

Reducing the presence of navigation risk eliminates strong environmental illusions

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Many researchers have assumed that navigational costs, as opposed to the visual stimuli per se, produce several large-magnitude distance illusions—in spite of the absence of experimental data. We used virtual reality to remove the presence of realistic falling costs, while leaving the visual information otherwise intact. This resulted in removal of the distance illusions proposed to have evolved in response to falling costs. These data hold important implications in vision research and ecological psychology, as well as in applied settings such as aviation.

Keywords: navigation, distance perception, evolution, virtual reality, evolved navigation theory

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Introduction

Many researchers suggest that navigational costs shape distance estimation—specifically, that high navigational costs result in distance overestimation. These navigational costs include energetic demands and risk of injury (Howard & Templeton, 1966; Jackson, 2005; Jackson & Cormack, 2008; Proffitt, Bhalla, Gossweiler, & Midgett, 1995; Sadalla & Magel, 1980; Solomon, 1949). The underlying logic of most of these approaches is that observers will choose to navigate overestimated distances less often than accurately estimated ones, which will reduce the likelihood of incurring the costs of navigation posed by the overestimated surface (Jackson & Vazquez, 2010).

An important navigational cost is that of falling. We have found such navigational costs to affect distance estimates in several studies, including the discovery of large magnitude distance illusions in everyday perception. For example, the *environmental vertical illusion* occurs such that observers overestimate the length of environmentally vertical, but not horizontal, surfaces—regardless of retinal position or size (Jackson & Cormack, 2008). We predicted the environmental vertical illusion based upon environmental verticality being the major predictor of falling risk in a surface. Likewise, the *descent illusion* occurs such that observers overestimate the height of a vertical surface more while standing on top of it than while standing at the bottom (Jackson & Cormack, 2007). We predicted the descent illusion because the likelihood and severity of falling are greater during descent than ascent. In addition to distance estimation, the risk of

falling has also been found to shape fear of falling. Jackson (2009) suggested that differences in distance estimation likely produced differences in height fear (however, see Teachman, Stefanucci, Clerkin, Cody, & Proffitt, 2008).

We conducted the preceding studies from a research approach titled *evolved navigation theory* (ENT), which focuses on how all sources of navigational costs may have shaped the evolution of perceptual and locomotor systems (Jackson, 2005; Jackson & Cormack, 2007). The idea that navigational costs could adaptively shape navigational mechanisms stems from evolution by natural selection (Darwin, 1859). Evolved navigation theory suggests that one such mechanism is distance perception. Distance perception may reflect many navigational costs.

The navigational costs of falling as investigated under ENT appear to produce among the largest magnitude distance illusions known. Whereas the magnitude of the best known distance illusions (such as the Mueller-Lyer, Ponzo, or horizontal–vertical illusion) are often no more than 10%, the observed magnitudes of the ENT illusions described above reach 84%. Further, the studies under ENT derive from real-world designs with high generalizability and application to realistic, everyday vision.

Unfortunately, no studies have yet experimentally manipulated falling costs in order to clarify a causal relationship between falling risk and distance estimation. Experimental manipulation of energetic costs have suggested that higher energetic demands may result in longer distance estimates (Solomon, 1949; also Proffitt et al., 1995, however, see Hutchison & Loomis, 2006). However, there are no experimental data in which researchers have manipulated falling costs while preserving visual

situational cues. This prevents concluding that the perception of such costs indeed produces the large visual distortions reported in everyday vision.

Experimental removal of falling costs

An experimental approach to these real-world data would predict that removing the presence of realistic falling costs should remove illusions hypothesized to exist in response to falling costs. We should be able to remove the falling risk, or ecologically valid triggers to risk, and observe that participants estimate distance accurately.

It is difficult to do this in the context in which these mechanisms evolved. For example, plausible falling risk mitigators, such as climbing harnesses, safety rails, or placing observers behind glass windows, do not always entirely remove falling risk. More importantly, such safety features did not exist in the environments in which distance estimation adaptations evolved. Thus, these safety features may affect distance estimation adaptations in random, unpredictable directions or not at all because distance estimation adaptations could not have evolved to use them as a cue to risk. What is necessary for the appropriate removal of falling costs is not the addition of evolutionarily novel safety gear, but the deletion of the believability of the risk posed by a surface.

There is an excellent experimental method recently available for deleting the presence of falling risk from a visual scene without adding safety gear. Virtual reality methods provide immersive visual scenes that can replicate nearly any research environment (Sanchez-Vives & Slater, 2005). Further, virtual reality methods provide the ability to manipulate falling costs via the manipulation of ‘presence’. Presence is an important index in virtual reality methods that specifies the degree to which participants feel that they are physically in the (virtual) environment and subject to the consequences of being in that environment (IJsselstein, de Ridder, Freeman, & Avons, 2000). Lombard and Ditton (2006) summarize presence as the extent to which a participant “responds as he/she would if the medium were not there,” which is to say that presence indicates the extent to which a participant reacts to the virtual world in the same way that the participant would react in the real world. Presence may most strongly relate to interaction with the environment (Hendrix & Barfield, 1996).

An important benefit of virtual reality methods to the current investigation is that there is large variance in the extent to which different visual cues contribute to presence. One of the strongest visual cues that determine presence is head-tracking (Snow, 1996; Snow & Williges, 1998). Head-tracking is the phenomenon wherein the view of the virtual environment changes with head movement, as occurs in real life. Unlike head-tracking, the visual realism of the virtual environment determines presence only weakly (see Sanchez-Vives & Slater, 2005).

This disparity between head-tracking and visual realism allows for a unique manipulation. It allows us to realistically replicate scenes that have been shown to induce illusions in the real-world without the (cognitively low-level) perception of falling risk that occurs in real or high-presence situations. This would present participants with the same visual information that has been shown to produce ENT illusions (such as the environmental vertical illusion), but participants should have little presence for falling risk. If the illusions persist, then falling risk likely does not cause these illusions. If the illusions cease, then it may suggest that falling risk is a causal factor.

Real world illusions and current predictions

Virtual reality procedures in the current study replicated as closely as possible the physical reality procedures of Jackson and Cormack (2008). In Jackson and Cormack (2008), we found that participants in real-world settings overestimate environmentally vertical distances, but not environmentally horizontal ones, regardless of retinal orientation. Additionally, Jackson (2009) found that falling costs in a surface likely generate fear of heights (acrophobia), even when observers are at no risk of falling. We predicted the above findings from ENT because environmental orientation is a major predictor of falling in the real world, while overestimation and fear are two adaptive methods for decreasing the likelihood of incurring the costs of falling. When falling costs are believably present, observers overestimate environmentally vertical surfaces and do so to an extent that correlates with their fear of heights.

We hypothesized that removal of falling cost presence would remove the expression of adaptations hypothesized to exist in response to falling. This generates the following predictions.

1. The environmental vertical illusion (Jackson & Cormack, 2008) should disappear, making participants’ estimates of the length of vertical surfaces equal to their estimates of the length of horizontal surfaces.
2. The correspondence between distance estimates of vertical surfaces and acrophobia measures (Jackson, 2009) should disappear, leaving no correlations between fear of heights and distance estimates of surfaces with falling costs.

Method

Participants

One hundred and five college student participants each met a researcher individually in a campus laboratory and

made distance estimates within a virtual world on a head-mounted display (HMD). Four other potential participants were unable to participate due to discomfort or inability to interact appropriately with the research apparatus. No participants appeared to experience vertigo, despite monitoring by research assistants to detect any visual-vestibular difficulties. Participants received course participation credit and the average time for participation was roughly 20 to 30 minutes.

Apparatus and stimuli

We used a Virtual Research V8 HMD displaying a resolution of 640×480 at 60 Hz. The HMD accommodated prescription eyeglasses (10–30 mm from eye to HMD optics) and interpupillary distances from 52 to 74 mm. Research assistants fitted participants with the HMD and insured that it was comfortable and that it displayed stimuli clearly throughout all procedures. We programmed and displayed all virtual environments in Matlab 7. We replicated the physical reality procedures of Jackson and Cormack (2008) as closely as possible. As in Jackson and Cormack (2008), participants in the current study stood in an environment featuring a building that appeared in the middle of an asphalt parking lot surrounded by grass. Participants estimated distances that were vertical and horizontal in the (virtual) environment with a distance matching task (described below). Participants estimated vertical distances on the side of the building while standing in the parking lot and estimated horizontal distances on the parking lot while standing on the building.

The display was not sensitive to participant head orientation. Researchers instructed participants when and where to point their heads as the computer-generated view rotated—for example, participants were instructed to point their heads down as the view rotated down while making their estimates of the horizontal distances on the ground. This provided the same body positions and views of the environment as participants would receive in the real world, but their head movements did not produce scene change. This resulted in stimuli similar to the real world, but with minimal presence.

Procedure

Participants began with a short tour of the environment in which they viewed the building from a distance of roughly 50 m and then were moved (at a brisk walking pace) to within 15 m, at which time the view pointed up to the top of the building and then back down to level. Participants then moved to within 2 m of the building at which time the view again pointed up to the top of the building, then back down to level, and then an estimation phase began.

On each trial, participants saw three dots configured in an ‘L’ shape. The two dots defining the vertical segment

of the ‘L’ were fixed, and the dot defining the remaining end of the horizontal segment was adjustable. The participant instructed the researcher to move the adjustable dot until the two segments of the ‘L’ appeared equal in length. In one orientation, the two fixed dots were placed vertically in the environment on the side of the building, and the judgments were made while standing on the (virtual) ground (Figure 1, right column). In the other orientation, the two fixed dots were placed horizontally in the environment on the ground extending away from the base of the building, and judgments were made while standing on the (virtual) building with the head pointed down (Figure 1, left column). The adjustable dot started at a randomly generated distance.

Participants received a roughly 30 second break after making all estimates at their first randomly assigned orientation and then again received the same initial tour and proceeded to estimates at the remaining orientation. We assigned the order of vertical- or horizontal-first randomly across participants, controlling for roughly equal numbers of participants of both sexes in both order conditions. At both orientations, participants received five trials at each of three distances (2.35, 8.37, and 14.39 m, as in Jackson & Cormack, 2008). This resulted in thirty total estimates by every participant. We randomized the order of distance estimates within each trial.

Participants received as much time, and could make as many adjustments, as they liked for every estimate. All research assistants were blind to the research hypotheses. In order to further limit experimenter bias, research assistants moved the indicator dot by a fixed distance and only when directed by participants. Research assistants were unaware of the accurate distance in each estimate.

Questionnaire

Participants completed the Acrophobia Questionnaire (Cohen, 1977) after completing all distance estimates. This questionnaire contains twenty questions that measure anxiety and avoidance in response to experiences with heights. It is the primary clinical tool for diagnosing acrophobia and also measures differences in fear of heights at sub-clinical levels. For simplicity, we use the term ‘acrophobia’ in order to refer to fear of heights across all levels, including subclinical levels.

Results

Primary findings

Participants estimated environmentally vertical distances indistinguishably from environmentally horizontal distances (Figure 2, top) and acrophobia did not correlate

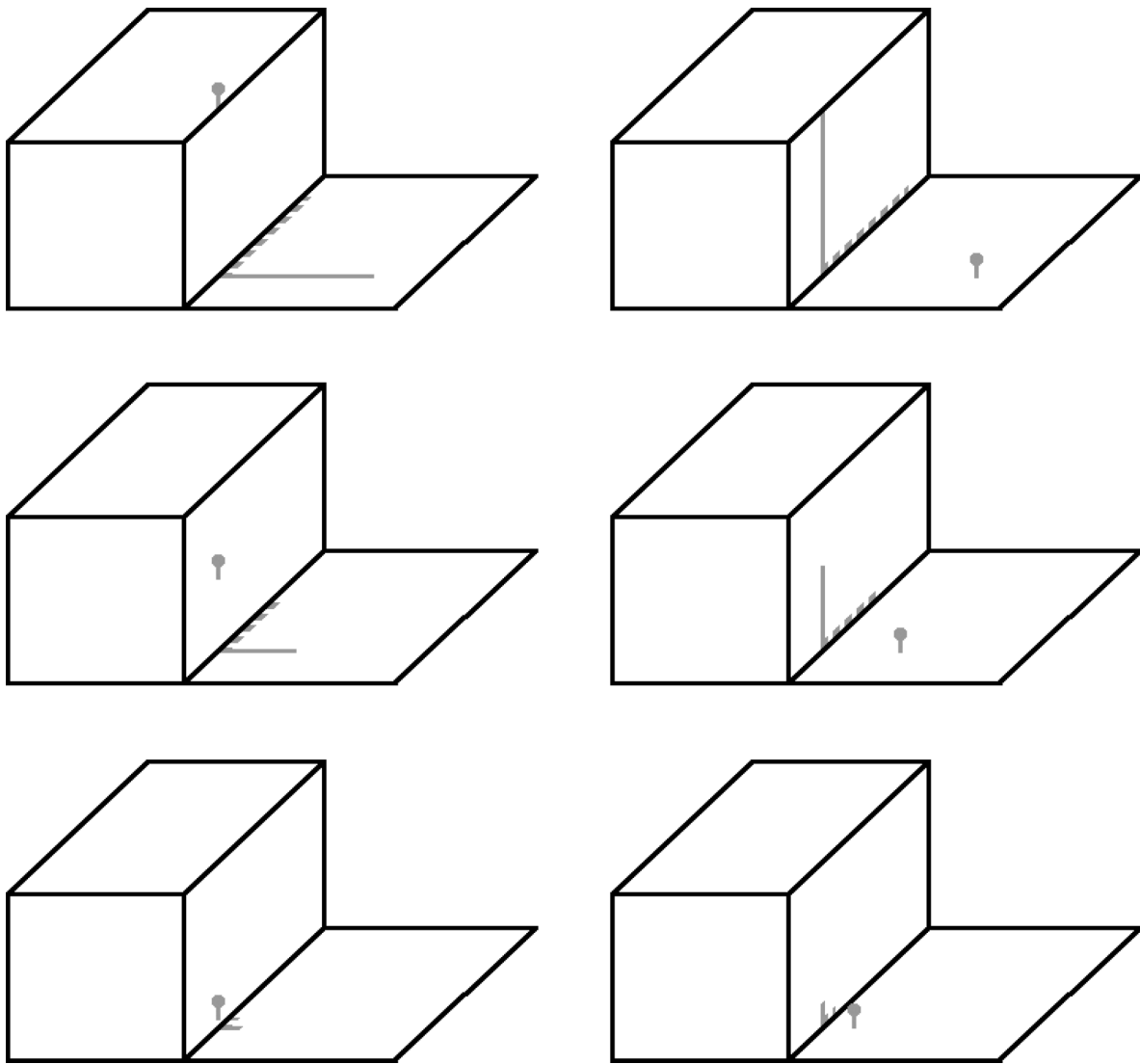


Figure 1. Participant location across six positions (not to scale). The gray dotted icon represents the participant. The solid gray line represents the distance being estimated and the dashed gray line represents participants' estimates. Environmentally horizontal distances appear on the left and vertical ones on the right. The top row represents the long (14.39 m) distance, the middle row represents the medium (8.37 m) distance, and the bottom row represents the short (2.35 m) distance.

with vertical (nor horizontal) estimates (see [Table 1](#)). These data clearly contradict equivalent estimates in environments with falling costs ([Figure 2](#), bottom).

Two distance estimates differed statistically significantly, albeit not meaningfully, by orientation (short: $t(104) = 3.333$, $p = .001$, and medium: $t(104) = 2.362$, $p = .020$). These differences were roughly 2% of the actual distances (.06 m at the short and .16 m at the medium distance), which would make little difference in real world interaction over distances of several meters. The differences within orientation in real-world stimuli of this length are .36 m and 2.12 m, or 14% and 18% (Jackson & Cormack, 2008).

No distance estimate correlated significantly with Acrophobia Questionnaire (AQ) score. The average correlation was $r = .033$. [Table 1](#) displays correlations

between each estimate and AQ score—the Bonferroni-corrected $p < .05$ threshold of significance for which would be $p < .008$.

Additional findings

Participants slightly overestimated the actual distance in all six estimates, the least significant of which: $t(104) = 8.063$, $p < .001$ (see [Table 1](#)). This ranged from an average of .32 m (14%) at the short distance to 1.04 m (7%) at the long distance.

Participants did not estimate more accurately or estimate differently over the course of the experiment (see [Figure 3](#)). No meaningful variance or overall trend appeared across trials within any of the six estimates; the

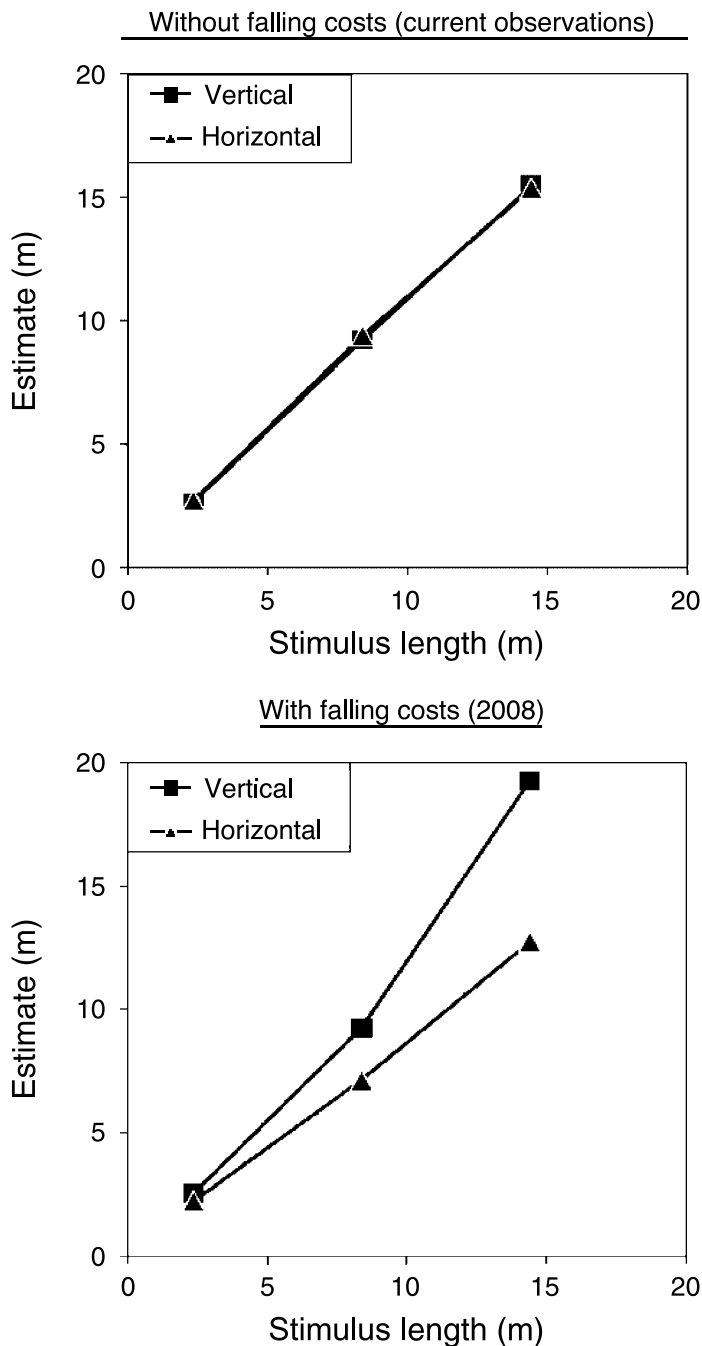


Figure 2. Mean distance estimates by stimulus orientation in meters from the current data without falling costs (top), compared to the same estimates with falling costs from Jackson and Cormack (2008) (bottom). Triangles indicate environmentally horizontal distance estimates and squares indicate environmentally vertical distance estimates. Error bars show 95% confidence intervals about the means, which are too small to be visible here and appear in Table 1.

entire range of the most variable estimate (horizontal long) comprised only 3.9% of the average estimate. Order of estimates (i.e. estimating environmentally vertical distances before horizontal ones or vice versa) may have

influenced distance estimates, but in a trivial manner in respect to the experimental predictions. Participants who first estimated vertical surfaces had larger differences between their vertical and horizontal estimates at the short distance only ($t(103) = 2.683, p = .009$). Although this difference was statistically significant, it was less than 10 cm and does not contradict any research prediction.

Conclusions

As predicted, apparent elimination of falling costs via presence manipulation eliminated the dramatic overestimation of heights seen in previous studies. The current participants did not experience the environmental vertical illusion. They instead estimated environmentally vertical distances indiscriminately from environmentally horizontal ones. Participants in environments with falling costs experience the environmental vertical illusion at average magnitudes up to 51% (Jackson & Cormack, 2008). Further, current participant fear of heights did not correspond with distance estimates. In environments with falling costs, participant acrophobia levels correlate with evolved navigation illusion magnitude and predict distance estimation differences up to 86% (Jackson, 2009). The current study likely provides the first evidence that removal of believable falling costs removes specific large-magnitude distance illusions thought to have evolved in order to reduce the risk of falling.

Participants slightly overestimated by a similar degree across horizontal and vertical estimates. This suggests that participants estimated the vertical distances in a way similar to the horizontal distances, which was the primary component of our predictions (see also Jackson & Willey, 2010). Nonetheless, the slight deviation from accuracy was unexpected. Such minor deviance from likely intended estimate is not uncommon (Bridgeman & Hoover, 2008; Chapanis & Mankin, 1967; Jackson, Cook, Vazquez, & Willey, 2010), but is worthy of further study.

It is important to note that participants estimated accurately these distances while viewing both their estimate and the estimated surface. It would seem to be a very simple task to make two distances in one's visual field look equal or to estimate a 45 deg. angle connecting the two distances. Importantly, this was the same situation in the real-world procedures (Jackson & Cormack, 2008) after which we modeled these methods. The fact that observers did not drastically overestimate the vertical surface here further emphasizes how distinct are estimates of falling cost surfaces in the real world.

Participants understood the procedures quickly and easily and data suggest that the results hold high external validity for situations without falling costs. If the task were too novel or difficult to understand, then we would have expected largely inaccurate estimates that fell

	Stimulus length	Orientation	Estimate \pm 95% CI	Correlation with AQ (<i>p</i> -value)	Correlation within length (<i>p</i> -value)
t1.1					
t1.2	Short (2.35)	Horizontal	2.70 \pm 0.04	.018 (.855)	.486 (<.001)
t1.3		Vertical	2.64 \pm 0.03	-.005 (.958)	
t1.4	Medium (8.37)	Horizontal	9.40 \pm 0.15	-.032 (.748)	.570 (<.001)
t1.5		Vertical	9.24 \pm 0.13	.061 (.536)	
t1.6	Long (14.39)	Horizontal	15.37 \pm 0.24	.005 (.962)	.664 (<.001)
t1.7		Vertical	15.49 \pm 0.20	.141 (.151)	

t1.80 Table 1. Descriptive statistics and correlations for distance estimates in meters.

randomly above and below the actual distance across the different estimates. Instead, we found that participants' estimates systematically reflected the estimates made by participants in equivalent outdoor settings (if slightly overestimated). Further, there were no systematic differences across trials—practice did not change distance estimates.

Other virtual reality research supports the idea that presence of falling costs induces large-scale visual illusions. Even though we could not employ head-tracking in the current study so as to induce the environmental vertical illusion present in real environments, other researchers have found that head-tracking in large-scale virtual scenes like the current one produce such vertical overestimation (Dixon & Proffitt, 2002; Yang, Dixon, & Proffitt, 1999) and avoidance of virtual falling risks (Tarr & Warren, 2002). The presence of perceivable falling costs in virtual reality conditions has previously induced large-scale illusions that we suggest likely evolved in order to reduce navigational costs. This experiment suggests further that apparent removal of falling costs removes these illusions.

Beyond the body of previous work, the current study contained built-in manipulation checks for generalization to a full presence condition. Observers' estimates were nearly indistinguishable from estimates in real-world conditions (for surfaces without falling risks). Further, the shape of the estimate function (straight line with positive slope parallel to accuracy) was identical to that of real-world estimates. The estimates observed here were nearly identical to those of a surface without falling costs in a full-presence environment using the same procedures on the exact same distances in roughly equivalent environments. Any confound that would have affected the current observations would likely produce random effects—the capacity for which was very high. Estimates could have fallen above, below, or near accuracy across six distances with five trials apiece; yet the data were rather precise and replicated those from previous full cue conditions that lacked falling costs (Jackson & Cormack, 2008). The observed data were highly specific and replicated full-cue conditions exactly as one would predict from ENT publications appearing several years prior to gathering the current data (Jackson, 2005; Jackson & Cormack, 2007, 2008).

What was the key factor that produced accuracy in spite of viewing environments that normally produce large magnitude illusions? The documented impact of head-tracking on presence seems to be the obvious candidate and the primary manipulated component to these methods. However, given the nearly infinite amount of information available in full-cue visual environments, we do not suggest that head-tracking was the sole presence cue. This is a risk inherent in all virtual reality research and many other methods with high experimental control. The point being that it is unnecessary to invoke head tracking per se in order to account for all presence in order to make the primary conclusions of this research. The main research finding remains: An absence of believable falling cues corresponded to the absence of illusions proposed to have evolved in response to falling. This is an important finding.

These data hold important implications in applied settings. They suggest fundamental differences in the perception of, and likely interaction with, distances across real and virtual settings. This suggests that pilots, whose estimates of distance hold particularly high costs for themselves and others, likely estimate distances differently based upon display media. Pilots viewing a given scene on a common desktop flight simulator will estimate

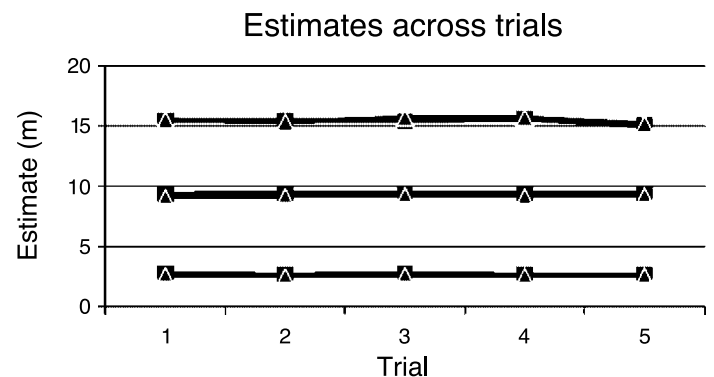


Figure 3. Mean estimates across trials for the long (top), medium (middle), and short (bottom) distances. Triangles indicate environmentally horizontal distance estimates and squares indicate environmentally vertical distance estimates. Error bars show 95% confidence intervals about the means, which are too small to be visible here.

distances differently than they would in a high-presence VR simulator or, more importantly, than they would in a real aircraft. This is even more prominent in an increasingly common piloting scenario, that of Unmanned Aerial Vehicle piloting, where the pilot is positioned in a remote location. Such scenarios may be particularly misinformative when multiple individuals collaborate on a single vessel from different displays. Outside of aircraft piloting, such scenarios are also prevalent in applications including unmanned submersible vehicles, the Mars Rovers, and endoscopic surgery.

These data may suggest that findings from the large number of distance perception studies conducted with fixed two-dimensional displays may be especially difficult to generalize to realistic environmental perception (Bian, Braunstein, & Andersen, 2006; Feria, Braunstein, & Andersen, 2003; Meng & Sedgwick, 2001; Sandstrom, Kaufman, & Huettel, 1998). The obvious solution for researchers wanting to exert the high experimental control afforded by computer displays, and yet retain the ability to generalize to actual human perception, would be to replicate laboratory studies in realistic scenarios.

These data hold important implications in theoretical settings. A pioneering approach to the study of how interaction with the environment can change perception is that of Ecological Psychology (Gibson, 1979). This approach continues to generate novel experimental findings. However, a basic assumption of this approach is that many illusions are byproducts of artificial displays and that, if the observer were to see a natural environment, such illusions should disappear (Gibson, 1966, p. 313). This is contrary to the current data. The current data suggest that illusions found in a real environment disappeared in an artificial one. A point of conflict between the current approach and that of Gibson may exist in that ENT does not assume that objective accuracy is necessarily optimal nor selected for, even when possible. ENT instead assumes that navigational mechanisms, of which distance perception is one, may reflect navigational costs in the environment in which they evolved. This can result in illusions under ENT because navigational costs do not correspond perfectly to objective environmental distances, even though the illusions themselves are the result of perceptual mechanisms designed to reflect navigational costs.

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