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Evolved navigation theory and the environmental vertical illusion

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Abstract

This study outlines a previously unknown, large illusory component to one of the most common psychological experiences. Evolved navigation theory (ENT) suggests that perceptual and navigational mechanisms reflect navigational costs over evolution. Vertical surfaces pose a distinct cost of falling not present in horizontal navigation. However, horizontal surfaces sometimes form retinally vertical images and researchers often assume that retinal image determines distance perception. We tested ENT-derived predictions suggesting that observers would overestimate surface lengths based on environmental, not retinal, verticality. Participants drastically overestimated environmentally vertical surfaces only and did so at a magnitude related to surface length. These results replicate across multiple settings and methods and are supported by previous studies. Although researchers often assume that selection pushes perceptual mechanisms toward objective accuracy, this study suggests that genetic fitness can sometimes benefit from systematic illusions.
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1. Introduction

It is often assumed that perceptual mechanisms function identically across most environmental features, especially basic visual perception of line or surface orientation, length, and location. However, evolved navigation theory (ENT) is a research approach that predicts specializations in the perception or navigation of environmental features that are reliably associated with navigational costs over evolutionary time (Jackson, 2005; Jackson & Cormack, 2007a). ENT is primarily an application of signal detection theory to navigation costs over evolutionary time as a means to predict the type and magnitude of specific navigational adaptations. A more general approach of looking at how decision consequences pose selection across domains has been summarized by Haselton and Buss (2000) as error management theory.

ENT focuses on understanding the selective forces particular to navigation as a means to predict unknown locomotor, visual, and other navigational adaptations. For example, vertical and inclined surfaces present a navigation risk of falling that is unmatched in horizontal surfaces. Falls of a few meters produce serious injuries that would be exceedingly rare when navigating a few horizontal meters. Vertical navigation likely posed a strong selective factor in the evolution of terrestrial organisms, certainly those with arboreal ancestors, such as humans. Thus, an implication under ENT is that some perceptual or navigational mechanisms might be specialized to lessen the risks of falling.

One possible method of establishing navigational route preferences is by exaggerating distance perceived from costlier routes because organisms prefer nearer navigational goals (Somervill & Somervill, 1977). A process that exaggerated perceived vertical surface length could thereby decrease vertical navigation in the presence of less costly alternatives. This would result in vertical surfaces perceived as longer than equidistant horizontal surfaces, which would decrease vertical navigation frequency and its associated falling costs. This simple mechanism could dynamically weight navigational decisions in real time across all surfaces by exaggerating perceived length based upon initial surface length and orientation. Such a mechanism captures both navigation difficulty and a primary predictor of falling costs: distance from the ground. This would also flexibly weight navigational decisions by cost without outright prevention of

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vertical navigation, which is beneficial for organisms such as humans, who have derived important benefits from vertical navigation over evolutionary time.

A previous investigation of ENT-derived predictions demonstrated that participants unknowingly overestimated vertical surface length at a magnitude corresponding to the potential falling risk (Jackson & Cormack, 2007a). However, many surfaces cast images that are oriented vertically with respect to the observer's head or eyes (i.e., egocentrically vertical) — including surfaces with trivial falling risk. For example, looking down at the distance from one's feet to a distant point ahead on horizontal ground casts an egocentrically vertical image on the retinae, yet poses negligible falling risk. Although researchers commonly assume that the retinal image largely determines perceived distance, it obviously does not predict falling costs accurately enough to decrease them.

The feature that does predict falling cost is environmental, or exocentric, verticality: the extent to which a surface parallels the direction of primary gravitational force. In order for the vertical overestimation derived from ENT to result in appropriate falling cost avoidance, it should exaggerate exocentrically vertical surface length, with little regard for egocentric verticality.

We addressed this question in the current study by comparing real-world distance estimates across effectively equal egocentric images that nonetheless had different exocentric orientations corresponding to very different falling costs. We predicted from ENT that participants would overestimate distance only from exocentrically vertical surfaces because such surfaces posed distinct falling costs over evolutionary time.

We also varied stimulus length in the current study, which we predicted could affect the hypothesized overestimation in one of two ways. First, participants might overestimate by a constant percentage of the stimulus length (i.e., Weber's law) because such a simple algorithm might provide sufficient falling cost avoidance. Alternatively, participants might overestimate by an ever-greater magnitude as stimulus length increases because longer vertical surfaces at these distances pose both greater likelihood and overall cost of falling.

2. Methods

Thirty-eight introductory psychology participants reporting normal (20:20) or corrected-to-normal vision estimated distances in an outdoor testing site. Fig. 1 schematically illustrates participants' distance estimates.

2.1. Procedure

On each trial, participants saw three dots configured in an "L" shape. The two dots defining the egocentrically vertical segment (the solid lines in Fig. 1) were fixed, and the dot defining the remaining end of the horizontal segment (the dashed lines in Fig. 1), which was a bright green spot formed by a laser pointer held by a research assistant (RA), was adjustable. The participant instructed the RA to move the adjustable dot until the two segments of the L appeared equal in length. In one condition, the two fixed dots were placed exocentrically vertically on the side of a building, and the judgments were made from the ground (Fig. 1, right column). In the other condition, the two fixed dots were placed along an exocentrically horizontal line extending away from the base of the building, and judgments were made from upon the building (Fig. 1, left column). Participants could take as much time and make as many adjustments as they liked. After a participant was satisfied with his or her estimate, the RA determined the corresponding length by comparing the position of the estimate in the real scene to a high-resolution digital photograph of the scene that had a calibrated distance scale superimposed upon it.

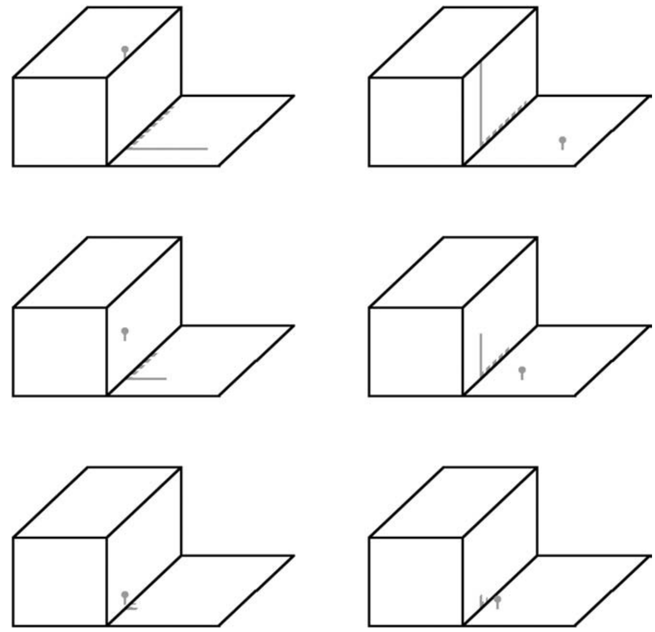

Fig. 1. Observer (dotted icon) position while estimating egocentrically vertical distances (solid gray lines) by showing an equivalent egocentrically horizontal distance (dashed gray lines). Exocentrically horizontal distance estimates are depicted in the left column, whereas vertical estimates are shown in the right column. Long distance (14.39 m) appears in the top row, medium distance (8.37 m) is shown in the middle row, and short distance (2.35 m) appears in the bottom row. Figures are not to scale.

We modeled these procedures after similar previous research in order to study this phenomenon in an ecologically valid outdoor setting with rich stimuli. In Chapanis and Mankin's (1967) research on the vertical–horizontal illusion in a realistic setting, they had participants direct an experimenter to move out at a right angle from a vertical surface until the distance looked equal to the height of the vertical surface. Yang, Dixon, and Proffitt (1999) also used this procedure in their work on distance estimation differences between reality and photographs. In other

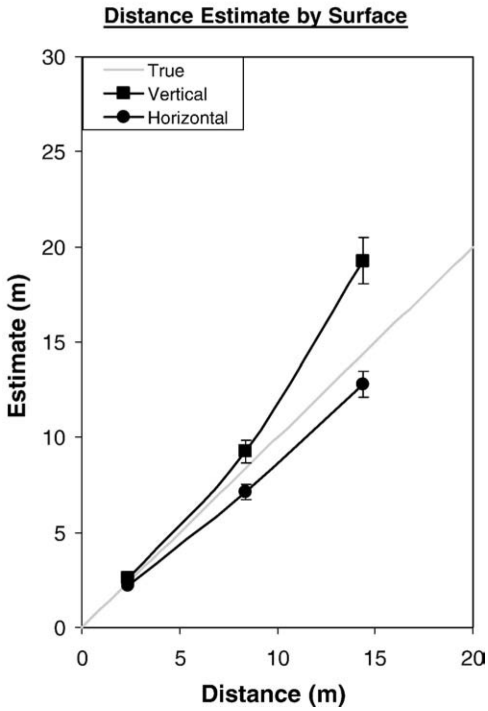

Fig. 2. Mean distance estimates by stimulus length in meters. The gray line indicates performing accurate estimation, circles indicate observed estimates of exocentrically horizontal surfaces, and squares indicate observed estimates of exocentrically vertical surfaces. Error bars show 95% confidence intervals about the means, which are very narrow at short distances.

work on the vertical–horizontal illusion in realistic settings, Higashiyama (1996) had participants adjust the distance from themselves to a wall until that distance appeared equal to the wall's height. In work on the descent illusion, Jackson and Cormack (2007a) had participants in one experiment direct an experimenter to move away from a wall until the distance appeared equal to the height of a building.

A strength of the current procedures is that the experimental predictions relied on estimation differences across positions, yet estimation method was invariant across positions.

2.2. Stimuli

Participants estimated exocentrically vertical distances on a parking garage while standing in an adjoining parking lot and estimated exocentrically horizontal distances in the parking lot while standing at various heights on the parking garage (see Fig. 1). White dots roughly 7 cm in diameter indicated either end of the exocentrically vertical distance. Participants estimated three stimulus distances (long: 14.39 m, medium: 8.37 m, and short: 2.35 m) in both exocentric orientations, constituting six estimates per participant. Vertical distances were large enough to inflict falling costs, and all participant positions were not impassably obstructed, such as with a window or screen.

Distance from participant to the stimulus surface was equal across both exocentric orientations within all three stimulus lengths. The distance being estimated was equal to the distance from the participant to the surface being estimated. We also added 30 cm to the distance from the participant to the vertical surface during exocentrically vertical estimates because estimates of the exocentrically horizontal surfaces positioned participants' eyes above the railing of the parking garage by an average of 30 cm. Participant positions were identical between subjects, and each estimate occurred at a different lateral position so that participants would not estimate a distance on which they had previously stood. We randomized stimulus order between vertical first versus horizontal first and long first versus short first in both vertical and horizontal estimates with roughly equal numbers of participants of both sexes in every order condition.

3. Results

Participants overestimated exocentrically vertical distances only and did so to a large, increasing degree as stimulus length increased (see Fig. 2). Distances that appear vertical on the retinae were only overestimated if they were vertical in the environment, with longer distances overestimated by greater magnitudes. Participants underestimated exocentrically horizontal distances to a slight degree that paralleled accuracy.

All six estimates significantly differ from both accuracy [the least significant of which: $t(37)=2.764$, $p=.009$, $d=.634$] and one another within distance [the least significant of which: $t(37)=6.442$, $p<.001$, $d=.975$].

Table 1 displays summary statistics, with the rightmost column displaying illusion magnitude. Illusion magnitude

Table 1
Descriptive statistics and difference scores for six distance estimates (in meters)

Stimulus length	Exocentric orientation	Estimate (95% CI)	Over-/ Underestimation	Orientation difference	Correlation within length (p value)	Illusion magnitude (95% CI)
Short (2.35 m)	Horizontal	2.22±0.09	−0.13	0.36	.249 (.001)	16±8%
	Vertical	2.58±0.14	+0.23			
Medium (8.37 m)	Horizontal	7.14±0.38	−1.23	2.12	.376 (<.001)	30±11%
	Vertical	9.26±0.57	+0.89			
Long (14.39 m)	Horizontal	12.78±0.67	−1.61	6.49	.224 (.002)	51±13%
	Vertical	19.27±1.22	+4.88			

increased with stimulus length from 16% at short distances to 51% at long distances. Compared to the average magnitude (32%), this does not appear to reflect Weber's constant. Illusion magnitude is equal to the mean vertical estimate divided by the mean horizontal estimate, minus 100%, that is, the amount of vertical extent estimated that exceeds the horizontal estimate. Illusion magnitude confidence intervals account for error propagation when dividing two random deviates (see Bevington & Robinson, 1992; Mandel, 1964).

4. Discussion

As predicted from ENT, participants overestimated exocentrically vertical distances and did not overestimate exocentrically horizontal distances — despite the fact that actual distance was equal across both orientations and that egocentric orientation and image size were highly similar. We title this the *environmental vertical illusion*.

We found the environmental vertical illusion at a very large magnitude for a previously unknown psychological process that likely occurs constantly throughout everyday activity. The 51% environmental vertical illusion magnitude at the long stimulus corresponds to vertical overestimates 6.5 m greater than horizontal estimates of a 14.4-m stimulus. This is roughly equivalent to estimating the height of a five-story building when the equivalent length perceived on the ground is equal to that of a school bus. Greater illusion magnitudes associated with longer stimuli may reflect both increased probability and severity of likely falling costs. Such an algorithm would still function simply, likely needing input only on surface length and orientation to reduce falling costs suggested under ENT.

The relatively constant, slight underestimation of exocentrically horizontal surfaces averaged 12% and may have resulted from a texture discontinuity only present in horizontal estimates (see Feria, Braunstein, & Andersen, 2003; Sinai, Ooi, & He, 1998). Horizontal stimuli spanned grass, cement, and asphalt, while the surface on which participants estimated spanned only grass. This was most prominent at the medium and long horizontal stimulus lengths, as reflected in participants' estimates.

The constant, slight underestimation of the exocentrically horizontal distance may have also indicated an anchoring effect in our conservative measurement techniques. Previous unrelated pilot study participants made seemingly shorter estimates when the distance indicator started at a point shorter than the true stimulus distance but made longer estimates when the indicator started at a point longer than the true distance. Other distance estimation researchers have found such an anchoring effect (Mankin, 1969; Taylor, 1961). We chose to start the laser dot at the shortest distance (i.e., 0 m) in this study in order to be conservative against our predictions. More importantly, this method was necessary in order to reduce tedium, as participants would have otherwise had to tell, and then wait for, the RA to move the laser dot in from 60 m in order to estimate distances of only 14, 8, and 2 m.

4.1. Perceptual navigation cost theories

Theories that suggest how or why visual distance estimation might account for costs associated with navigation include foreshortening of receding horizontals, 'gravity theory,' affordance, and ENT.

4.1.1. Foreshortening of receding horizontals

Foreshortening of receding horizontals is primarily a phenomenon wherein receding surfaces appear smaller on the retina than other surfaces. However, Segall, Campbell, and Herskovitz (1966) proposed a theory by the same name in which they suggested that foreshortening as a phenomenon causes observers to exaggerate distance perceived from horizontal surfaces in order to increase distance estimation accuracy. Predictions derived from this viewpoint suggested that the current participants would estimate accurately at both orientations because there was equal and minimal foreshortening across orientations. Existence of the environmental vertical illusion, as well as the descent illusion described below, refutes the theory of foreshortening asserted by Segall et al.

4.1.2. Gravity theory

Gravity theory (see description by Howard & Templeton, 1966, p. 37) is a collection of approaches that suggest that distance perception translates the energy of locomotion, coupled with the effort to overcome gravity, into perceived distance. Gravity theory applies only to a subset of navigation costs (energetic expense), without accounting for risk of injury. This view proposes that greater perceived effort associated with traversing a surface should increase its perceived length, often as a function of the amount of ascending required to traverse the surface.

The environmental vertical illusion found here could support predictions under gravity theory, which would suggest that the illusion results from the substantial effort, rather than falling costs, inherent in navigating vertical surfaces. However, existence of the descent illusion (below) directly refutes predictions made under gravity theory.

4.1.3. Affordance

Affordance (Gibson, 1979) broadly suggests that elements in the environment allow (afford) a limited number of behaviors specific to an organism. Essentially, the ways in which an organism can interact with its environment determine what the organism perceives from its environment.

A stipulation of affordance and its underlying approach (termed *ecological psychology*) is that illusions are often artificial by-products of impoverished stimuli (Gibson, 1966). Gibson suggests that the richness of sensory information available to organisms is precisely that which determines how organisms interact with their environments; thus, illusions should disappear when observers view all cues that are present when perceiving the object in realistic settings. Contrary to this prediction, we found that unrealistic scenes can make the environmental vertical illusion disappear in virtual reality replications of the current study (Jackson & Cormack, 2007b). Not only does the environmental vertical illusion magnitude exist at large magnitude in an outdoor and, thus, realistic setting, but its magnitude decreases or disappears as the realism (primarily of falling costs) decreases. Additional illusions in natural environments, such as the descent illusion, also contradict predictions derived from affordance.

4.2. Evolved navigation theory

ENT (Jackson, 2005; Jackson & Cormack, 2007a) is an approach to understanding navigational mechanisms based on the costs of navigation in the environment in which the specific mechanism evolved. ENT suggests that many inherited navigation mechanisms evolved in contexts where variance in their gene frequencies corresponded to variance in gene propagation. These mechanisms could include any aspect of navigation, including perception, locomotion, decision making, and others.

ENT shares many features with error management theory (Haselton & Buss, 2000), which describes the more general phenomenon where signal detection theory applied over evolutionary time can produce decision-making mechanisms that appear to depart from objective reality because they reflect fitness consequences. ENT applies similar principles focused on specific predictions within human navigation, such as distance overestimation as a means for cost avoidance. As with other theories, ENT is primarily a framework for facilitating lower-level predictions. ENT itself is directly testable in ways beyond the scope of the current data.

4.3. Related research

If, as suggested from ENT, likely interaction and falling costs primarily drive the observed distance overestimation, then it should occur at similar magnitudes across similar lengths and orientations. This is exactly what we have found, even when estimates come from different participants, settings, visual angles, observer positions, head orientations, and estimation procedures (Jackson & Cormack, 2007a). Additionally suggested from ENT, we should find even greater magnitude overestimation of a vertical surface when standing on top of it than when standing on the ground because people are more likely to fall when descending than ascending (Cohen & Lin, 1991; Haslam & Bentley, 1999; Svanstrom, 1974; Tinetti, Speechley, & Ginter, 1988). This is exactly what we have found (Jackson & Cormack, 2007a). This descent illusion results in heights perceived as taller while standing at the top than at the bottom by nearly a factor of 2 over the actual distance at 14 m.

The descent illusion was only predicted from ENT. The existence of the descent illusion directly contradicts predictions from foreshortening of receding horizontals (equal distance perceived from top and bottom), gravity theory (greater from bottom than top), and affordance (accurate distance from top and bottom). One might interpret such an effect as a by-product of anxiety or arousal to standing on top of a height (i.e., fear of heights). The current study suggests that the descent illusion does not result from anxiety or arousal per se. Participants in the current study estimated a (horizontal) surface that would not likely pose falling costs and did not overestimate its length — even though they stood at the top of a height. Across studies, differences in distance estimation seem to correspond with likely navigation costs related to falling.

The well-known vertical–horizontal illusion occurs such that participants tend to overestimate vertical line length on two-dimensional displays. The ultimate cause of the vertical–horizontal illusion is unknown. One might predict from ENT that the vertical–horizontal illusion could be the two-dimensional by-product of adaptations that arose to facilitate three-dimensional navigation, primarily via falling cost avoidance. However, although the vertical–horizontal illusion and the current environmental vertical illusions seem similar, they may not derive from the same cognitive processes. The vertical–horizontal illusion plainly presents no falling risk, and estimating lines on paper is evolutionarily novel. The vertical–horizontal illusion magnitude of 3–7% is far less than that of the environmental vertical illusion observed here (16–51%). Additionally, the vertical–horizontal illusion also appears to be affected by bisection (Yang et al., 1999) and visual field shape (Künnapas, 1957), both of which apparently failed to affect the environmental vertical illusion as tested here.

It might seem to some that selection should push perceptual systems toward accuracy, rather than apparently systematic ‘error’ observed here. However, no biological law dictates that objectively accurate perception is universally best — it is the genetic fitness consequences that determine selection on perceptual (or any other) mechanisms. If departure from objective reality more appropriately captures fitness consequences, researchers should anticipate some perceptual mechanisms that do not reflect ‘ideal observers’ or exocentric truth, as is occasionally assumed. This stems directly from signal detection theory and evolution by natural selection and may be reflected in the current data. Haselton and Buss (2000) describe this approach as error management theory. An excellent illustration of such adaptive perceptual bias may exist in the phenomenon of auditory looming, where some qualities of sounds emitted by approaching sources are overestimated (and perceived to be nearer), compared to those of receding sources (Neuhoff, 1998, 2001).

One empirical method of determining the target of perceptual accuracy is to determine the associated signal detection matrix of the perceptual task (for a recent evolutionary application of signal detection, see Nesse, 2005). Such an analysis can also determine if the magnitude of the perceptual target is reflected in behavioral change, that is, whether or not people avoid vertical navigation to the same degree that they overestimate vertical distances (A.J. Figueredo, personal communication, June 30, 2006).

ENT suggests that navigational costs can lead to perceptual specialization over evolutionary time. Exocentric, not egocentric, orientation accurately predicts falling costs, while distance overestimation provides a convenient mechanism to weight navigation choices. Our ENT-derived predictions suggested that participants would only overestimate exocentrically vertical surfaces. Experimental results across different settings, participants, and methods support these predictions.

These findings may be most important because distance and orientation perception occurs constantly in most visual systems. Because navigation is prerequisite to nearly all animal behavior, navigational expense implicitly precedes the costs of most other behaviors, whether they be fighting, fleeing, feeding, or mating. Understanding how distance perception occurs thus helps us to understand one of the most common prerequisite costs in behavioral evolution across domains. These data suggest that a previously unknown, yet ubiquitous, component of human visual experience is illusory. However, through the use of a theory rooted in evolution (ENT), we may be able to predict and better understand these important features of human psychology.

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