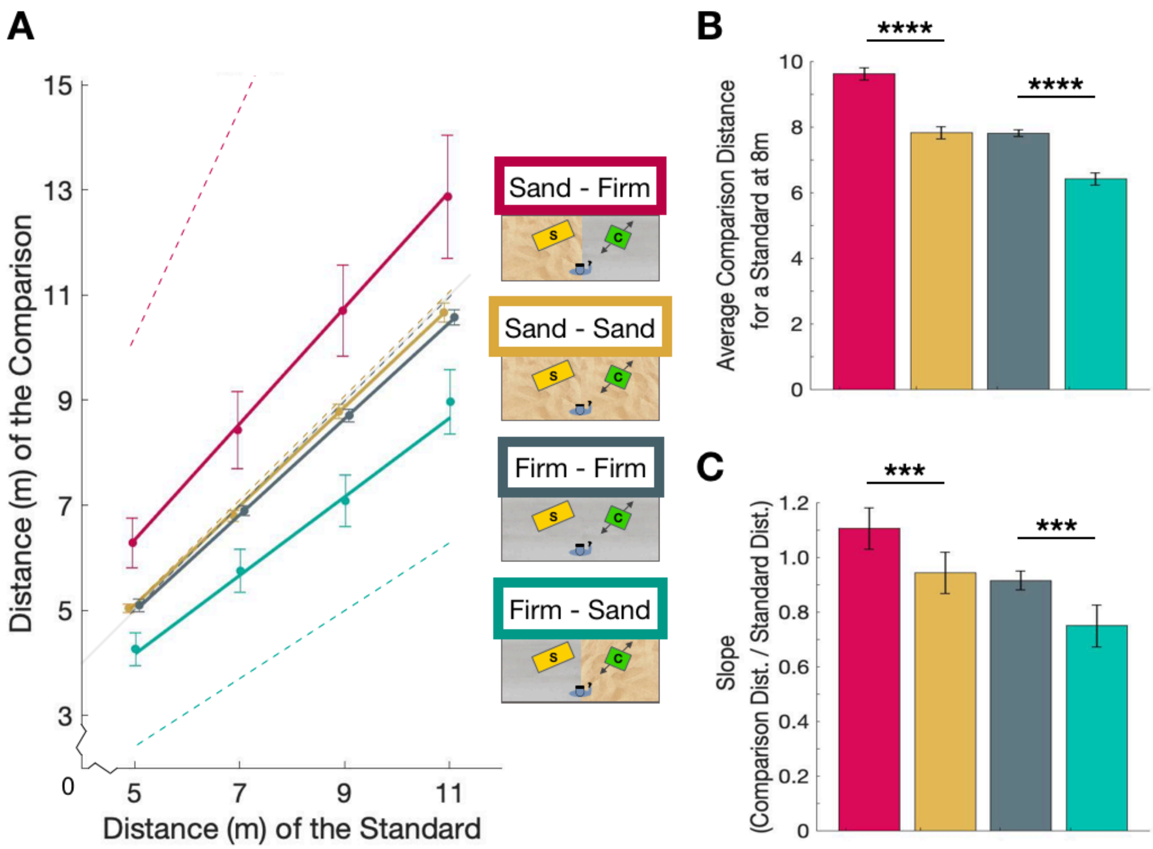

Figure 7. Matching Energetic Cost. (A) The distance of the comparison (m) plotted as a function of the standard distance (m). Means (± SE) are based on the Target distances, of 5, 7, 9, and 11 m, and the Standard-Comparison terrain pair combinations; the terrain that the standard appeared on is the Standard Terrain and the terrain that the participant moved the comparison across, making their distance judgement, is the Comparison Terrain. Solid lines are the marginal regression model predictions. Means and predictions are slightly jittered horizontally for visibility. (B) Regression predictions of the marginal mean (± SE) comparison distances for the terrain pair combinations, at the average standard distance (8 m). (C) Regression predictions of the marginal slopes (± SE) for the terrain pair combinations.
*** $p < 0.001$; **** $p < 0.0001$.

When the standard and comparison targets appeared on incongruent surfaces (Sand-Firm and Firm-Sand conditions), however, the mean settings (Figure 7B) and slopes (Figure 7C) differed significantly from the corresponding congruent conditions.

The relevant contrasts are between conditions that share the same standard terrain but differ in their comparison terrain.

First consider conditions in which the standard was presented on sand. When the comparison appeared on firm ground, the mean adjustment was greater (Sand-Firm, 9.62 m ± 0.12 SE) than when it appeared on sand (Sand-Sand, 7.82 m ± 0.12 SE) ($F(1, 1509.3) = 304.951$, $p < 0.0001$) (warm tones in Figure 7B). Moreover the slope in the Sand-Firm condition (1.11 ± 0.03 SE) was 1.2 times greater than that in the Sand-Sand condition (0.94 ± 0.03 SE) ($F(1, 1509.2) = 12.576$, $p < 0.001$) (Figure 7C). Given that the energetic cost of walking on sand is twice that of firm ground, the distance settings in the Sand-Firm condition should be two times those in the Sand-Sand condition (top dashed line in Figure 7A). However, the actual slope was significantly lower than the predicted slope of 2.0 ($F(1, 1509.2) = 757.436$, $p < 0.0001$), implying that participants underestimated the actual energetic cost of walking on sand.

Conversely, consider conditions in which the standard was presented on firm ground. When the comparison appeared on sand, the mean setting was significantly less (Firm-Sand, 6.43 m ± 0.12 SE, cool tones in Figure 7B) than when it appeared on firm ground (Firm-Firm, 7.81 m ± 0.11 SE) ($F(1,1510.1) = 182.329$, $p < 0.0001$). In addition, the Firm-Sand slope (0.75 ± 0.03 SE) was significantly shallower than the Firm-Firm slope (0.92 ± 0.03 SE)($F(1, 1509.3) = 12.590$, $p < 0.001$) (Figure 7C). Note, however, that this was significantly greater than the predicted slope of 0.5 (bottom dashed line in Figure 7A) ($F(1,1509.4) = 58.661$, $p < 0.0001$), again implying that participants underestimated the cost of walking on sand.

In sum, the results indicate that participants judged the sand surface to have a significantly greater energetic cost than the firm ground, but they underestimated the energetic distance ratio of 2:1, on average the distance on firm ground to the distance on sand is set at a ratio of 1.2:1 (underestimating actual relative cost by approximately 80%).

Matching Distance

The distance group was instructed to adjust the comparison target to match the perceived distance of the standard target. Overall, the mean comparison setting (7.61m ± 0.09 SE) (Figure 8B) underestimated the distance of the standard by 0.39m, with a slope of 0.88 m (± 0.03 SE) (Figure 8C). When the targets appeared on congruent surfaces (Firm-Firm and Sand-Sand conditions), the mean comparison settings ($F(1, 1509.7) = 0.111$, $p = 740$) and the slopes (0.87 in the Firm-Firm condition, 0.88 in the Sand-Sand condition) ($F(1, 1510.1) = 0.093$, $p = 0.761$) were no different. The means and slopes were nearly identical, again for the contrasts between conditions that share the same standard terrain but differ in their comparison terrain. When the standard appeared on sand, the comparison setting was similar on firm ground (Sand-Firm, 7.70m ± 0.09 SE) and sand (Sand-Sand, 7.59 m ± 0.09 SE) ($F(1,1509.4) = 1.329$, $p = 0.25$). Moreover, the slope in the Sand-Firm condition (0.91 ± 0.03 SE) was indistinguishable from the Sand-Sand condition (0.88 ± 0.03 SE) ($F(1, 1509.4) = 1.329$, $p = 0.249$). Likewise, when the standard appeared on firm ground, the mean comparison setting on sand (Firm-Sand, 7.53 m ± 0.09 SE) was similar to that on firm ground (Firm-Firm, 7.63 m ± 0.09 SE) ($F(1,1509.6) = 0.964$, $p = 0.33$). The slope in the Firm-Sand conditions (0.87 ± 0.03 SE) is no different from the slope in the Firm-Firm conditions (0.87 ± 0.03 SE) ($F(1,1509.4) = 0.011$, $p = 0.92$). These results indicate that perceived distance is unaffected by the viewed terrain.

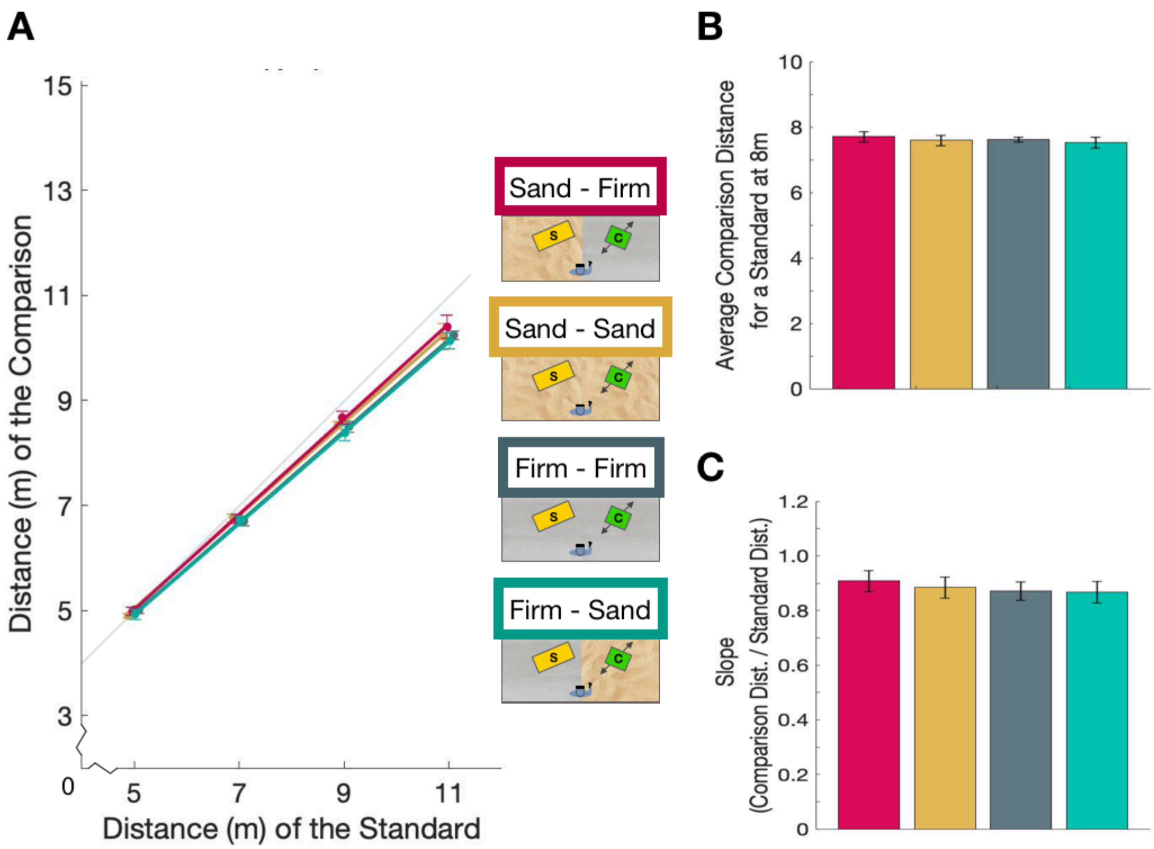

Figure 8. Matching Egocentric Distance. (A) The distance of the comparison (m) plotted as a function of the standard distance (m). Solid lines are the marginal regression model predictions. Means and predictions are slightly jittered horizontally for visibility. (B) Regression predictions of the marginal mean (± SE) comparison distances for terrain pair combinations, at the average standard distance (8 m). (C) Regression predictions of the marginal slopes (± SE) for the terrain pair combinations.

Between-Group Comparisons

The three-way interaction between Standard Terrain, Comparison Terrain, and Group was significant ($\chi2(1) = 3.87$, $p = 0.049$). The three-way interactions between Target Distance and Group with the Standard Terrain ($\chi2(1) = 13.43$, $p < 0.001$) and the Comparison ($\chi2(1) = 11.05$, $p < 0.001$) are also significant. The four-way interaction, however, between Standard Terrain, Comparison Terrain, Target Distance, and Group was non-significant ($\chi2(1) = 0.05$, $p = 0.829$).

When the standard and comparison targets appeared on congruent terrain (Firm-Firm or Sand-Sand), the mean comparison setting in the distance group (7.61 m ± 0.09 SE) was no different from that in the energy group (7.82 m ± 0.12 SE) ($F(2, 56.236) = 0.306$, $p = 0.737$). Moreover, the slopes of the congruent terrains did not differ statistically between the distance group (0.88 ± 0.03 SE) and the energy group (0.93 ± 0.03 SE) ($F(2,1509.8) = 1.615$, $p = 0.199$). The distance and energetic cost matches were equivalent when viewing the standard and comparison on the same terrain; this was expected, given that the energy per meter needed to walk to the standard and the comparison is equal for congruent terrain conditions.

For the incongruent terrain conditions, on the other hand, there was a significant difference in the mean setting between groups ($F(2, 56.084) = 87.097$, $p < 0.0001$). In the Sand-Firm condition, the mean energetic match (9.62 m ± 0.12 SE) was greater than the mean distance match (7.70 m ± 0.09 SE) ($F(1, 53.212) = 75.705$, $p < 0.0001$). Conversely, in the Firm-Sand condition, the mean energetic match (6.43 m ± 0.12 SE) was smaller than the mean distance match (7.53 m ± 0.09 SE) ($F(1, 55.773) = 22.412$, $p < 0.0001$). Thus, there was a greater difference between sand and firm ground when matching energetic cost than when matching egocentric distance.

Similarly, instruction group had a significant effect on the slope of the incongruent conditions ($F(2, 1510) = 4.1418$, $p < 0.0001$). Specifically, in the Sand-Firm condition, the slope was steeper when participants were instructed to match energetic cost (1.11 ± 0.03 SE) than to match distance (0.91 ± 0.03 SE) ($F(1, 1509.5) = 42.698$, $p < 0.0001$). Conversely, in the Firm-Sand condition, the slope was shallower when instructed to match energetic cost (0.75 ± 0.03 SE) than to match distance (0.87 ± 0.03 SE) ($F(1, 1509.6) = 6.182$, $p = 0.013$).

In sum, matching distance and matching energy yields significantly different means and slopes for incongruent terrain conditions. Compared to matching distance, the mean and slope of Sand-Firm is greater when matching energetic cost; while Firm-Sand, conversely, yields a smaller mean and more compressed slope. These results indicate that although walking on sand is reliably perceived as more energetically costly than walking on firm ground, perceived egocentric distance is independent of the associated effort of walking on the terrain.

Discussion

To investigate whether the energetic cost of walking is accurately judged and subsequently affects visually perceived distance, we manipulated the terrain on which a standard target was viewed and a comparison target was adjusted (firm ground or soft sand) to match the perceived energetic cost or perceived distance. We found that the energetic cost of walking on sand was judged to be significantly greater than firm ground, although the actual magnitude of the difference (two times) was underestimated by about 80%, on average. In contrast, we found that the terrain had no effect on distance judgments. These results indicate that perceived egocentric distance is independent of perceived energetic cost.

The embodied view asserts that the content of distance perception is a function of both optical information and non-visual influences such as anticipated effort (Bhalla & Proffitt, 1999; White, 2012; Witt & Proffitt, 2008; Witt et al., 2004). This hypothesis predicts that perceived egocentric distance over sand should expand compared to firm ground. Walking on sand requires twice the energy expenditure of walking the same distance on firm ground, implying that perceived distance over sand might be up to twice that over firm ground. The judged energetic cost of sand was only about 1.2 times that of firm ground, however, but still a significant difference. The embodied hypothesis thus predicts a significant increase in perceived distance over sandy terrain. Specifically, it predicts that distance matches in the incongruent terrain conditions will significantly differ from the congruent conditions, and this difference will become more pronounced as egocentric distance increases (i.e. the slopes of the response functions will differ). Contrary to this hypothesis, we find that the perceived effort of walking on sand or firm ground has no influence on perceived distance. Distance matches are nearly accurate (slopes of 0.93) and virtually identical in all terrain conditions.

The geometric view and the information-based view agree that visual perception of spatial layout should depend on the available optical information, and not on other influences such as anticipated effort or behavioural potential. In addition, the information-based view holds that the affordances of the environment – relations between the surface layout and one's action capabilities – can also be perceived, based on body-scaled and action-scaled information. Alternative explanations of the evidence for embodied perception suggest that demand characteristics or post-perceptual processes are responsible for reported 'action-specific' effects (Durgin, 2017; Firestone, 2013; Hutchison & Loomis, 2006b; Russell & Durgin, 2008).

Critically, both the geometric and information-based views predict that distance matching should be accurate regardless of the congruency of the terrain. Our results support this prediction, for perceived distance was accurate and independent of the anticipated cost of walking on the terrain. We observed a slight underestimation of the standard distance by approximately 5%, well within the range of previous research on distance matching in virtual environments, which found that settings of the comparison were within +7% to -15% of the distance of the standard (Kunz et al., 2009; Sinai et al., 1999; Witmer & Kline, 1998).

We report for the first time that the energetic cost of walking on surfaces of different compliance is reliably differentiated based on their visual appearance, although the actual relative cost is underestimated. The underestimation may be attributable to making judgements in a virtual environment, the stimulus was a graphic image of sand, or due to the unfamiliar explicit scale of energetic cost. While explicit judgements of energetic cost are rarely made, compared to relative judgements made using a distance scale (metric or imperial), implicit judgments are made during everyday route selection. Retrospective ratings of perceived effort upon completion of a task correlate with the metabolic cost of the action, and could serve to ground prospective judgments of the energetic cost. And so, a preference task (see Chapter 5) may better reveal how the energetic cost of the substrate relative to the energetic cost of distance is perceived.

Conclusion

The present experiment tested the embodied hypothesis that the visual perception of egocentric distance depends on the anticipated cost of walking on the terrain. Using a perceptual matching paradigm, we found an effect of terrain when matching the energetic cost of walking to the targets, but no effect of terrain when matching the egocentric distance of the targets. The results indicate that, while visual judgments of the cost of walking on sand are significantly greater than firm ground, this difference in energetic cost had no influence on perceived distance: visually perceived distances on sand, a substrate judged to be substantially more energetically expensive, are no different than visually perceived distances on firm ground. The results support the hypothesis that visually perceived distance is independent of perceived effort and is based on optical information.

CHAPTER 4

Perceiving 'Walkability': Does Visually Perceived Distance Depend on the Judged Ease of Walking (and Vice Versa)?

Introduction

When we are walking, vision provides a wealth of information about our current course and the terrain ahead. The surface properties of the ground greatly influence the difficulty of walking and the potential cost of different routes. Firm, level ground affords easy traversal, but walking becomes more difficult on steep, uneven, slippery, or compliant surfaces. The ease of walking to a goal – its *walkability* – thus varies with the properties of the intervening terrain as well as the egocentric distance of the goal. The purpose of the present experiment is to investigate the visual perception of walkability, operationalized as 'ease of walking'. Specifically, I ask whether visually perceived ease of walking depends on both goal distance and the energetic cost of the terrain, and reciprocally, whether visually perceived distance depends on the judged ease of walking.

It is generally assumed that the visual perception of distance is independent of the energetic cost of an associated action, but in recent years that assumption has been questioned. Two current accounts of egocentric distance perception, the geometric and information-based views, hold that perceived distance depends solely on visual information. Recently, the embodied view has held that perceived distance also depends on the anticipated cost of walking. When it comes to the affordances of the ground surface for action, the information-based view agrees that perceiving an affordance such as walkability depends on the energetic cost of walking. The present experiment is thus designed to test whether visually perceived distance is influenced by ease of walking on the terrain, and vice versa.

The *geometric view* proposes that perceived egocentric distance generally corresponds to physical distance in the world around us (Loomis & Beall, 2004; Loomis et al., 1992). It is assumed that depth cues combine to yield a percept of the surrounding spatial layout, which can then support any action. The cost of the action itself does not contribute to the visually perceived distance. According to this view, distance perception can be measured through both non-action and action-based indicator variables. In particular, perceptual matching and blind-walking tasks yield similar egocentric distance estimations, both in the real world and in virtual reality (Sinai et al., 1999; Sinai et al., 1998; Swan et al., 2006). The geometric view predicts that visually perceived egocentric distance will be unaffected by the ease or difficulty of walking on the substrate. However, it makes no predictions about affordance perception: how visually perceived ease of walking will be influenced by the energetic cost of the substrate.

The *information-based view* focuses on the visual information that specifies distance under natural conditions, and how this information is used to guide action (J. Gibson, 1979/2015; Warren, 1998). Like the geometric view, it holds that visually perceived distance is based solely on optical information, independent of the costs of action. In the open field, for instance, the location of an object on the ground plane is specified by its point of optical contact with the ground surface (J. Gibson, 1950; Epstein, 1966), and its egocentric distance is specified by the declination angle from the horizon (Sedgwick, 1973, 1986).

In particular, the angular declination from the horizon to the contact point (α) specifies egocentric distance (*Z*) in units of eye-height (*E*):

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

There is convergent behavioural evidence that manipulating the visual horizon or the declination angle produces systematic changes in perceived distance (Ooi et al., 2001; Messing & Durgin, 2005; Wallach & O'Leary, 1982; Williams & Durgin, 2015). This has been demonstrated by using a base-up wedge prism to deflect the visual horizon, increasing the declination angle, resulting in decreased perceived distance, as measured by blind-walking (Ooi et al., 2001). Conversely, lowering the visual horizon in virtual reality yields increases in perceived distance (Messing & Durgin, 2005), collectively indicating that declination provides effective information for egocentric distance. The information-based view holds that distance estimates are based on such visual information and are independent of the potential cost of locomotion.

Finally, the *embodied view* claims that the perceived spatial layout is not based solely on optical information, but incorporates the expected consequences of action. In particular, Proffitt and colleagues (Proffitt, 2006; Witt et al., 2004) proposed that visual perception relates egocentric distance to the anticipated effort of walking. The quintessential experimental manipulation had participants make egocentric distance judgements with or without a heavy backpack (Proffitt et al., 2003). The weight of the backpack was used to increase the effort of walking, yielded the expected increase in perceived distance, compared to the no-backpack group. Proffitt appeals to Gibson's (1979/2015) theory of affordances to argue that, if egocentric distance is viewed as an affordance, then perceived distance should depend on both the visually specified distance and the observer's action abilities, such as their 'physiological potential' or the 'anticipated effort' of action (Proffitt & Linkenauger, 2013; Proffitt et al., 2003). The embodied account thus conflates the perception of surface layout with perception of what the layout affords for action (e.g. Proffitt, 2009; Proffitt et al., 2003).

Gibson (1979/2015) described *affordances* as properties of environmental surfaces taken with reference to the action capabilities of an animal. He proposed that if the relation between environmental properties and the observer's action system can be perceived, then so too can the affordances of the environment. On a ship, for example, the walkability of the deck depends on dynamic properties of the surface due to the ship's roll and pitch. Participants judged the ability to walk a straight line to be greater in the athwart direction than in the fore-aft direction, corresponding to their actual performance; this demonstrates a sensitivity to the affordance of walkability (Walter et al., 2017). Static surface properties such as grade, unevenness, slipperiness, and compliance, also affect the affordances of the ground surface for walking – its walkability. Warren (1984) showed that such properties can have significant energetic consequences, which influence perceived affordances. For example, a firm ground surface affords optimal walking for a bipedal human, a soft compliant surface affords effortful walking, while a slippery, uneven surface may not afford walking at all. Although it is more difficult to walk on some ground surfaces than others, the visual information for target distance over those surfaces (e.g. declination angle) is the same. The information-based account thus predicts that affordance judgments should depend on such surface properties, whereas distance judgments should not (Warren, 2019).

In the previous chapters, I found that the perception of egocentric distance is independent of the energetic cost of walking on the terrain and that egocentric distances are accurately matched, consistent with the information-based view. In this chapter, I pose the same questions about the perception of the affordances of the terrain and perception of egocentric distance: does perceived walkability depend on the compliance of the substrate? And does perceived distance over the substrate depend on its judged walkability?

In the present study, we first investigate the perceived relative ease of walking to a target on firm ground or soft sand (i.e. relative walkability judgements). We use the results to evaluate the contribution of perceived ease of walking to perceived egocentric distance. Our control substrate, firm ground, is typically used in tests of perceived egocentric distance (Bodenheimer et al., 2007; Knapp & Loomis, 2004; Proffitt et al., 2003). To test the influence of the ease of walking, we compare firm terrain to soft sand, because the compliance and slip of the displaced granules makes it twice as difficult to walk across (Appendix A, Table 1) (Davies & Mackinnon, 2006; Lejeune et al., 1998; Zamparo et al., 1998).

In the present study we use a perceptual matching task to investigate the relation between perceived ease of walking and perceived egocentric distance. One group of participants was asked to match the perceived ease of walking to two targets, and another group was asked to match the perceived egocentric distance of the targets. Participants viewed the 'standard' target over sand or firm ground, and adjusted the distance of the 'comparison' target over the same or different terrain until it appeared to match the standard. This design yielded four standard-comparison terrain conditions in each group: Firm-Firm, Sand-Sand, Firm-Sand, and Sand-Firm.

When asked to match ease of walking, we expected that, in the congruent terrain conditions (Firm-Firm and Sand-Sand), participants would set the comparison target to the same distance as the standard, because ease of walking was equated. In contrast, in the incongruent terrain conditions (Sand-Firm and Firm-Sand), we expected the adjustments to reflect the difference in perceived ease of walking per unit distance on the two substrates. Specifically, when viewing the standard over sand, participants should set the comparison at a greater distance on firm ground, thereby matching the perceived ease of walking to the targets. Conversely, when viewing the standard on firm ground, they should set the comparison at a closer distance on sand. The settings thus provide an estimate of the relative difference in perceived ease of walking per unit distance on sand and firm ground, reflecting the perceived affordance of walkability.

The second group was asked to match the perceived egocentric distance of the targets in the four terrain conditions. If egocentric distance is viewed as the affordance of walkability – as held by the embodied view (Proffitt et al., 2003) – then perceived distance should depend on the perceived difficulty of walking, as judged by the first group. Assuming that sand is perceived to be more difficult to walk on than firm ground, the embodied hypothesis predicts that distance over sand should appear to be greater than the same distance over firm ground. Specifically, in the incongruent conditions, when the standard target is viewed over sand, the comparison target should be set farther away on firm ground (and vice versa). On the other hand, if perceived distance depends only on the visual information for distance (e.g. declination angle), then the comparison target should be set at the same distance as the standard in all terrain conditions.

In sum, on the information-based view, perceived walkability should depend on the substrate, but perceived distance should not. Thus, one would expect differences between the congruent and incongruent terrain conditions when matching ease of walking, but equal settings when matching distance. In contrast, on the embodied view, both perceived walkability and distance perception should depend on the substrate, so one would expect differences between the congruent and incongruent conditions for both matching distance and ease of walking (in opposite directions).

We found a small main effect of terrain on perceived ease of walking, whereas there were no such effects on perceived distance. These results are contrary to the embodied hypothesis. However, the effect was not proportional to distance, and when ease of walking judgments were directly compared with distance judgments, it went away. In contrast to the robust influence of terrain on judged energetic cost reported in Chapter 3, terrain had little or no influence on judged ease of walking. This suggests that the matching task was a poor measure of perceived walkability, and thus a forced choice method will be developed in Chapter 5.

Methods

Participants

Sixteen participants were randomly assigned to instruction groups, seven received distance instructions (5F, 2M) and nine received ease of walking instructions (5F, 4M). (Note that the data from the distance matching group were previously described in Chapter 3.) None of the participants 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, and in accordance with the Declaration of Helsinki.

Apparatus

The research was conducted in the Perception and Action Lab at Brown University. The participant stood on a wooden platform (6.5m wide x 2.5m long x 0.15m high) which contained a sandbox (1.5m wide x 2.5m long) in the middle, so that the sand was flush with the plywood surface on either side (Figure 1A). A square viewing plate (rubber first-base; 0.3m x 0.3m, 0.005m thick) was positioned on the plywood to the left or right of the sand, from which the participant viewed a virtual environment in a head-mounted display (HMD; Samsung Odyssey+ Windows mixed-reality, Irvine CA; 110º diagonal field of view; 1440 x 1600 pixels per eye). Stereoscopic images of a virtual environment were generated in Vizard (WorldViz, Santa Monica CA). Head position was tracked using the Odyssey's built-in cameras and inertial motion unit and used to update the visual display at a frame rate of 90 Hz, with a total latency of approximately 11ms. Responses were made with a wireless controller (Samsung Odyssey+) held in the right hand. The comparison target could be moved slowly or quickly (1.8m/sec or 3.6m/sec in depth) depending on the deflection of the controller's thumbpad.

Displays

The two groups viewed the same virtual environments: an orientation environment that contained a box for the participant to step up on, and a test environment that displayed sand and concrete ground surfaces. In the orientation environment, the sky was blue and the ground plane was textured with a purple-grey marble pattern. A small burgundy box (0.58 m wide x 0.35 m deep x 0.15 m high) appeared on the ground a couple of steps in front of the participant, with a tall white viewing box placed on top (0.3 m wide x 0.3 m deep x 1.3 m high). The virtual ground plane was matched to the physical floor of the lab, the burgundy box to the front edge and height of the plywood platform, and the viewing box to the position of the base plate.

The test environment had a blue sky and a ground plane composed of two adjacent surfaces: a greyscale random noise texture with the appearance of solid concrete, and a photorealistic sand texture. The boundary between them corresponded to one of the boundaries between the plywood platform and the sandbox in the testing room. A red pole (0.35 m radius, 1.3 m tall) and two rectangular boxes (the 'standard' and 'comparison' targets) rested on the ground plane (refer to Figure 9). The two targets had a green or yellow granite texture (counterbalanced between participants) and various 3D sizes; the texture map was constant and did not scale with the simulated box size.

During *controller practice* trials, only the comparison target (0.9 m wide x 0.15 m deep x 0.8 m high) was presented, at a distance of 2 m from the centre of the base plate on the sand or firm surface, for a duration of 10 seconds. The participant used the controller to vary the distance of the comparison (within the bounds of 1.5 m to 24 m). During *matching practice* trials, both the standard and comparison targets were presented (with the same size), and the participant adjusted the distance of the comparison to match the standard. The standard target appeared 6, 8, 10, or 12 m from the base plate and the comparison target appeared at a random initial distance (1.5 to 24 m) along two of the four possible target axes (Figure 9C). During *experimental* trials, the standard and comparison targets each had four possible sizes (0.5 to 0.86 m wide, 1.0 to 1.75 m high, 0.15 m deep; see Appendix D, Table 7), and on each trial their sizes were randomly selected from the 12 possible non-identical pairs. The standard appeared 5, 7, 9, or 11 m from the base plate and the comparison at a random initial distance (3 to 13 m). On all matching trials, the comparison appeared 90° to the left or right of the standard, on the same or different terrain (Figure 9C). To ensure that the two boxes were never visible at the same time within the field of view, their opacities were determined by the direction the participant was facing. When the HMD was oriented to the left or right of a box by more than 40°, it was rendered as transparent (alpha = 0), and it faded into view as the participant turned toward it, reaching 100% opacity at 10° away.

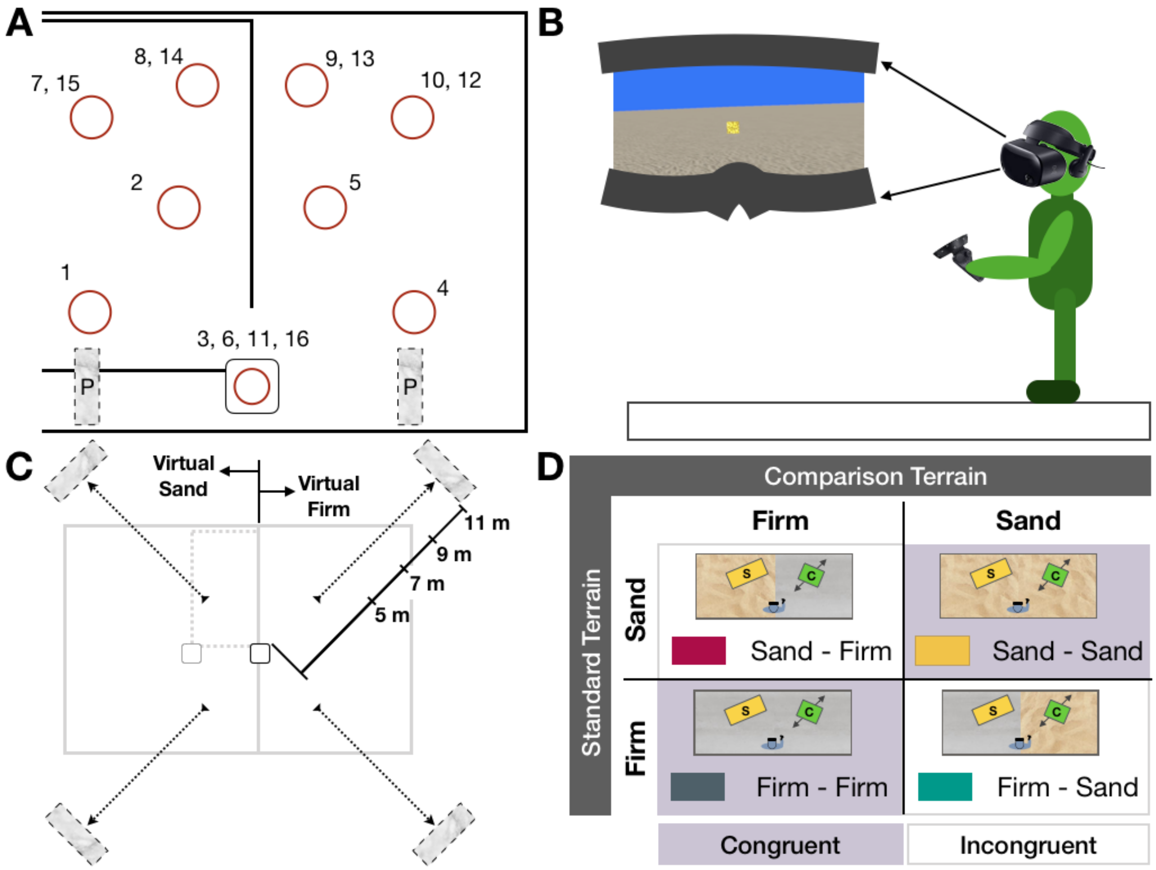

Figure 9. Experimental set-up. (A) Illustration of comparison position for controller practice and exploration pole positions. Pole positions are numbered for starting the exploration on sand. Numbers are mirrored when starting on the firm platform. (B) Participant perspective of the virtual sand overlaying the physical platform and sandbox while using the controller to move the comparison (yellow box). (C) The four possible axes that the standard and comparison appear on. The standard was viewed at one of four distances, as illustrated in the (virtual) firm ground area. The comparison appears at a random distance between 3 m (the start of the dashed, arrowed line) and 13 m. The controller is used to move the comparison along the dashed axis. (D) Standard-Comparison terrain pair combinations. The terrain that the standard appeared on is the Standard Terrain and the terrain that the participant moved the comparison across, making their distance judgement, is the Comparison Terrain.

Design

There were two Standard Terrain and two Comparison Terrain conditions: the standard target appeared on the sand or on the firm surface (Standard Terrain), and the participant adjusted the distance of the comparison target, which appeared on the sand or the firm surface (Comparison Terrain). This yielded four Standard-Comparison terrain conditions: Sand-Sand, Firm-Firm, Sand-Firm, and Firm-Sand. Each combination was repeated eight times at the four standard distances resulting in 128 randomized trials, controlling for equal left-right presentation.

Procedure

The participant put on the HMD and used a dial, built into the headset, to adjust the distance between the lenses. They were instructed to adjust the lenses to make the scene as sharp as possible (this is the point at which the distance between the lenses best matches their inter-ocular distance). The experimenter then pulled back the curtain between the participant and the testing platform. Pre-recorded instructions played through the HMD's headphones. The participant was instructed to step up onto the burgundy box (corresponding to the platform), stand within the white box (corresponding to the base plate), and look up at the horizon, which triggered the appearance of the sand and firm ground surfaces. The participant was asked to note the appearance of the soft sandy surface and the solid, firm surface on either side. They then completed controller practice, exploration, and matching practice phases, before moving onto the test phase.

Controller practice phase. Participants first practiced using the hand-held controller to move the comparison target in depth at the fast and slow speed. The comparison appeared at 3 m on either the sand or on the firm terrain; the terrain was counterbalanced across subjects. The participants listened to audio instructions (13 seconds) on how to use the thumbpad on the controller to move the comparison target, during which they could practice with an additional 7 seconds following the recording.

Exploration phase. Participants next explored the environment by walking to a series of red target poles. They were instructed to walk across the platform or the sand to reach a pole, which triggered the appearance of the next pole. The participant walked across the two surfaces circling back to the base plate four times, totalling 16 exploration pole positions (Figure 9A). The first loop involved walking to two poles on one surface (sand or platform) and returning to the base plate. The next loop was on the other surface. On the last two loops, the participant crossed from one surface to the other in one direction and then in reverse (e.g. Figure 9A, pole 8 to 9 and then pole 13 to 14). The pole positions were different from the standard and comparison target positions in the other phases. Arriving at the final pole position on the base plate triggered an audio recording that made the connection between the real and virtual environments explicit ("as you have experienced, the sand you see is really sand and the firm ground is truly solid").

Matching practice phase. Participants were then familiarized with the matching task (ease of walking or distance matching) in four practice trials. The participant stood on the base plate and turned on the spot until they could see the standard and comparison targets. The ease of walking group was instructed to "Adjust the [green/yellow] box until it looks like it would be equally easy to walk to as the [yellow/green] box". The distance group was instructed to "Adjust the [green/yellow] box until it looks to be the same distance from you as the [yellow/green] box," (see Appendix E, Audio Instructions). There was one practice trial in each of the four Terrain conditions.

Test phase. Before the test trials began, the relevant instructions were played again. On all matching trials, the participant was free to look back and forth between the standard and comparison, as both were not visible at the same time. Additionally, the comparison target had to be within ±10° of the center of the field of view in order to adjust its position (Figure 1B). When the adjustment was completed, the participant pulled the trigger on the controller to record their decision and initiate the next trial. An experimental session lasted about an hour.

Statistical Analysis

One participant in the ease of walking group withdrew from the experiment after completing 56 of the 128 trials. Due to time constraints, one participant in the distance group only completed 71 trials. On average 4.6% of trials were missing due to an error with the controller's trigger, including 4.5% in the Distance group and 4.7% in the Ease of Walking group; within the instruction groups, the missing data were evenly distributed among the four terrain combinations. No participants were excluded from the analysis.

We performed a linear mixed-effects regression analysis, which analyzes nested dependencies within data sets and copes well with missing data. The dependent variable was the adjusted distance (m) of the comparison target. As fixed effects, we entered the distance of the standard target (5, 7, 9, and 11 m; centered continuous variable), the instruction group (Ease of Walking or Distance matching), the Standard Terrain (sand or firm), the Comparison Terrain (sand or firm), and the possible interactions. As random effects, we had by-subject intercepts and uncorrelated slopes, for the effect of instruction group. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. The data was analyzed in *Matlab* using the *fitlme* function (Maximum likelihood approximation; R2020a). P-values were obtained by likelihood ratio tests of the full model against the reduced model without the effect in question.

Contrasts comparing the congruent terrain conditions were performed on the mean settings and slopes; Sand-Sand and Firm-Firm were expected to be no different from each other. Contrasts between conditions that shared the same standard terrain but differed in the comparison terrain (Sand-Firm vs. Sand-Sand and Firm-Sand vs. Firm-Firm) were performed for both the mean comparison settings and the slopes. F-ratios are reported and Satterthwaite approximation was used to adjust the denominator degrees of freedom.

Results

The mean comparison settings are plotted as a function of the standard distance for the walking ease matching group in Figure 10, and the distance matching group in Figure 11. When participants match the ease of walking to the target, the comparison on firm ground is adjusted to be slightly farther away than the standard on sand, and vice versa. This pattern implies that, on average, the sand is judged to be more difficult to walk on than the firm ground by a small margin. However, the slopes of the four conditions are similar, indicating that matching the ease of walking does not proportionally increase with distance.

When distance is matched, all four conditions lie close to the diagonal, with no effect of terrain, and no differences in slope (Figure 11). These results indicate that perceived distance is unaffected by the viewed terrain.

Comparing the two groups, the ease of walking group does not significantly differ from the distance group when the standard and comparison are on incongruent terrains. This confirms that judged ease of walking was largely determined by perceived target distance, with little influence of the substrate. Moreover, the cost of walking on either surface did not influence perceived distance.

We first report the analysis of the specific prediction contrasts for each group, and then compare the results across groups. Regression results for fixed effects are summarized in Appendix E Table 9.

Matching Ease of Walking

For participants who matched the ease of walking, when the targets appeared on congruent surfaces (Firm-Firm and Sand-Sand conditions), the comparison settings were quite accurate, slightly undershooting the mean distance of the standard (8.0m) by 0.12 m (Figure 2A, yellow and grey solid lines). The mean comparison setting in the Firm-Firm condition (7.87 m ± 0.07 SE) was no different from that in the Sand-Sand condition (7.89 m ± 0.07 SE) ($F(1, 1846.1) = 0.089$, $p = 0.766$). Moreover, their regression slopes were close to 1.0 and nearly identical (0.95 in the Firm-Firm condition, 0.98 in the Sand-Sand condition) ($F(1, 1845.5) = 1.502$, $p = 0.221$). These results indicate that participants perceive the ease of walking on the same terrain as very similar.

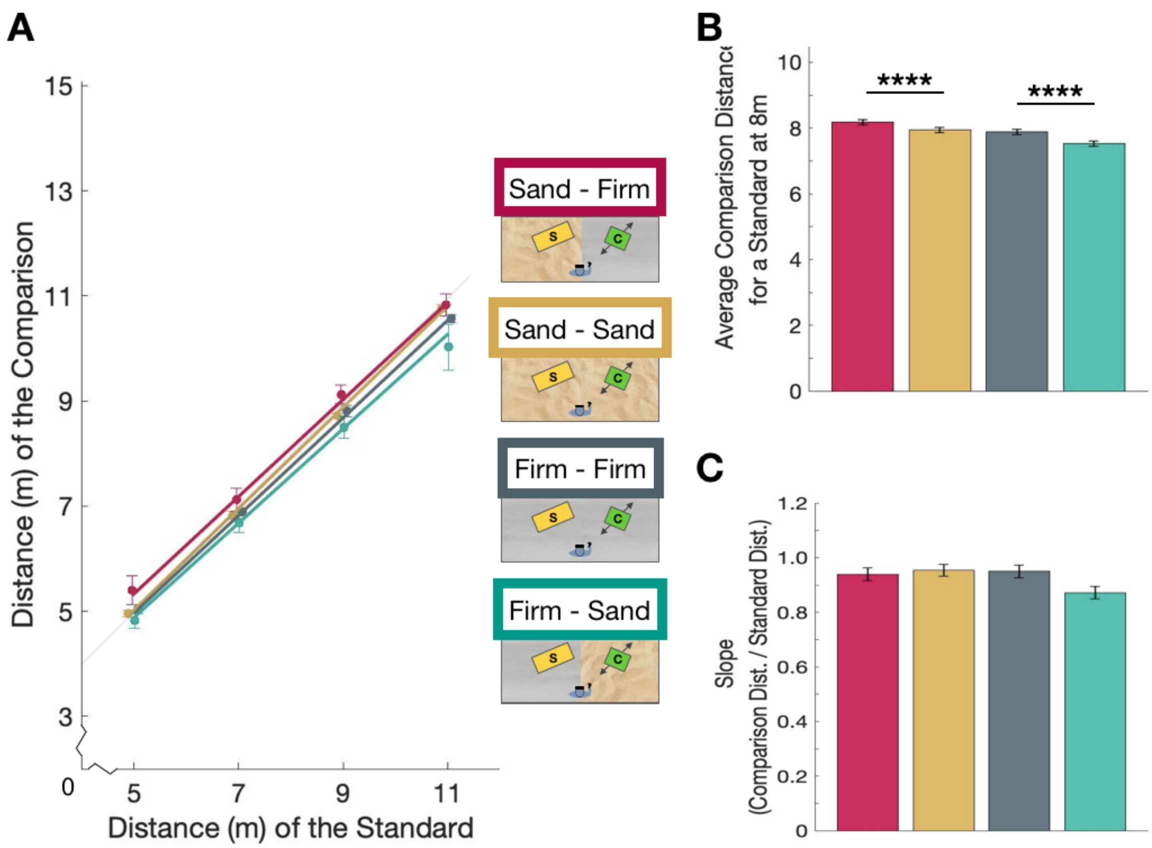

Figure 10. Matching the Ease of Walking. (A) The distance of the comparison (m) plotted as a function of the standard distance (m). Means (± SE) are based on the Target distances, of 5, 7, 9, and 11 m, and the Standard-Comparison terrain pair combinations; the terrain that the standard appeared on is the Standard Terrain and the terrain that the participant moved the comparison across, making their distance judgement, is the Comparison Terrain. Solid lines are the marginal regression model predictions. Means

and predictions are slightly jittered horizontally for visibility. (B) Bar plots of the regression predictions of the marginal mean (± SE) comparison distances for the terrain pair combinations, at the average standard distance (8 m). (C) Bar plots of the regression predictions of the marginal slopes (± SE) for the terrain pair combinations. *** $p < 0.001$; **** $p < 0.0001$.

When the standard and comparison targets appeared on incongruent surfaces (Sand-Firm and Firm-Sand conditions), however, the mean settings (Figure 10B) differed significantly from the corresponding congruent conditions. However, the slopes in the incongruent conditions were no different from those in the corresponding congruent conditions (Figure 10C). The relevant contrasts are between conditions that share the same standard terrain but differ in their comparison terrain.

First consider conditions in which the standard was presented on sand. When the comparison appeared on firm ground, the mean adjustment was greater (Sand-Firm, 8.17 m ± 0.07 SE) than when it appeared on sand (Sand-Sand, 7.89 m ± 0.07 SE) ($F(1, 1845.4) = 25.200$, $p < 0.001$) (warm tones in Figure 10B). However, the slope in the Sand-Firm condition (0.95 ± 0.02 SE) did not differ from that in the Sand-Sand condition (0.98 ± 0.02 SE) ($F(1, 185.4) = 1.575$, $p = 0.21$) (Figure 10C). This implies that the relative ease of walking between sand and firm ground did not scale in proportion to the distance of the target, only a mean difference between the substrates was observed.

Conversely, consider conditions in which the standard was presented on firm ground. When the comparison appeared on sand, the mean setting was significantly less (Firm-Sand, 7.50 m ± 0.07 SE, cool tones in Figure 2B) than when it appeared on firm ground (Firm-Firm, 7.87 m ± 0.07 SE) ($F(1, 1845.4) = 43.211$, $p < 0.001$). But the Firm-Sand slope (0.90 ± 0.02 SE) was not significantly different from the Firm-Firm slope (0.95 ± 0.02 SE) ($F(1, 1846.1) = 3.667$, $p = 0.056$) (Figure 10C). Once again, this result implies that the relative ease of walking between sand and firm ground was not proportional to the distance of the standard, but only a constant difference was observed.

In sum, the mean difference in ease of walking to a target on sand and a target on firm ground to be equivalent to a distance of just 0.33 m. The results imply that the sand was judged to be slightly more difficult to walk on, but that difficulty did not scale with distance.

Matching Distance

When participants matched target distance, overall the mean comparison setting (7.61m ± 0.09 SE) (Figure 11B) underestimated the distance of the standard (8.0 m) by 0.39m, with a slope of 0.88 m (± 0.03 SE) (Figure 11C). When the targets appeared on congruent surfaces (Firm-Firm and Sand-Sand conditions), the mean comparison settings ($F(1, 1509.7) = 0.111$, $p = 0.740$) and the slopes (0.87 in the Firm-Firm condition, 0.88 in the Sand-Sand condition) ($F(1, 1510.1) = 0.093$, $p = 0.761$) were no different.

For contrasts between conditions that shared the same standard terrain but differed in the comparison terrain, the means and slopes were again nearly identical. When the standard appeared on sand, the comparison setting on firm ground was quite similar (Sand-Firm, 7.70m ± 0.09 SE) and sand (Sand-Sand, 7.59 m ± 0.09 SE) ($F(1,1509.4) = 1.329$, $p = 0.25$). Moreover, the slope in the Sand-Firm condition (0.91 ± 0.03 SE) was indistinguishable from that in the Sand-Sand condition (0.88 ± 0.03 SE) ($F(1, 1509.4) = 1.329$, $p = 0.249$). Likewise, when the standard appeared on firm ground, the mean comparison setting on sand (Firm-Sand, 7.53 m ± 0.09 SE) was similar to that on firm ground (Firm-Firm, 7.63 m ± 0.09 SE) ($F(1,1509.6) = 0.964$, $p = 0.33$). The slope in the Firm-Sand conditions (0.87 ± 0.03 SE) is no different from the slope in the Firm-

Firm conditions (0.87 ± 0.03 SE) ($F(1,1509.4) = 0.011$, $p = 0.92$). These results indicate that perceived distance is unaffected by the viewed terrain.

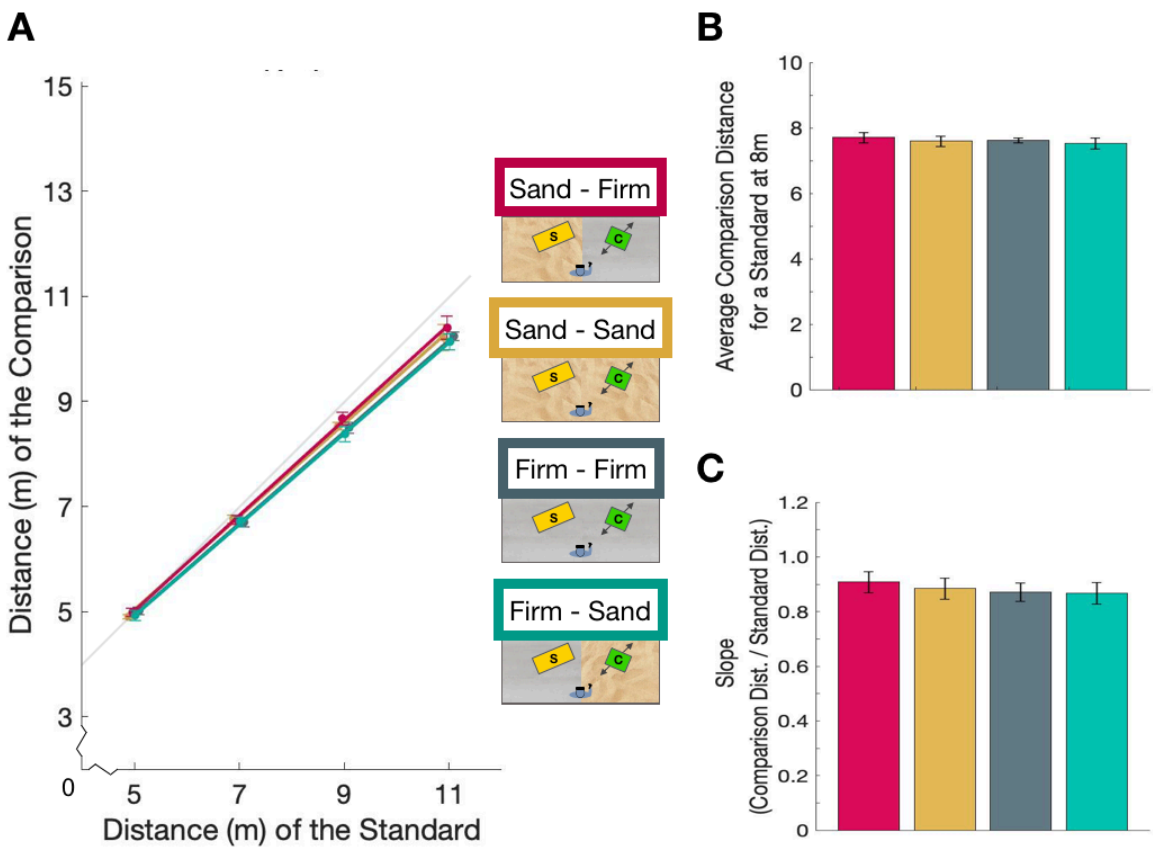

Figure 11. Replication of Figure 8 for ease of reference: Matching Egocentric Distance. (A) The distance of the comparison (m) plotted as a function of the standard distance (m). Solid lines are the marginal regression model predictions. Means and predictions are slightly jittered horizontally for visibility. (B) Bar plots of the regression predictions of the marginal mean (± SE) comparison distances for terrain pair combinations, at the average standard distance (8 m). (C) Bar plots of the regression predictions of the marginal slopes (± SE) for the terrain pair combinations.

Between-Group Comparisons

The two-way interactions between Group and Standard Terrain ($\chi2(1) = 19.94$, $p < 0.001$) and between Group and Comparison Terrain were significant ($\chi2(1) = 13.48$, $p < 0.001$). The two-way interactions between Target Distance and Standard Terrain ($\chi2(1)$

= 6.00, $p = 0.014$) and Target Distance and Group ($\chi2(1) = 19.85$, $p < 0.001$) were also significant. No other interactions were significant.

In the congruent terrain conditions (Firm-Firm or Sand-Sand), the mean comparison setting in the distance group (7.61 m ± 0.09SE) was no different from that in the ease of walking group (7.88 m ± 0.07 SE) ($F(2, 1845.8) = 1.7597$, $p = 0.173$). Moreover, the slopes for congruent terrains did not differ statistically between the distance group (0.88 ± 0.03 SE) and the ease of walking group (0.96 ± 0.02 SE) ($F(2, 1845.7) = 0.295$, $p = 0.744$). The distance and ease of walking matches were thus equivalent when viewing the targets over the same terrain; this was expected, given that the difficulty of walking to the targets was equated in the congruent terrain conditions.

For the incongruent terrain conditions, the difference in the mean setting between groups was not significant ($F(2, 1846) = 2.567$, $p = 0.077$). In the Sand-Firm condition, the mean ease of walking match (8.17 m ± 0.07 SE) was not significantly different from the mean distance match (7.70 m ± 0.09 SE) ($F(1,1845.9) = 0.987$, $p = 0.321$). Similarly, in the Firm-Sand condition, the mean ease of walking match (7.50 m ± 0.07 SE) was not different from the mean distance match (7.53 m ± 0.09 SE) ($F(1,1845.5) = 1.585$, $p = 0.208$). Thus, there was no difference between sand and firm ground when matching the ease of walking than when matching egocentric distance.

Similarly, instruction group had no effect on the slopes in the incongruent conditions ($F(2, 1846) = 0.707$, $p = 0.493$). In the Sand-Firm condition, the slope was no different when participants were instructed to match ease of walking cost (0.95 ± 0.02 SE) than to match distance (0.91 ± 0.03 SE) ($F(2, 1846) = 0.707$, $p = 0.493$). And, in the Firm-Sand condition, the slope was similar when instructed to match ease of walking (0.90 ± 0.02 SE) and to match distance (0.87 ± 0.03 SE) ($F(2, 1845.5) = 0.933$, $p = 0.531$).

In sum, matching the ease of walking and matching distance yields similar means and slopes in the incongruent terrain conditions. These results indicate that the ease of walking judgments were largely driven by perceived distance, with little influence of surface compliance. When compared to the distance group, the small effects of terrain observed in the incongruent conditions for the ease of walking group were not reliable. Thus, the distance to the target largely determined the judged ease of walking, whereas the cost of walking did not influence perceived distance.

Discussion

To investigate whether the perceived ease of walking to a target depends on the intervening terrain, and subsequently influences perceived target distance, we manipulated the terrain over which targets were viewed (firm ground or soft sand). When matching ease of walking to two targets, we found that sand was judged to be slightly more difficult than firm ground, but the difference did not scale proportionally with distance, as would be expected if the judgment were based on the cost or effort of walking. When matching perceived distance, we found that the terrain had no effect, indicating that perceived distance was independent of the cost of walking. However, direct comparisons failed to find any differences between ease of walking judgments and distance judgments. This pattern of results implies that judgments of the ease of walking to a target largely depend on perceived target distance, but distance judgments do not depend on the cost of walking on the substrate.

The embodied hypothesis (Bhalla & Proffitt, 1999; White, 2012; Witt & Proffitt, 2008; Witt et al., 2004) states that the perception of egocentric distance should depend on the anticipated effort or difficulty of walking. Given that the energetic cost of walking on sand is twice that of walking on firm ground, the hypothesis predicts that perceived distance should be much greater over sand than firm ground and, importantly, that difference should increase with distance (i.e. the slopes will differ). Contrary to this prediction, we observed no effect of terrain on perceived distance: distance matches were nearly accurate (slopes of 0.93) and virtually identical in all terrain conditions. The results are consistent with the geometric and information-based views, which both predict that distance perception should only depend on the available visual information, not the anticipated effort or energetic cost of walking (see Chapter 3).

In addition, the information-based view holds that the affordances of the environment – relations between the surface layout and one's action capabilities – can also be perceived, based on action-scaled information (Mark, 1987; Warren, 2007b; Warren & Whang, 1987). The perception of affordances includes categorical judgments about whether an action can or cannot be performed, as well as graded judgements about the relative difficulty of an action, which often depends on energetic cost (Warren, 1984). The information-based account thus predicts that affordance judgments of walkability, operationalized as the 'ease of walking' to a target, should depend on surface properties that affect the cost of walking, such as the compliance of the substrate, whereas distance judgments should not (Warren, 2019).

However, the results indicate that matching the ease of walking to two targets was primarily driven by matching their egocentric distance; small effects of terrain compliance (sand vs. firm ground) did not reliably contribute once distance matches were controlled for. This result was surprising, considering that matching the energetic cost of walking to targets previously revealed large effects of the same terrains (Chapter 3). It is possible that operationalizing the affordance as 'ease of walking' was ambiguous or unreliable compared to matching distance or energetic cost, and thus participants matched well-specified egocentric distance. It is also possible that a more sensitive measure, such as an implicit forced choice task, would yield a stronger effect than an explicit matching task. In Chapter 5, I propose an experiment to investigate the perceived affordance of ‘walkability’ by asking participants to choose which of two targets they would prefer to walk to, while varying both target distance and the intervening terrain (sand vs. firm ground).

Conclusion

The present experiment tested the hypotheses that the visually perceived ease of walking depends on both target distance and the cost of the terrain, and reciprocally, that visually perceived target distance depends on the anticipated ease of walking. Using a perceptual matching task, I found a small effect of terrain on matched ease of walking, but no effect of terrain on matched distance; moreover, the terrain effect on ease of walking result was not significant when compared to its effect on distance. The results support the hypothesis that perceived egocentric distance depends on visual information, independent of the anticipated effort or the judged ease of walking. However, the unreliable effect of energetic cost on judged ease of walking was surprising, and a more sensitive affordance judgment task will be developed in the next chapter.

CHAPTER 5

The Long and Short of It: Does Route Selection Depend On the Energetic Cost of Walking?

Introduction

Is the path most travelled an efficient one? In our complex world we walk on different types of terrain and have to circumvent both static and dynamic obstacles. With every obstacle blocking the way, the number of possible routes increases, alternative paths present themselves, and a route needs to be selected. What variables determine the preferred route? For instance, the length of the path, the compliance of the substrate, the unevenness of the terrain, and the slope of the ground might all influence route selection. Route selection is thus based on the affordances of the available paths for walking, that is, on the properties of the ground surface that determine a more "walkable" path to a goal.

In previous chapters, I found that the perception of egocentric distance is independent of the energetic cost of walking on the terrain, and that egocentric distances are accurately matched, consistent with the information-based view. In addition, the results showed that the actual energetic cost of walking on sand is underestimated by about 80% (Chapter 3). In this chapter, I pose the same questions about the perception of the affordances of the terrain: Does route selection depend only on the egocentric distance to a goal? Or is the preferred route also influenced by the energetic cost of walking on the substrate, that is, by the perceived affordance of walkability? In this case, the information-based view predicts that route selection should depend on both the distance and the (underestimated) energetic cost of walking to a goal.

The process of route selection is usually framed in terms of minimizing a relevant cost function. *Global path planning* algorithms generally choose a route to a goal by minimizing the total path length or path curvature within the given constraints, and assume an accurate map of object locations (for review see Bonin-Font et al., 2008; DeSouza & Kak, 2002; Güzel, 2013). In contrast, *local path planning algorithms* are based on current information, and include rules such as minimizing the deviation of heading from the goal direction while avoiding obstacles (Dutra et al., 2017; Ulrich & Borenstein, 1998). Although such heuristics do not ensure an optimal path, they tend to reduce overall cost.

Similar local strategies have been reported in human walking. When faced with two competing goals (Cohen & Warren, 2007) or two possible routes around a barrier to a goal (Baxter & Warren, 2018, 2020), humans tend to select a path that minimizes (a) the distance to the goal, (b) the heading deviation from the goal direction, and (c) the heading deviation from the current walking direction. Importantly, these local variables are better predictors of human route selection than the global path length or path curvature (Baxter & Warren, 2018), but they also tend to reduce the overall length and energetic cost of the route (Baxter & Warren, 2018, 2020; Fajen & Warren, 2010). Local models of locomotor control that make iterative adjustments to the heading direction based on visual information about the egocentric directions and distances of objects in the scene exhibit similar behaviour (Fajen & Warren, 2003; Baxter et al., in prep).

Circumventing an obstacle requires turning away from the direction of the goal, and some available paths require larger deviations or sharper turns than others. These maneuvers impact the energetic cost of the route, which is a consequence of the total path length and the forces required to turn, brake, and accelerate. Minimizing the deviation from the goal direction commonly produces shorter, more direct paths through cluttered environments (Borenstein & Koren, 1991; Fajen & Warren, 2010; Fox et al., 1997; Simmons, 1996; Ulrich & Borenstein, 1998). Minimizing changes in one’s heading also reduces the energetic cost of a route by reducing the lateral forces required to make a turn, as well as the longitudinal forces required to make the speed changes that accompany turning. These findings suggest that local variables account for human route selection, and result in paths that tend to be energetically efficient without requiring global optimization procedures.

There is considerable evidence that human locomotion tends to minimize the energetic cost of transport. For instance, the preferred walking speed coincides with the minimum energy expenditure per unit distance, and the preferred combination of step length and step frequency at a given speed also minimizes energetic cost (Molen et al., 1972; Ralston, 1958). Gait transitions between walking and running act to reduce energetic cost by shifting to a more efficient gait at a higher or lower speed (Diedrich & Warren, 1998; Minetti et al., 1994). On a longer time scale, when required to travel a given distance (122 m) in a prescribed time (0.5 to 2 min), humans choose a mixture of walking and running that minimizes the total cost of transport (Long & Srinivasan, 2013). There is thus reason to believe that a preferred path may likewise depend on the energetic cost of the possible routes. Warren (1983, 1984) proposed that route selection is based on the “ecological efficiency” of various paths to an intended goal, and hypothesized that visual information must specify paths of least cost.

Previous work on route selection was predicated on a ground plane that is flat, solid, and continuous. If the terrain varies in its compliance, grade, evenness, or slipperiness – that is, in its affordances for walking – this can have significant energetic consequences. In particular, walking the same physical distance on two substrates with different compliance can yield a large difference in energetic cost. The mechanical work and metabolic cost of walking on dry sand is 2.1 to 2.7 times greater than walking at the same speed on a firm surface (Appendix A, Table 1) (Davies & Mackinnon, 2006; Lejeune et al., 1998; Zamparo et al., 1998). Thus, selecting a route that minimizes distance may not effectively minimize energetic cost. If route selection is based not on perceived distance per se but on the perceived affordance for walking, the preferred route should depend on both goal distance and the energetic cost of the substrate.

In this proposed study, we will investigate the influence of energetic cost on route selection. We plan to use a two-alternative forced-choice paradigm in which the participant views two targets resting on two flat ground surfaces, and chooses the target to which they would prefer to walk. Varying the distances of the two targets and the energetic cost of the two surfaces (concrete or sand) will allow us to determine the relative contribution of these variables to route selection (i.e. perception of the more walkable path). Specifically, participants will view the two targets over sand or over firm ground, yielding two congruent (Firm-Firm or Sand-Sand) and two incongruent (Firm-Sand or Sand-Firm) terrain conditions, where order indicates the standard and comparison terrain. One target will appear on the standard terrain at three specified distances, and the distance of the target on the comparison terrain will be adjusted on each trial using an adaptive staircase procedure to identify the point of subjective equality.

We expect that in the congruent terrain conditions, equal preference will be observed when the targets appear at equal egocentric distances. Obviously, the energetic cost of walking is equated when the terrain is the same, so route preference should be based solely on target distance. In the incongruent terrain conditions, however, more energy is required to walk an equivalent distance on sand than on firm ground. If route selection is based only on target distance, then the terrain should have no effect, and the result would be the same as the congruent conditions. On the other hand, if route selection is based on minimizing overall energy expenditure, then target distance and terrain cost should trade off: equal preference should be observed when the target on sand is about 50% of the distance to the target on firm ground. However, as shown in Chapter 3, participants match the energetic cost of walking on firm ground by to walking to on sand to a ratio of 1:0.8 distance. Thus I predict that equal route preference will occur when the target on sand is about 80% of the distance to the target on firm ground.

The incongruent terrain manipulation previously revealed that perceived egocentric distance does not depend on the anticipated effort of walking. In this experiment, by contrast, I expect that the perceived affordances of possible paths will depend on the anticipated effort of walking.

Methods

Participants

A statistical power analysis was performed for sample size estimation, based on data from Chapter 3, the matching energetic cost group, (N= 6). The effect size (ES) in this study was 0.77, considered to be medium using Cohen's (1988) criteria. With an alpha = .05 and power = 0.80, the projected sample size needed with this effect size (*pwr* package; R Core Team, 2019) is approximately N = 13. A sample size of 13 will gain the specific power of 0.89 (the probability to reject the null).

The volunteers will be recruited through word-of-mouth and the Brown University GSBB listserve, which includes graduate and undergraduate students, as well as members of the local community. Volunteers meeting the inclusion criteria, of having no visual or motor impairment, will be paid for their participation. The protocol is approved by Brown University’s Institutional Review Board, and was in accordance with the Declaration of Helsinki.

Apparatus

The research will be conducted in the Perception and Action Lab at Brown University. The participant stood on a wooden platform (6.5m wide x 2.5m long x 0.15m high) which contains a sandbox (1.5m wide x 2.5m long) in the middle, so that the sand was flush with the plywood surface on either side (Figure 12A). A square viewing plate (rubber first-base; 0.3m x 0.3m, 0.005m thick) will be positioned on the plywood to the left or right of the sand, from which the participant will view a virtual environment in a head-mounted display (HMD; Samsung Odyssey+ Windows mixed-reality, Irvine CA; 110° diagonal field of view; 1440 x 1600 pixels per eye). Stereoscopic images of a virtual environment were generated in Vizard (WorldViz, Santa Monica CA). Head position will be tracked using the Odyssey's built-in cameras and inertial motion unit and used to update the visual display at a frame rate of 90 Hz, with a total latency of approximately 11ms. Responses were made with a wireless controller (Samsung Odyssey+) held in the right hand.

Displays

The participants will view an orientation environment that displayed a box for the participant to step up on, and a test environment that displayed sand and concrete ground surfaces. In the orientation environment, the sky is blue and the ground plane is textured with a purple-grey marble pattern. A small burgundy box (0.58 m wide x 0.35 m deep x 0.15 m high) appears on the ground a couple of steps in front of the participant, with a tall white viewing box placed on top (0.3 m wide x 0.3 m deep x 1.3 m high). The virtual ground plane was matched to the physical floor of the lab, the burgundy box to the front edge and height of the plywood platform, and the viewing box to the position of the base plate.

The test environment has a blue sky and a ground plane composed of two adjacent surfaces: a greyscale random noise texture that appeared like concrete, and a photorealistic sand texture. The boundary between them corresponded to one of the boundaries between the plywood platform and the sandbox in the testing room. One red pole and two blue poles (0.35 m radius, 1.3 m tall), each with a granite texture, rested on the ground plane (refer to Figure 12).

During experimental trials, a star appeared low in the sky, 60° below the zenith, to indicate the direction the participant should face for that trial. The blue standard pole then appeared 5, 7, 9, or 11 m from the base plate, and an adaptive staircase procedure was used to determine the distance of the blue comparison pole. The comparison appeared 50° to the left or right of the standard, on the same or different terrain. The poles disappeared after 2 seconds of viewing.

Design

The standard target will appear at three possible distances (7, 9, 11m) on the sand or firm surface (Standard Terrain), and the comparison target will appear at a variable distance on the sand or the firm surface (Comparison Terrain). This yields four Terrain Conditions: Sand-Sand, Sand-Firm, Firm-Firm, and Firm-Sand (standard-comparison). Two conditions thus have congruent terrains, and two have incongruent terrains. There will be 4 staircases, half with the standard on the left and half on the right, for each terrain condition at each of the distances, totalling 48 staircases.

An adaptive psychometric method, QUEST+ (Watson, 2017) will be used to determine the point of subjective equality at which the preference between the two routes is equal for each staircase. The initial-guess threshold will be based on the mean comparison settings of the matching distance and matching energy groups in Chapter 3. For each unique staircase, the initial comparison target distance will be randomly selected from the range between the distance and energy comparison settings. For example, when the standard appears 7 m away on the sand and the comparison appeared on the firm ground then the initial comparison distance will be selected from a range of 6.88 m to 8.51 m. Initially there will be 48 staircases that are randomly selected on each trial, as each threshold is found that staircase will not be replaced (i.e. a completed staircase will not be drawn). And so, the number of staircases running in tandem will diminish through out the experiment until the thresholds are found for each of the 48 staircases. This design will yield four estimates of the point of subjective equality at each standard distance in each Terrain condition for each participant.

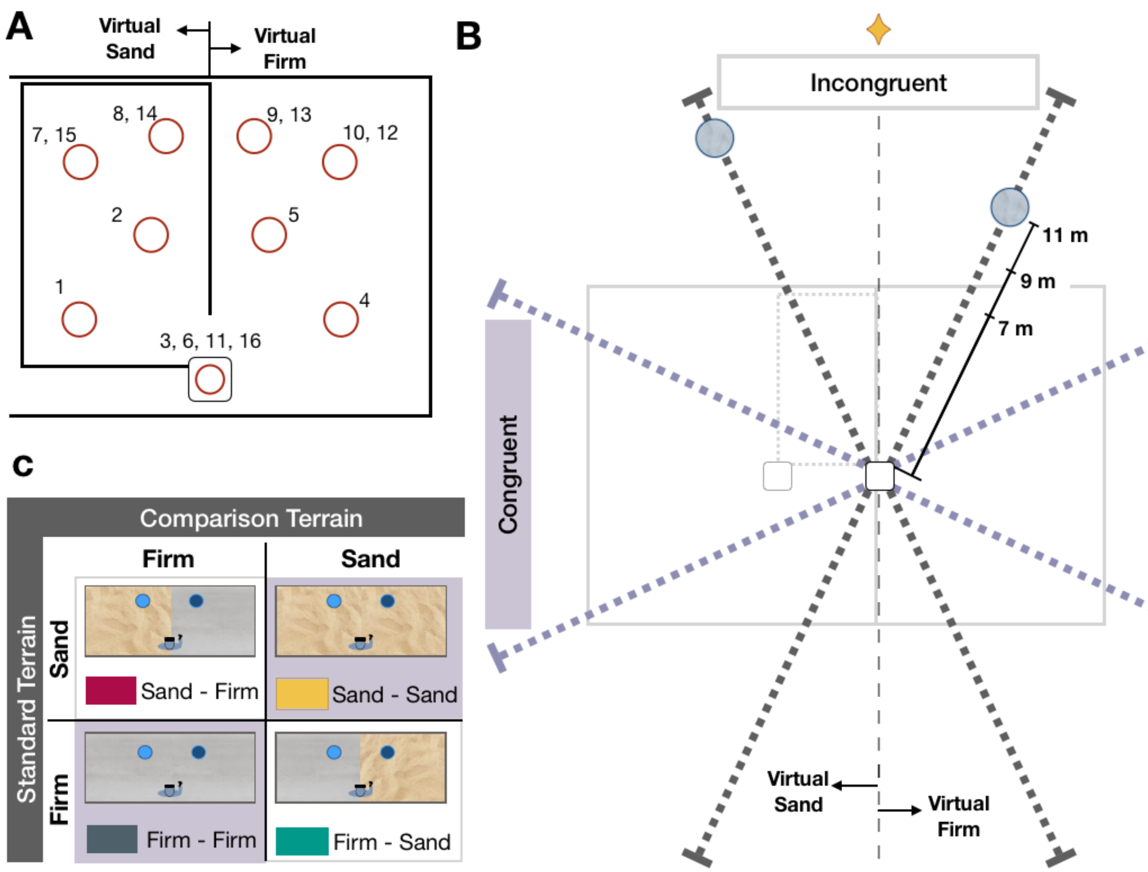

Figure 12. Experimental Set-up. Illustration of exploration pole positions (red circles). Pole positions are numbered for starting the exploration on sand. Numbers are mirrored when starting on the firm platform. (B) The yellow star is what participants orient towards, triggering the appearance of the standard and comparison (blue circles). The standard and comparison appear along the two axes, both on the same terrain (purple, congruent terrain) or the standard on a different terrain than the comparison (as shown) (grey, incongruent). The standard appeared at one of three distances, as illustrated at 11 m in the (virtual) firm ground area. The comparison appeared on the (virtual) sand at a distance determined by the Quest+ function. The controller is used to select the goal the participant would prefer to walk to. (C) Standard-Comparison terrain pair combinations.

The terrain that the standard appeared on is the Standard Terrain and the terrain that the comparison appeared on is the Comparison Terrain. Top-down view highlights the standard with light blue but the goals were the same in colour when viewed by the participant.

Procedure

When the participant entered the testing room, the wooden platform and sandbox were hidden behind a black theatre curtain. The participant put on the HMD and adjusted the interocular distance of the lenses to make the scene as sharp as possible. The experimenter then pulled back the curtain and pre-recorded instructions played through the HMD's headphones. The participant was instructed to step up onto the burgundy box (corresponding to the platform), stand within the white box (corresponding to the base plate), and look up at the horizon, triggering the appearance of the sand and firm ground surfaces. The participant was asked to note the appearance of the soft sandy surface and the solid, firm surface on either side. They then completed an exploration phase, before moving onto the test phase.

Exploration phase. To help immerse the participants in the virtual terrain, they then explored the firm and sand surfaces by walking to a series of 16 red target poles. They were instructed to walk across the wooden platform or the sandbox to reach a pole, which triggered the appearance of the next pole. The participant walked on both surfaces, circling back to the base plate four times (Figure 12A). The first loop involved walking to two poles on one surface (sand or platform) and returning to the base plate. The next loop was on the other surface. On the last two loops, the participant crossed from one surface to the other in one direction and then in reverse (e.g. Figure 12A, pole 8 to 9 and then pole 13 to 14). The pole positions were different from the standard and comparison target positions in the test phase. Arriving at the final pole position on the base plate triggered an audio recording that made the connection between the real and virtual environments explicit ("as you have experienced, the sand you see is really sand and the firm ground is truly solid").

Test phase. Before the test trials began, the relevant instructions were played again. On each trial the participant turned to face the star in the distance, triggering the appearance of the standard and comparison poles (Figure 12B). Both targets were positioned within the field of view and were simultaneously visible for 2 s. The participant was given 2.5 s to respond, from the appearance of the goals to 0.5 s after its disappearance. The participant pointed with the controller at the target to which they would prefer to walk, and pulled the trigger to record their decision and initiate the next trial. An experimental session lasted about an hour.

Data Analysis

The point of subjective equality (PSE), or the distance of the comparison target resulting in an equal preference for the standard and the comparison, is generated by the Quest+ function for each staircase. We will perform a linear mixed-effects regression analysis, assuming significant by-subject random-effects based on Chapters 1, 2, and 3, regressing PSE onto the distance of the standard target (7, 9, and 11 m; centered continuous variable), the Standard Terrain (sand or firm), the Comparison Terrain (sand or firm), and the possible interactions. The data will be analyzed in *Matlab* using the *fitlme* function (Maximum likelihood approximation; R2020a). P-values will be obtained by likelihood ratio tests of the full model against the reduced model without the effect in question.

Predicted Results

The possible mean comparison settings are plotted as a function of the standard distance for the point of subjective equality (PSE) based on minimizing distance in

Figure 13A, and the PSE based on minimizing the energetic cost of walking in Figure 13B.

Route preference based on minimizing distance. Equal preference (PSE) will be observed when the comparison appears at the same egocentric distance as the standard, for all terrain conditions. Overall, the mean comparison distance will match the mean standard distance (9 m) and all four conditions lie close to the diagonal (slope of 1), with no effect of terrain (Figure 13A). These results indicate that preference is based on distance and is unaffected by the viewed terrain.

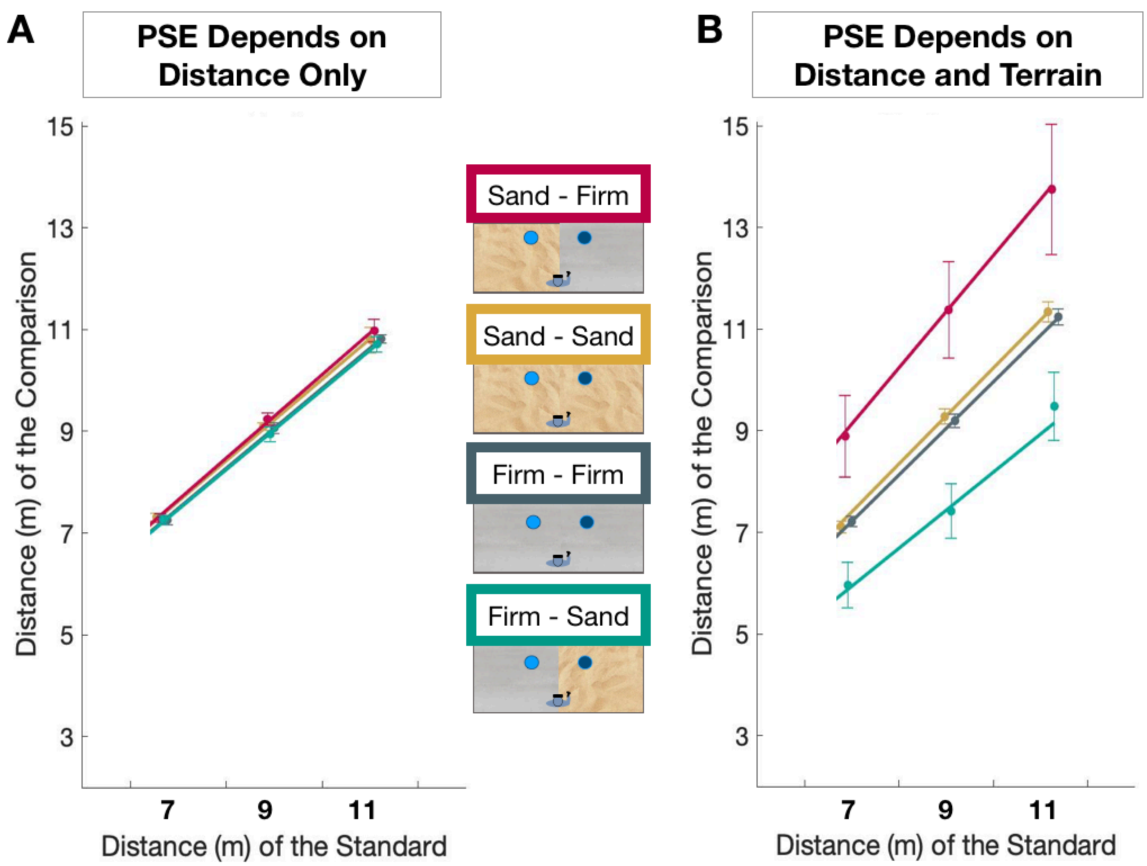

Figure 13. The distance of the comparison (m) at the point of subjective equality(PSE) as a function of the standard distance (m). Means (± SE) are based on the Target distances, of 7, 9, and 11 m, and the Standard-Comparison terrain pair combinations; the terrain that the standard appeared on is the Standard Terrain and the terrain that the participant moved the comparison across, making their distance judgement, is the

Comparison Terrain. Solid lines are the marginal regression model predictions. Means and predictions are slightly jittered horizontally for visibility. (A) PSE based on egocentric distance. (B) PSE based on perceived energetic cost.

Route preference based on minimizing perceived effort. Equal preference (PSE) will be observed when the comparison appears at the same egocentric distance as the standard, for congruent terrain conditions. When the standard and comparison targets appeared on incongruent surfaces (Sand-Firm and Firm-Sand conditions), however, the comparison distances at PSE were equal to the standard distance, averaging 9 m and regression slopes close to 1.0 (along the diagonal) (Figure 13B, yellow and grey solid lines). When participants selected the preferred target from incongruent surfaces (Firm-Sand and Sand-Firm conditions), the PSE occurred when the target on sand was closer than the target on firms ground.

First consider conditions in which the standard was presented on sand. When the comparison appeared on firm ground, the mean distance at PSE will be greater (Sand-Firm, 1/0.8*9 = 11.25 m) than when it appeared on sand (Sand-Sand, 9 m) (warm tones in Figure 13B). Moreover the slope in the Sand-Firm condition will be approximately 1.2 times greater than that in the Sand-Sand condition. Conversely, consider conditions in which the standard was presented on firm ground. When the comparison appeared on sand, the mean setting was significantly less (Firm-Sand, 7.2 m, cool tones in Figure 13B) than when it appeared on firm ground (Firm-Firm, 9 m). In addition, the Firm-Sand slope will be 25% shallower than the Firm-Firm slope (1.0). These results would indicate that participants base their preferred route on the perceived effort or ‘walk-ability’ of the terrain.

Discussion

Route preference based on minimizing distance. In this proposed study, we will investigate the influence perceived 'walkability' on route selection by manipulating the terrains on which a standard and a comparison target were viewed (firm ground or soft sand). We found that the point of subjective equality occurred was observed when the targets appeared at equal egocentric distances regardless of the terrain they were on. These results indicate that the choice between competing goals did not depend on the energy is takes to walk to the target, rather, the preferred goal was selected by minimizing egocentric distance.

Previous research suggests that local variables account for human route selection, and result in paths that tend to be energetically efficient (Baxter & Warren, 2018, 2020; Baxter et al., in prep; Cohen & Warren, 2007; Fajen & Warren, 2003). In Chapter 3, we found that the perceived effort of walking to a target on sand was reliably differentiated from a target on firm ground, and that perceived egocentric distance was independent of effort. And yet, our results suggest that the properties of the ground surface that determine a more "walkable" path to a goal do not influence the choice between two competing goals. This suggests that the preference to minimize distance when selecting between competing goals (Cohen & Warren, 2007) and route selection during obstacle avoidance (Baxter & Warren, 2018, 2020; Baxter et al., in prep.) is a general rule that extends to navigation over various substrates. In our engineered world there is a high occurrence of firm surfaces en route to any given goal and so, egocentric distance is reliable visual information that may serve as a proxy for the translational cost of walking.

Route preference based on minimizing perceived effort. In this proposed study, we will investigate the influence perceived 'walkability' on route selection by manipulating the terrains on which a standard and a comparison target were viewed (firm ground or soft sand). Obviously, the ‘walkability’ is equated when the terrain is the same for both targets. We observe an equal preference when the egocentric distance is the same, which is coincidental with the ‘walk-ability’ being equal. When the terrain is different between the two targets, we found that the point of subjective equality was observed when the target on sand is about 80% of the distance to the target on firm ground. These results indicate that the choice between competing goals minimized the perceived energy it takes to walk to the target, which depends on the surface properties as a function of egocentric distance.

Warren’s (1983, 1984) proposed “ecological efficiency” of various paths to an intended goal, predicts that visual information must specify paths of least cost. Our results support this prediction, for equal preference was given for routes having the same perceived effort of walking. We observed that targets on sand had to be approximately 80% closer than targets on firm ground to be equally chosen, similar to previous perceptual matching of the perceived energetic cost of walking on sand relative to sand (Chapter 3). This implies that route selection is based on the affordances of the available paths for walking.

We report for the first time that the perceived effort of walking on surfaces of different compliance reliably predicts selection between competing goal. This suggests that distance is not sufficient when considering the broader scope of differing terrains that are encountered during daily navigation; surface properties are highly relevant to the selection of competing routes during navigation. Heuristics of human path selection minimizes (a) the distance to the goal, (b) the heading deviation from the goal direction, and (c) the heading deviation from the current walking direction (Baxter & Warren, 2018, 2020; Baxter et al., in prep; Cohen & Warren, 2007; Fajen & Warren, 2003) can be applied environments were pedestrians traverse firm, non-slippery surfaces (common surfaces in urban-scapes) but reframing distance into translational cost (or perceived effort) would provide a more robust description of pedestrian behaviour.

CHAPTER 6

General Discussion

The purpose of the present experiments was to investigate the influence of energetic cost on both visually perceived egocentric distance and the visually perceived affordance of the terrain for walking. The *embodied* view treats distance perception as affordance perception, and thus predicts that a target viewed over sand should appear significantly farther away than the same target viewed over firm ground, because the anticipated effort or energetic cost of walking on sand is greater. In contrast, the *geometric* view predicts that visually perceived distance will be the same on both substrates, regardless of the cost of walking. The *information-based* view distinguishes layout perception from affordance perception. Thus, it also predicts that perceived distance is based on visual information, independent of the energetic cost of walking, so should be the same on both terrains. In addition, it predicts that the affordances of the terrain for walking can be visually perceived, so in this case, perceived 'walkability' should depend on the energetic cost of walking. The results support the geometric and information-based hypotheses, but contradict the embodied hypothesis. First, perceived egocentric distance is independent of the judged energetic cost of walking, and is based on visual information alone. Second, judgements of the energetic cost of walking imply that the walkability of the terrain is perceived, although judgments of the ease of walking had a smaller effect size. A path preference task was proposed as a more appropriate measure of affordance perception.

In Chapter 2, I used a blind-walking task to estimate perceived distance, and manipulated the terrain over which a target was viewed and on which the blind-walking response was made (firm brick or soft sand). There was no overall effect of Walked Terrain on the response distance, indicating that walking was calibrated to both sand and firm ground. There was an effect of Viewed Terrain, however, but in the unexpected direction: blind-walking responses were accurate for targets viewed over sand, but *overshot* targets viewed over brick, in proportion to the target distance. When the topography of the test site was taken into account, this puzzling overshooting could be explained by the shallow uphill slope of the brick walkway, which reduced the sensed declination angle and increased the perceived distance. This natural experiment thus showed that perceived distance is determined by the optical information present at the test site, consistent with the geometric and information-based hypotheses. Contrary to the embodied hypothesis, I conclude that perceived egocentric distance does not depend on the energetic cost of walking on the viewed substrate.

In Chapter 3, I used a perceptual matching task to estimate the perceived energetic cost or perceived distance, and manipulated the terrain on which a standard target was viewed and a comparison target was adjusted (firm ground or soft sand). The energetic cost of walking on sand was judged to be significantly greater than firm ground, proportional to target distance, although the actual relative magnitude was underestimated by about 80%, on average. In contrast, the terrain had no effect on distance judgments. Distance matches were nearly accurate (slopes of 0.93) and virtually identical in all terrain conditions. Moreover, the distance matches are similar to the responses in Chapter 2; distance matching in virtual reality compared to a paradigm where there is an intention to walk does not change the response, in both experiments the responses are accurate and there is no effect of the terrain that targets were viewed over. Once again, contrary to the *embodied* hypothesis, we find that the perceived energetic cost of walking on the substrate had no influence on perceived distance. The results support both the geometric and information-based views, which predict accurate distance matches regardless of the energetic cost of the terrains. We report for the first time that the energetic cost of surfaces with different compliance is reliably differentiated based on their visual appearance.

In Chapter 4, I asked participants to either match the ‘ease’ of walking to two targets or match their perceived distances. Ease of walking on sand was judged to be slightly more difficult than firm ground (equivalent to 0.33 m on average), but the difference did not scale proportionally with distance, as would be expected if it were based on energetic cost or effort. Thus, ease of walking matches were primarily based on matching target distances. When instructed to match distance, the terrain had no effect on the responses, indicating that perceived distance was independent of perceived ease of walking. However, when the two tasks were directly compared, there was no statistical difference between them. The information-based account predicts that affordance judgments should depend on such surface properties (Warren, 2019). The finding that ease of walking judgements did not reliably depend on the terrain was surprising, given that judgements of energetic cost did so strongly (Chapter 3).

Thus, in Chapter 5, I proposed another way to measure the perceived affordance of walkability, using a forced choice of the preferred path to goals at different distances on different substrates.

Taken together, the research reported in this dissertation provides experimental evidence for the independence of perceived egocentric distance and perceived walkability, by manipulating the compliance of the ground surface. This work extends previous research on the perception of spatial layout by distinguishing between perceived layout and perceived affordances of the layout, based on empirically derived predictions of energetic cost.

Theoretical Implications

These results support the proposition that perception of spatial layout is independent of the energetic consequence of action, consistent with the geometric and information-based views. My work joins a number of other studies that fail to find effects of anticipated effort on perceived distance, slant, width, and other properties of spatial layout (Durgin et al., 2009; Durgin et al., 2011; Durgin et al., 2012; Firestone & Scholl, 2014; Hutchison & Loomis, 2006a; Woods et al., 2009). On the embodied view, perceived egocentric distance should be extended in depth when anticipated effort is greater. Thus, a target viewed over sand should appear significantly farther away than the same target viewed over firm ground. Yet both the blind-walking and the perceptual matching responses indicate that the relative effort of walking on sand and firm ground has no influence on perceived distance. The means and slopes of the responses are virtually identical in the congruent and incongruent terrain conditions. Other failures to find an effect of anticipated effort include unsuccessful replications of Proffitt et al's (2009) experiments on perceived distance and perceived slope (Durgin et al., 2009; Hutchison & Loomis, 2006a; Woods et al., 2009). Critics attribute reported effects of anticipated effort to the demand characteristics of the experiment, post-perceptual processing, or a tendency to judge affordances rather than spatial properties. Indeed, when experimental demands are reduced or manipulated through the use of deception, effects of anticipated effort disappear (Durgin et al., 2009; Firestone & Scholl, 2014). Collectively, the present and previous work demonstrates that when a task is designed to minimize demand characteristics, judgements of spatial layout are driven by visual information.

The present results underscore that judgements of spatial layout should not be conflated with judgments of what the layout affords for action. Perceived egocentric distance is based on visual distance information such as declination angle, whereas the perceived cost of walking is based upon visual information about the structure and composition of the ground surface, such as its slope, compliance, slipperiness, etcetera. Perception of the affordance of walkability – the difficulty of walking on the ground surface to a goal – is presumably based on a higher-order relation of distance and surface information (J. Gibson, 1979/2015).

I report for the first time that the relative energetic cost of walking on surfaces of different compliance is reliably judged based on their visual appearance. However, the actual magnitude of the difference was underestimated by about 80%, on average. Such underestimation may be due to the unfamiliarity of making explicit prospective judgements of energy expenditure, or to the visual quality of the rendering of soft sand and solid concrete. Nevertheless, the import of this finding is that sand is reliably judged to be more costly than firm ground, even when making a novel visual judgment. Similar retrospective judgements of the perceived effort of a completed action strongly correlate with variables related to the energetic cost of the action, such as heart rate, muscular discomfort, and walking speed (Chung & Wang, 2010; Noble et al., 1973). There is recent evidence that prospective judgements of the stability of walking on grassy, cobbled, and paved surfaces are predicted by visual information about the composition, slope, and local curvature of the surface, and the corresponding symmetry of gait when walking on the surface (Thomas et al., 2020). The present research adds to these findings and supports the information-based account that the affordances of the terrain for walking are perceived based on action-scaled information about the surface layout.

Warren (1983, 1984) proposed that the affordances of surface layout might be compared in terms of their ‘ecological efficiency’, the energy expenditure required to achieve a goal. Thus, the affordance of sand or firm ground for walking to a goal – its walkability – depends on both the goal distance and the energetic cost of walking on the substrate. When adjusting the distance of a one target to match the energetic cost of walking to another (Chapter 3), we expect that the settings indicate the relative ecological efficiency of walking to each goal on each substrate. When choosing between possible paths to two goals (Chapter 5), the preferred path should also have a greater ecological efficiency of walking, as predicted by the matching settings. Similarly, Warren (1984) found the the ecological efficiency of two different stairways, the energetic cost of climbing to the same height as determined by oxygen consumption, predicts the visually preferred stairway. Even infants are sensitive to the relation between their mode of locomotion and surface compliance; when selecting between walking across a rigid surface and a waterbed surface to reach their mother, they choose to walk across the rigid surface (E. Gibson et al., 1987). Judgement of the distance that can be 'successfully' walked reliably discriminates between two surfaces with different dynamic properties (Walter et al., 2017). In sum, route selection may be based on the "ecological efficiency" of alternative paths to an intended goal (Warren, 1983, 1984), where distance and the substrate both influence the total energetic cost of the path.

In sum, I have demonstrated that visually perceived distances on sand, a substrate judged to be more energetically expensive for walking, are no different than perceived distances on firm ground. The results are contrary to the embodied view, but support the geometric and information-based views that perceived distance is based on visual information, independent of energetic cost. Additionally, the information-based account argues that judgements of spatial layout should not be conflated with affordance judgments, which should depend on the energetic cost of walking on the substrate. Using a perceptual matching task, I have shown that the energetic cost of walking on surfaces of different compliance is reliably differentiated based on their visual appearance (Chapter 3). This ability to discriminate the relative cost of the terrain implies that such information will also influence route selection (Chapter 5).

Thus, when modelling human locomotion, distance may not be a robust predictor of route selection. Minimizing distance has served as a good proxy because the tested ground surfaces have been limited to firm, level terrain. However, I suggest that route selection will be based on the ecological efficiency of the alternative paths, the least total energetic cost required to walk to the goal. Such a prediction of ‘ecological efficiency’ is consistent with previous behavioural evidence that local visual information is used to minimize energy expenditure (Baxter & Warren, 2018, 2019, 2020; Cohen & Warren, 2007; Fajen & Warren, 2010). Understanding how energetic efficiency influences route selection has implications for the modelling pedestrian behaviour in a wide range of conditions.

REFERENCES

Alexander, R. M. (1989). Optimization and gaits in the locomotion of vertebrates. *Physiological reviews*, *69*(4), 1199-1227.

Baxter, B. A., & Warren, W. H. (2018). Optical Variables Influencing Barrier Avoidance. Poster session presented at the Annual Meeting of the Vision Sciences Society, St Pete's Beach, FL.

Baxter, B. A. & Warren, W. H. (2019) Spatial updating of remembered goal position during barrier avoidance. Oral presentation at the International Society of Posture & Gait World Congress, Edinburgh, UK.

Baxter, B. A., & Warren, W. H. (2020). Route Selection in Barrier Avoidance. *Gait & Posture*, *80,* 192-198. https://doi.org/10.1016/j.gaitpost.2020.04.009

Baxter, B. A., Free, B. A., & Warren, W. H. (in prep). Barrier avoidance using an ecological steering potential function.

Bhalla, M., & Proffitt, D. R. (1999). Visual-motor recalibration in geographical slant perception. Apr 1997. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(4), 1076–1096.

Bodenheimer, B., Meng, J., Wu, H., Narasimham, G., Rump, B., McNamara, T. P., Carr, T. H., & Rieser, J. J. (2007). Distance estimation in virtual and real environments using bisection. In Proceedings of the 4th symposium on applied perception in graphics and visualization (pp. 35-40): ACM.

Bonin-Font, F., Ortiz, A., & Oliver, G. (2008). Visual navigation for mobile robots: A survey. *Journal of intelligent and robotic systems*, *53*(3), 263.

Borenstein, J., & Koren, Y. (1991). The vector field histogram-fast obstacle avoidance for mobile robots. *IEEE transactions on robotics and automation*, *7*(3), 278-288.

Bruggeman, H., Zosh, W., & Warren, W. H. (2007). Optic flow drives human visuo-locomotor adaptation. *Current biology*, *17*(23), 2035-2040.

Cavagna, G. A., Thys, H., & Zamboni, A. A. (1976). The Sources of External Work in Level Walking and Running. *J. Physiol*, *262*, 639–657.

Chardenon, A., Montagne, G., Buekers, M. J., & Laurent, M. (2002). The visual control of ball interception during human locomotion. *Neuroscience letters*, *334*(1), 13-16.

Chrastil, E. R., & Warren, W. H. (2014). Does the human odometer use an extrinsic or intrinsic metric? Attention, Perception, & Psychophysics, 76(1), 230-246.

Chung, M., & Wang, M. J. (2010). The change of gait parameters during walking at different percentage of preferred walking speed for healthy adults aged 20 – 60 years. *Gait & Posture*, *31*, 131–135. https://doi.org/10.1016/j.gaitpost.2009.09.013

Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). Hillsdale,NJ: Lawrence Erlbaum.

Cohen, J. A., & Warren, W. H. (2007). Choosing between competing goals during walking in a virtual environment. Journal of Vision, 7(9), 1021-1021.

Cutting, J. E., Vishton, P. M., & Braren, P. A. (1995). How we avoid collisions with stationary and moving objects. *Psychological review*, *102*(4), 627.

Da Silva, J. A. (1985). Scales for perceived egocentric distance in a large open field: Comparison of three psychophysical methods. *The American Journal of Psychology*, 119-144.

Davies, S. E. H., & Mackinnon, S. N. (2006). The energetics of walking on sand and grass at various speeds. *Ergonomics*, *49*(7), 651-660. https://doi.org/10.1080/00140130600558023

DeSouza, G. N., & Kak, A. C. (2002). Vision for mobile robot navigation: A survey. *IEEE transactions on pattern analysis and machine intelligence*, *24*(2), 237-267.

Diedrich, F. J., & Warren, W. H. (1998). Dynamics of human gait transitions. In D. A. Rosenbaum & C. Collyer (Eds.), *Timing of behavior: Neural, computational, and psychological perspectives* (pp. 323-343). Cambridge, MA: MIT Press.

Durgin, F. H. (2017). Counterpoint: Distinguishing between perception and judgment of spatial layout. Perspectives on Psychological Science, 12, 344–346.

Durgin, F. H., Baird, J. A., Greenburg, M., Russell, R., Shaughnessy, K., & Waymouth, S. (2009). Who is being deceived? The experimental demands of wearing a backpack. *Psychonomic Bulletin & Review*, *16*(5), 964-969.

Durgin, F. H., DeWald, D., Lechich, S., Li, Z., & Ontiveros, Z. (2011). Action and motivation: Measuring perception or strategies? *Psychonomic bulletin & review*, *18*(6), 1077-1082.

Durgin, F. H., Klein, B., Spiegel, A., Strawser, C. J., & Williams, M. (2012). The social psychology of perception experiments: Hills, backpacks, glucose, and the problem of generalizability. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(6), 1582.

Dutra, T. B., Marques, R., Cavalcante-Neto, J. B., Vidal, C. A., & Pettré, J. (2017, May). Gradient-based steering for vision-based crowd simulation algorithms. In *Computer Graphics Forum* (Vol. 36, No. 2, pp. 337-348).

Elliott, D. (1987). The influence of walking speed and prior practice on locomotor distance estimation. *Journal of motor behavior*, *19*(4), 476-485.

Epstein, W. (1966). Perceived depth as a function of relative height under three background conditions. Journal of Experimental Psychology, 72(3), 335.

Fajen, B. R., & Warren, W. H. (2003). Behavioral dynamics of steering, obstacle avoidance, and route selection. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(2), 343.

Fajen, B. R., & Warren, W. H. (2004). Visual guidance of intercepting a moving target on foot. *Perception*, *33*(6), 689-715.

Fajen, B. R., & Warren, W. H. (2007). Behavioral dynamics of intercepting a moving target. *Experimental Brain Research*, *180*(2), 303-319.

Fajen, B. R., & Warren, W. H. (2010). Route selection in complex scenes emerges from the dynamics of steering and obstacle avoidance. In *Poster at the VSS 2010 conference, Naples, Florida*.

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

Firestone, C., & Scholl, B. J. (2014). “Top-down” effects where none should be found: The El Greco fallacy in perception research. *Psychological science*, *25*(1), 38-46.

Foley, J. M., Ribeiro-Filho, N. P., & Da Silva, J. A. (2004). Visual perception of extent and the geometry of visual space. *Vision Research*, *44*(2), 147-156.

Fox, D., Burgard, W., & Thrun, S. (1997). The dynamic window approach to collision avoidance. *IEEE Robotics & Automation Magazine*, *4*(1), 23-33.

Gérin-Lajoie, M., & Warren, W. (2008). The circumvention of barriers: Extending the steering dynamics model. *Journal of Vision*, *8*(6), 1158-1158.

Gibson, E. J., Riccio, G., Schmuckler, M. A., Stoffregen, T. A., Rosenberg, D., & Taormina, J. (1987). Detection of the traversability of surfaces by crawling and walking infants. *Journal of Experimental Psychology: Human Perception and Performance*, *13*(4), 533.

Gibson, J. J. (1950). Perception of the visual world. Boston: Houghton Mifflin.

Gibson, J. J. (1979/2015). The ecological approach to visual perception: classic edition. New York: Psychology Press. (originally published in 1979).

Güzel, M. S. (2013). Autonomous vehicle navigation using vision and mapless strategies: a survey. *Advances in Mechanical Engineering*, *5*, 234747.

Helbing, D., & Molnar, P. (1995). Social force model for pedestrian dynamics. *Physical review E*, *51*(5), 4282.

Hicheur, H., Pham, Q. C., Arechavaleta, G., Laumond, J. P., & Berthoz, A. (2007). The formation of trajectories during goal-oriented locomotion in humans. I. A stereotyped behaviour. *European Journal of Neuroscience*, *26*(8), 2376-2390.

Hutchison, J. J., & Loomis, J. M. (2006a). Does Energy Expenditure Affect the Perception of Egocentric Distance? A Failure to Replicate Experiment 1 of Proffitt, Stefanucci, Banton, and Epstein (2003). *The Spanish Journal of Psychology*, *9*(2), 332–339.

Hutchison, J. J., & Loomis, J. M. (2006b). Reply to Proffitt, Stefanucci, Banton, and Epstein. *The Spanish Journal of Psychology*, *9*(2), 343-345.

Jones, A. M., & Doust, J. H. (1996). A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *Journal of sports sciences*, *14*(4), 321-327.

Kerdok, A. E., Biewener, A. A., McMahon, T. A., Weyand, P. G., & Herr, H. M. (2002). Energetics and mechanics of human running on surfaces of different stiffnesses. *Journal of applied physiology*.

Knapp, J. M., & Loomis, J. M. (2004). Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments. *Presence: Teleoperators & Virtual Environments*, *13*(5), 572-577.

Kunz, B. R., Wouters, L., Smith, D., Thompson, W. B., & Creem-Regehr, S. H. (2009). Revisiting the effect of quality of graphics on distance judgments in virtual environments: A comparison of verbal reports and blind walking. *Attention, Perception, & Psychophysics*, *71*(6), 1284–1293. https://doi.org/10.3758/APP

Kuo, A. D. (2007). The six determinants of gait and the inverted pendulum analogy: A dynamic walking perspective. *Hum Mov Sci, 26*, 617-656.

Lee, D. N. (1980). The optic flow field: The foundation of vision. Philosophical Transactions of the Royal Society of London. B, Biological Sciences, 290(1038), 169-179.

Leicht, A. S., & Crowther, R. G. (2007). Pedometer accuracy during walking over different surfaces. *Medicine and Science in Sports and Exercise*, *39*(10), 1847–1850. https://doi.org/10.1249/mss.0b013e3181405b9f

Lejeune, T. M., Willems, P. A., & Heglund, N. C. (1998). Mechanics and energetics of human locomotion on sand. *The Journal of Experimental Biology*, *201*(13), 2071–2080. https://doi.org/10.3923/biotech.2002.28.33

Lenoir, M., Musch, E., Thiery, E., & Savelsbergh, G. J. (2002). Rate of change of angular bearing as the relevant property in a horizontal interception task during locomotion. *Journal of motor behavior*, *34*(4), 385-401.

Lessard, D. A., Linkenauger, S. A., & Proffitt, D. R. (2009). Look before you leap : Jumping ability affects distance perception. *Perception, 38,* 1863–1867. https://doi.org/10.1068/p6509

Long, L. L., & Srinivasan, M. (2013). Walking, running, and resting under time, distance, and average speed constraints: optimality of walk–run–rest mixtures. *Journal of The Royal Society Interface, 10*, 20120980.

Loomis, J. M., & Beall, A. C. (2004). Model-based control of perception/action. In *Optic flow and beyond* (pp. 421-441). Springer, Dordrecht.

Loomis, J. M., Da Silva, J. A., Fujita, N., & Fukusima, S. S. (1992). Visual space perception and visually directed action. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 906-921.

Loomis, J. M., Da Silva, J. A., Philbeck, J. W., & Fukusima, S. S. (1996). Visual perception of location and distance. *Current Directions in Psychological Science*, *5*(3), 72-77.

Loomis, J. M., & Knapp, J. M. (2003). Visual perception of egocentric distance in real and virtual environments. In L. J. Hettinger & M. W. Haas (Eds.), Virtual and adaptive environments (pp. 21-46). Mahwan, NJ: Erlbaum.

Loomis, J. M., & Philbeck, J. W. (2008). Measuring spatial perception with spatial updating and action. In *Carnegie Symposium on Cognition, 2006, Pittsburgh, PA, US*. Psychology Press.

Mark, L. S. (1987). Eyeheight-scaled information about affordances: A study of sitting and stair climbing. *Journal of experimental psychology: human perception and performance*, *13*(3), 361.

Matin, L., & Fox, C. R. (1989). Visually perceived eye level and perceived elevation of objects: Linearly additive influences from visual field pitch and from gravity. *Vision research*, *29*(3), 315-324.

Messing, R., & Durgin, F. H. (2005). Distance Perception and the Visual Horizon in Head-Mounted Displays. *ACM Transactions on Applied Perception*, *2*(3), 234–250. https://doi.org/10.1145/1077399.1077403

Minetti, A E., Ardigo, L. P., & Saibene, F. (1994). The transition between walking and running in humans: Metabolic and mechanical aspects at different gradients. *Acta Physiologia Scandinavica, 150,* 315-323.

Molen, N. H., Rozendal, R. H., & Boon, W. (1972). Fundamental characteristics of human gait in relation to sex and locomotion. Proceedings Koninklijke Nederlandse Academie van Wetenschappen, C-75, 215-223.

Moussaïd, M., Helbing, D., & Theraulaz, G. (2011). How simple rules determine pedestrian behavior and crowd disasters. *Proceedings of the National Academy of Sciences*, *108*(17), 6884-6888.

Noble, B. J., Metz, K. F., Pandolf, K. B., Bell, C.W., Cafarelli, E., & Sime, W. (1973). Perceived exertion during walking and running-II. *Medicine and Science in Sports and Exercise, 5*,116-120.

Ooi, T. L., Wu, B., & He, Z. J. (2001). Distance determined by the angular declination below the horizon. *Nature*, *414*(6860), 197–200.

O'Shea, R. P., & Ross, H. E. (2007). Judgments of visually perceived eye level (VPEL) in outdoor scenes: Effects of slope and height. *Perception*, *36*(8), 1168-1178.

Patla, A. (1998). How is human gait controlled by vision? *Ecological Psychology, 10*(3-4), 287-302.

Philbeck, J. W., & Loomis, J. M. (1997). Comparison of two indicators of perceived egocentric distance under full-cue and reduced-cue conditions. Journal of Experimental Psychology: Human Perception and Performance, 23(1), 72-85.

Proffitt, D. R. (2006). Embodied Perception and the Economy of Action. *Perspectives on Psychological Science*, *1*(2), 110–122. https://doi.org/10.1111/j.1745-6916.2006.00008.x

Proffitt, D. R. (2009). Affordances matter in geographical slant perception. *Psychonomic Bulletin & Review*, *16*(5), 970-972.

Proffitt, D. R. (2013). An embodied approach to perception: By what units are visual perceptions scaled?. *Perspectives on Psychological Science*, *8*(4), 474-483.

Proffitt, D. R., & Linkenauger, S. A. (2013). Perception viewed as a phenotypic expression. In W. Prinz, M. Beisert, & A. Herwig (Eds.), Action science: Foundations of an emerging discipline (pp. 171–197). Cambridge, MA: MIT Press.

Proffitt, D. R., Stefanucci, J., Banton, T., & Epstein, W. (2003). The role of effort in perceiving distance. *Psychological Science, 14*(2), 106–112.

Purdy, W. C. (1958). The hypothesis of psychophysical correspondence in space perception. Dissertation Abstracts International, 42, 1454. (University Microfilms No. 58-5594)

Ralston, H. J. (1958). Energy-speed relation and optimal speed during level walking. Internationale Zeitschrift for Angewandte Physiologie Einschliesslich Arbeitsphysiologie, 17, 277-283.

Rieser, J. J., Ashmead, D. H., Talor, C. R., & Youngquist, G. A. (1990). Visual perception and the guidance of locomotion without vision to previously seen targets. *Perception, 19*(5), 675-689.

Rieser, J. J., Pick, H. L., Ashmead, D. H., & Garing, A. E. (1995). Calibration of human locomotion and models of perceptual-motor organization. Journal of Experimental Psychology: Human Perception and Performance, 21, 480-497.

Russell, R., & Durgin, F. H. (2008). Demand characteristics, not effort: The role of backpacks in judging distance. *Journal of Vision*, *8*(6), 755-755.

Schnall, S. (2017). No magic bullet in sight: A reply to Firestone and Scholl (2017) and Durgin (2017). *Perspectives on Psychological Science*, *12*(2), 347-349.

Sedgwick, H. A. (1973). The visible horizon: A potential source of visual information for the perception of size and distance. (Ph.D.), Cornell, Ithaca, NY.

Sedgwick, H. A. (1986). Space perception. In B. KR, K. L, & T. JP (Eds.), Handbook of Perception and Human Performance, Vol 1: Sensory Processes and Perception (Vol. i, pp. 21.21-21.57). New York: Wiley.

Selinger, J. C., O'Connor, S. M., Wong, J. D., & Donelan, J. M. (2015). Humans can continuously optimize energetic cost during walking. *Current Biology*, *25*(18), 2452-2456.

Sezer, V., & Gokasan, M. (2012). A novel obstacle avoidance algorithm: "Follow the gap method". *Robotics and Autonomous Systems, 60,* 1123-1134.

Sherrill, K. R., Chrastil, E. R., Ross, R. S., Erdem, U. M., Hasselmo, M. E., & Stern, C. E. (2015). Functional connections between optic flow areas and navigationally responsive brain regions during goal-directed navigation. *Neuroimage*, *118*, 386-396.

Silder, A., Besier, T., & Delp, S. L. (2012). Predicting the metabolic cost of incline walking from muscle activity and walking mechanics. *Journal of biomechanics*, *45*(10), 1842-1849. https://doi.org/10.1016/j.jbiomech.2012.03.032

Simmons, R. (1996, April). The curvature-velocity method for local obstacle avoidance. In *Robotics and Automation, 1996. Proceedings., 1996 IEEE International Conference on* (Vol. 4, pp. 3375-3382). IEEE.

Sinai, M. J., Krebs, W. K., Darken, R. P., Rowland, J. H., & McCarley, J. S. (1999). Egocentric Distance Perception in a Virtual Environment Using a Perceptual Matching Task (Vol. 43, pp. 1256–1260).

Sinai, M. J., Ooi, T. L., & He, Z. J. (1998). Terrain influences the accurate judgement of distance. *Nature*, (95), 497-500.

Soule, R. G., & Goldman, R. F. (1972). Terrain coefficients for energy cost prediction. *Journal of Applied Physiology*, *32*(5), 706-708.

Steenhuis, R. E., & Goodale, M. A. (1988). The effects of time and distance on accuracy of target-directed locomotion: Does an accurate short-term memory for spatial location exist?. *Journal of Motor Behavior*, *20*(4), 399-415.

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

Stoper, A. E., & Bautista, A. (1992, May). Apparent height as a function of pitched environment and task. Paper presented at the meeting of the Association for Research in Vision and Ophthalmology, Sarasota. FL.

Stoper, A. E., & Cohen, M. M., (1989) Effect of structured visual environments on apparent eye level. *Perception & Psychophysics, 46,* 469 - 475.

Swan, J. E., Livingston, M. A., Smallman, H. S., Brown, D., Baillot, Y., Gabbard, J. L., & Hix, D. (2006). A Perceptual Matching Technique for Depth Judgments in Optical, See-Through Augmented Reality. In *Proceedings of the IEEE Virtual Reality Conference* (pp. 19–27).

Thomas, N. D., Gardiner, J. D., Crompton, R. H., & Lawson, R. (2020). Physical and perceptual measures of walking surface complexity strongly predict gait and gaze behaviour. *Human movement science*, *71*, 102615.

Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion?. *Journal of Experimental Psychology: Human Perception and Performance*, *9*(3), 427.

Tresilian, J. R. (1990). Perceptual information for the timing of interceptive action. *Perception*, *19*(2), 223-239.

Turvey, M. T., Romaniak-Gross, C., Isenhower, R. W., Arzamarski, R., Harrison, S., & Carello, C. (2009). Human odometer is gait-symmetry specific. *Proceedings of the Royal Society B: Biological Sciences*, *276*(1677), 4309-4314.

Ulrich, I., & Borenstein, J. (1998, May). VFH+: Reliable obstacle avoidance for fast mobile robots. In *Proceedings. 1998 IEEE international conference on robotics and automation (Cat. No. 98CH36146)* (Vol. 2, pp. 1572-1577). IEEE.

Voloshina, A. S., Kuo, A. D., Daley, M. A., & Ferris, D. P. (2013). Biomechanics and energetics of walking on uneven terrain. *Journal of Experimental Biology*, *216*(21), 3963-3970.

Wallach, H., & O'Leary, A. (1982). Slope of regard as a distance cue. *Perception & Psychophysics, 31*(2), 145-148.

Walter, H., Wagman, J. B., Stergiou, N., Erkmen, N., & Stoffregen, T. A. (2017). Dynamic perception of dynamic affordances: walking on a ship at sea. *Experimental brain research*, *235*(2), 517-524.

Warren, W. H. (1983). A biodynamic basis for perception and action in bipedal climbing. *Dissertation Abstracts International, 43*, 4183-B (University Microfilms No. 4183-09263).

Warren, W. H. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 683-703.

Warren, W. H. (1998). Visually controlled locomotion: 40 years later. *Ecological Psychology*, *10*(3-4), 177-219.

Warren, W.H. (2007a). Optic flow. In R.R. Hoy, G.M. Shepherd, A.I. Basbaum, A. Kaneko, and G. Westheimer (Eds.), *The senses: A comprehensive reference*. Elsevier, 219–230.

Warren, W. H. (2007b). Action-scaled information for the visual control of locomotion. *Closing the gap: The scientific writings of David N. Lee*, 243-258.

Warren, W.H. (2019). Perceiving surface layout: Ground theory, affordances, and the objects of perception. In J. Wagman & J. Blau (Eds.), *Perception as information detection: Reflections on Gibson's ecological approach to visual perception*. Taylor & Francis, 151-173.

Warren, W. H., & Fajen, B. R. (2008). Behavioral dynamics of visually guided locomotion. In *Coordination: neural, behavioral and social dynamics* (pp. 45-75). Springer, Berlin, Heidelberg.

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature neuroscience*, *4*(2), 213-216.

Warren, W. H., & Whang, S. (1987). Visual guidance of walking through apertures: body-scaled information for affordances. *Journal of experimental psychology: human perception and performance*, *13*(3), 371.

Watson, A. B. (2017). QUEST+: A general multidimensional Bayesian adaptive psychometric method. *Journal of Vision,17,* 10, 1–27.

White, E. (2012). *The role of multimodally specified effort in action-relevant distance perception*. [Doctoral dissertation, University of Cincinnati].

White, E., Shockley, K., & Riley, M. A. (2013). Multimodally specified energy expenditure and action-based distance judgments. Psychonomic Bulletin & Review, (20), 1371–1377. https://doi.org/10.3758/s13423-013-0462-8

Williams, M. J., & Durgin, F. H. (2015). Direct manipulation of perceived angular declination affects perceived size and distance: A replication and extension of Wallach and O'Leary (1982). *Attention, Perception, & Psychophysics*, *77*(4), 1371-1378.

Winsmann, F. R., Vanderbie, J. H., & Daniels, F. Jr. (1953). Energy cost of wearing armored vests and carrying pack loads on treadmill, level course, and mountain slopes. QUARTERMASTER RESEARCH AND ENGINEERING COMMAND NATICK, Natick, Massachusetts, United States.

Witmer, B. G., & Kline, P. B. (1998). Judging Perceived and Traversed Distance in Virtual Environments. *Presence*, *7*(2), 144–167. https://doi.org/10.1162/105474698565640

Witt, J. K., & Proffitt, D. R. (2008). Action-specific influences on distance perception: a role for motor simulation. *Journal of experimental psychology: Human perception and performance*, *34*(6), 1479.

Witt, J. K., Proffitt, D. R., & Epstein, W. (2004). Perceiving distance: A role of effort and intent. *Perception*, *33*(5), 577–590. https://doi.org/10.1068/p5090

Wittlinger, M., Wehner, R., & Wolf, H. (2007). The desert ant odometer: a stride integrator that accounts for stride length and walking speed. *Journal of Experimental Biology, 210*(2), 198-207.

Woods, A. J., Philbeck, J. W., & Danoff, J. V. (2009). The various perceptions of distance: An alternative view of how effort affects distance judgments. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(4), 1104.

Zamparo, P., Perini, R., Orizio, C., Sacher, M., & Ferretti, G. (1992). The energy cost of walking or running on sand. *European Journal of Applied Physiology and Occupational Physiology*, *65*(2), 183–187. https://doi.org/10.1007/BF00705078

APPENDIX A

Calculations of Energetic Cost

Table 1. Calculation of energetic cost from Zamparo et al. (1992) for walking on firm ground versus sand. Calculated assuming the surface specific preferred walking speed, of sand or firm ground, and assuming the same walking speed (Leicht & Crowther, 2007). At the same speed of 5.6 km/hr walking on sand is ~2 times more costly (agrees with Lejeune et al., 1998). Step frequency for preferred walking speed determined from Lejeune et al.'s (1998) figures.

Surface	Preferred Walking Speed (km/hr)	Preferred Walking Speed (m/sec)	Energetic Cost @ Preferred Speed (J/m·kg)	Energetic Cost @ 5.6 km/hr (J/m·kg)	Step frequency (steps/sec)	Steps per m
Firm Ground (concrete/grass)	5.6 ± 0.5	1.56 ± 0.14	$4.5 - .99v + .11v^2$ = 2.4056	= 2.4056	1.92	1.92/1.56 = 1.23
Sand	5.0 ± 0.5	1.39 ± 0.14	$1.46 + .59v$ = 4.44	= 4.794	1.8	1.8/1.39 = 1.29

The energetic cost of sloped ground

Jones and Doust (1996) find that the increased work to walk up sloped ground is not significantly different from level ground walking until the incline exceeds a 2% gradient (1.19º) and even so, the difference is small. The cost is still substantially less than walking across sand. At a 5% or 2.86º incline the metabolic cost increases by half from level walking (Silder et al., 2012), compared to double when walking across dry sand (Lejeune et al., 1998; Zamparo et al., 1992).

APPENDIX B

Blind-walking Regression Estimates

Table 2. Estimates of Fixed Effects of the Regression Model. The intercept represents the grand mean for a Target Distance of 8m.

	Estimate	SE	tStat	DF	pValue	Lower	Upper
Intercept	8.299	0.336	24.687	653	< 0.001	7.639	8.959
Viewed Terrain	0.342	0.083	4.107	653	< 0.001	0.179	0.506
Walked Terrain	0.119	0.159	0.746	653	0.456	- 0.194	0.432
Target Distance	1.091	0.050	21.976	653	< 0.001	0.993	1.188
Viewed:Walked	- 0.049	0.052	- 0.934	653	0.351	- 0.151	0.054
Distance:Viewed	0.139	0.050	2.810	653	0.005	0.042	0.237
Distance:Walked	- 0.007	0.032	- 0.218	653	0.827	- 0.070	0.056
Distance:Viewed:Walked	0.026	0.044	0.588	653	0.557	- 0.060	0.112

Table 3. Estimates of Fixed Effects of the Regression Model for a ground slope of 1° for Brick I. The intercept represents the grand mean for a Visually Perceived Eye Level (VPEL) Specified Target Distance of 8m.

	Estimate	SE	tStat	DF	pValue	Lower	Upper
Intercept	8.026	0.322	24.899	653	< 0.001	7.393	8.658
Viewed Terrain	0.068	0.070	0.973	653	0.331	0.207	- 0.070
Walked Terrain	0.115	0.149	0.770	653	0.442	- 0.178	0.407
VPEL Target Distance	1.028	0.047	22.101	653	< 0.001	0.936	1.119
Viewed:Walked	- 0.054	0.048	- 1.112	653	0.266	- 0.149	0.041
VPEL Distance:Viewed	0.077	0.047	1.642	653	0.101	- 0.015	0.169
VPEL Distance:Walked	- 0.006	0.030	- 0.196	653	0.845	0.053	- 0.065
VPEL Distance: Viewed:Walked	0.027	0.041	0.656	653	0.512	- 0.054	0.108

Table 4. Estimates of Fixed Effects of the Regression Model. Binomial (Yes/No) responses indicating consciously adjusting for the relative difference in the number of steps and effort of walking between sand and firm ground.

	Estimate	SE	tStat	DF	pValue	Lower	Upper
Intercept	8.458	0.391	21.615	546	< 0.001	7.689	9.227
Viewed Terrain	0.380	0.096	3.957	546	< 0.001	0.191	0.568
Walked Terrain	0.170	0.193	0.876	546	0.381	- 0.210	0.550
Target Distance	1.103	0.058	19.091	546	< 0.001	0.990	1.217
Adjust Steps	- 0.160	0.205	- 0.781	546	0.435	- 0.563	0.243
Adjust Effort	0.037	0.205	0.180	546	0.858	- 0.366	0.440
Viewed:Walked	- 0.044	0.060	- 0.726	546	0.468	- 0.163	0.075
Distance:Viewed	0.151	0.060	2.514	546	0.012	0.033	0.269
Distance:Walked	0.011	0.035	0.331	546	0.741	- 0.057	0.080
Adjust Steps:Effort	- 0.281	0.210	- 1.341	546	0.180	- 0.694	0.131
Distance:Viewed:Walked	0.036	0.050	0.723	546	0.470	- 0.062	0.134
Walked:Steps:Effort	0.063	0.075	0.834	546	0.405	- 0.085	0.211

Table 5. Estimates of Fixed Effects of the Regression Model. Binomial (Yes/No) responses indicating visualization of target location and surroundings while blind-walking.

	Estimate	SE	tStat	DF	pValue	Lower	Upper
Intercept	8.012	0.373	21.503	546	< 0.001	7.280	8.743
Viewed Terrain	0.386	0.094	4.085	546	< 0.001	0.200	0.571
Walked Terrain	0.175	0.188	0.931	546	0.352	- 0.194	0.544
Target Distance	1.104	0.058	19.171	546	< 0.001	0.991	1.218
Visualize Target	-0.027	0.180	- 0.150	546	0.881	- 0.381	0.327
Visualize Surroundings	0.684	0.180	3.786	546	< 0.001	0.329	1.038
Viewed:Walked	- 0.044	0.061	- 0.717	546	0.474	- 0.165	0.077
Distance:Viewed	0.154	0.061	2.522	546	0.012	0.034	0.273
Distance:Walked	0.014	0.033	0.407	546	0.684	- 0.052	0.079
Visualize Target:Surroundings	0.055	0.183	0.301	546	0.763	- 0.305	0.416
Distance:Viewed:Walked	0.039	0.051	0.751	546	0.453	- 0.062	0.140
Walked:Steps:Effort	- 0.047	0.073	- 0.639	546	0.523	- 0.190	0.096

Table 6. Estimates of Fixed Effects of the Regression Models with days spent at the beach as continuous predictors. Regression estimates with original data and the change in the estimate when the outlier is removed indicate that the outlier is not an influential data point. Removal of the outlier, however, yielded null significance of the regression estimates for days at the beach (bolded p-value).

	Original	Change in Estimate	Original	pValue w/o
Intercept	7.536	- 0.016	< 0.001	< 0.001
Viewed Terrain	0.378	0.027	< 0.001	< 0.001
Walked Terrain	0.129	0.001	0.504	0.563
Target Distance	1.099	0.022	< 0.001	< 0.001
Beach Life	0.012	0.004	0.013	**0.235**
Beach Year	0.071	0.038	0.011	**0.703**
Viewed:Walked	- 0.049	0.030	0.390	0.177
Distance:Viewed	0.153	- 0.001	0.014	0.029
Distance:Walked	0.007	0.006	0.824	0.965
Beach Life:Year	- 0.001	- 0.0001	0.006	**0.997**
Distance:Viewed:Walked	0.043	- 0.004	0.424	0.435
Walked: Beach Life:Year	< 0.0001	< 0.0001	0.137	0.678

APPENDIX C

Blind-walking Post-experiment Questionnaire

1. How many days have you spent at the beach in your life (best guess)?

____

2. How many days have you spent at the beach in the past year (best guess)?

____

3. What do you think this experiment was testing?

____
____
____
____

4. Did you use any particular strategy to walk the same distance as the target?

____
____
____

(a) Did you count your steps? Y N

(b) Did you consciously adjust the number of steps for walking on sand vs. pavement? Y N
If so, how?

____
____

(c) Did you consciously compensate for the effort of walking on sand vs. pavement?
Y N

If so, how?

____
____

(d) Did you visualize the target location as you walked? Y N

(e) Did you visualize your surroundings as you walked? Y N

APPENDIX D

Perceptual Matching Methodology Materials

Table 7. Possible boxes sizes for practice and experimental trials.

Box	Width (m)	Depth (m)	Height (m)
Practice	0.9	0.15	0.8
B1	0.86	0.15	1.0
B2	0.74	0.15	1.25
B3	0.62	0.15	1.5
B4	0.5	0.15	1.75

Google drive folder access: Audio Instructions

APPENDIX E

Perceptual Regression Estimates

Table 8. Significant Fixed-Effects of the Mixed-Effects Linear Regression. The intercept represents the grand mean for a Target Distance of 8m.

	Estimate	SE	tStat	DF	pValue	Lower	Upper
Intercept	7.767	0.066	117.79	1506	< 0.001	7.638	7.896
Instructions	0.153	0.066	2.32	1506	0.02	0.024	0.282
Standard Terrain	- 0.418	0.025	- 16.755	1506	< 0.001	- 0.467	- 0.369
Comparison Terrain	0.424	0.025	16.962	1506	< 0.001	0.375	0.473
Distance of Standard	0.907	0.011	80.944	1506	< 0.001	0.885	0.929
Instructions:Standard Terrain	- 0.383	0.025	- 15.321	1506	< 0.001	- 0.432	- 0.334
Instructions: Comparison Terrain	0.372	0.025	14.889	1506	< 0.001	0.323	0.421
Standard:Comparison Terrain	- 0.053	0.025	- 2.114	1506	0.035	- 0.102	- 0.004
Distance:Instructions	0.024	0.011	2.148	1506	0.032	0.002	0.046
Distance:Standard Terrain	- 0.055	0.011	- 4.887	1506	< 0.001	- 0.077	- 0.033
Distance:Comparison Terrain	0.044	0.011	3.957	1506	< 0.001	0.022	0.066
Instructions:Standard: Comparison Terrain	- 0.049	0.025	- 1.968	1506	0.049	- 0.098	- 0.0001
Instructions:Distance: Standard Terrain	- 0.041	0.011	- 3.673	1506	< 0.001	- 0.063	- 0.019
Instructions:Distance: Comparison Terrain	0.037	0.011	3.33	1506	0.001	0.015	0.059

Table 9. Significant Fixed-Effects of the Mixed-Effects Linear Regression. Intercept represents the grand mean.The intercept represents the grand mean for a Target Distance of 8m.

	Estimate	SE	tStat	DF	pValue	Lower	Upper
Intercept	7.737	0.048	162.63	1845	< 0.001	7.643	7.83
Instructions	-0.123	0.048	-2.584	1845	0.01	-0.216	-0.03
Standard Terrain	- 0.104	0.015	- 6.856	1845	< 0.001	- 0.133	- 0.074
Comparison Terrain	0.107	0.015	7.11	1845	< 0.001	0.078	0.137
Distance of Standard	0.913	0.007	134.78	1845	< 0.001	0.900	0.926
Instructions:Standard Terrain	0.068	0.015	4.477	1845	< 0.001	0.038	0.097
Instructions: Comparison Terrain	- 0.055	0.015	- 3.678	1845	< 0.001	- 0.085	- 0.026
Distance:Instructions	- 0.03	0.007	- 4.467	1845	< 0.001	- 0.044	- 0.017
Distance:Standard Terrain	- 0.017	0.007	- 2.451	1845	0.014	- 0.03	- 0.003