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Angular Declination and the Dynamic Perception of Egocentric Distance

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Abstract

The extraction of the distance between an object and an observer is fast when angular declination is informative, as it is with targets placed on the ground. To what extent does angular declination drive performance when viewing time is limited? Participants judged target distances in a real-world environment with viewing durations ranging from 36–220 ms. An important role for angular declination was supported by experiments showing that the cue provides information about egocentric distance even on the very first glimpse, and that it supports a sensitive response to distance in the absence of other useful cues. Performance was better at 220 ms viewing durations than for briefer glimpses, suggesting that the perception of distance is dynamic even within the time frame of a typical eye fixation. Critically, performance in limited viewing trials was better when preceded by a 15 second preview of the room without a designated target. The results indicate that the perception of distance is powerfully shaped by memory from prior visual experience with the scene. A theoretical framework for the dynamic perception of distance is presented.

Keywords

distance perception; angular declination; walking; time course; intrinsic bias

For humans, the extraction of visual information from the environment is a dynamic process, even when the head is stationary and the scene is static. The eyes are directed from one location to another in a scene at a rate of around three times per second to resolve and encode the details (Henderson & Hollingworth, 1998; Rayner, 1998). Further, because visual information is extracted primarily during fixation, when the point of regard is relatively stable (Matin, 1974), one's representation of scene is necessarily built up from a sequence of brief glimpses (Hollingworth & Henderson, 2002). Within the domain of scene perception, there has been considerable interest in the kinds of information that can be quickly extracted from a visual scene. We know, for example, that the meaning, or gist, of a scene can be determined on the basis of a single brief glimpse (e.g., Greene & Oliva, 2009a;

Schyns & Oliva, 1994), presumably on the basis of global image properties (Greene & Oliva, 2009b). Extraction of visual information about multiple objects typically occurs within the time frame of a series of fixations (Hollingworth & Henderson, 2002; Nelson & Loftus, 1980) because each must be fixated in turn. In contrast, within the domain of visual space perception, the time course for the extraction of distance information is typically considered at a very coarse scale (e.g., Creem & Proffitt, 2001; Cutting & Vishton, 1995; Gibson, 1979; Milner & Goodale, 1995; Proffitt, 2006; Previc, 1998) or considered as essentially static in a given cue configuration (e.g., Foley, 1991; Gogel, 1990; Landy, Maloney, & Johnston, 1995). While any theory could be modified to accommodate a more prominent role for the time course of cue extraction, we argue that a focus on perception after all cues have been fully extracted fails to capture systematic localization errors that occur as visual representations of distance evolve over time. This is a critical consideration given that dynamic real-world situations such as driving and pedestrian navigation arguably create circumstances where the time needed to extract important spatial information may be quite limited. Further, by neglecting the time course for the extraction of distance, the important roles for memory from prior views and general knowledge in the perception of distance may be underappreciated. Thus, determining the factors that govern the extraction of spatial information from a scene is of practical as well as theoretical importance.

In the present article we develop and test a framework founded on three fundamental assumptions. First, we review a series of experiments showing that viewing time matters (Gajewski, Philbeck, Pothier and Chichka, 2010). Accordingly, the first assumption is that the perception of distance is dynamic: While some cues are extracted very quickly--within the time frame of an eye fixation--there are additional useful sources of information that require more time to extract. A second assumption is that *angular declination*, the angular direction of the object with respect to eye level (Ooi, Wu, & He, 2001), is the primary functional cue that is available for localizing floor-level objects beyond 2–3 m when viewing is limited to the time frame of a single eye fixation. While there may be other cues extracted in that time frame, this hypothesis suggests they provide no functional advantage. Additional useful sources of information are expected to require more time for extraction, presumably because eye movements are needed. Finally, a third assumption is that a memory representation built from prior viewing episodes can facilitate the extraction of information about distance when viewing time is limited. This notion is based on past work (Gajewski et al., 2010) showing that the time course for the extraction of distance depends on one's prior experience with the task and/or environment. Here, we test the idea that it is visual information about the environment, specifically, that plays the supportive role in performance.

The foundation for the dynamic framework was laid by a series of experiments that examined the time course for the extraction of distance using a limited-viewing-time paradigm (Gajewski et al., 2010). Participants walked without vision to the remembered location of an object previewed through a liquid crystal shutter window, which controls the viewing duration of a real-world room environment and can provide glimpses that range from 9–5000 ms followed by a masking stimulus (see Pothier, Philbeck, Gajewski, & Chichka, 2009). Performance in the task was better when the viewing duration was extended

to several seconds than when it was limited to a time frame that would not afford an eye movement (113 ms), but sensitivity was high (i.e., the slope relating response distance to target distance was near 1) even with viewing durations that were exceedingly brief (9 ms). Critically, the level of performance observed, particularly with brief viewing durations, depended on the configuration of cues that were available. When objects were of constant angular size, the time course for the extraction of distance to eye-level targets was more protracted than it was for floor-level targets. In the latter case, angular declination varies systematically with distance and therefore is an informative cue within the manipulated distance range (2.5–5 m). The results of these initial experiments thus suggested that the angular declination cue is driving performance when viewing time is limited, presumably because it is both reliable and quickly extracted. However, the data also suggest a supportive role for memory in performance when viewing time is limited. When brief and extended viewing durations were administered in blocks, the advantage for extended viewing was observed only when the brief viewing durations were administered in the first block. Information extracted specifically during the extended-viewing trials was argued to remain available to support judgments of distance during subsequent brief trials because a control experiment revealed no benefits of task familiarity -- performance in two consecutive 100-ms blocks was very nearly identical.

The overall pattern of results strongly suggested the need for a dynamic framework for distance perception, one that not only accommodates a dominant role for angular declination but also a strong role for one's prior experience with a given environment in the on-line perception of object distances within that environment. We propose a framework that builds upon the work of Wu, Ooi, & He (2004; He, Wu, Ooi, Yarbrough, & Wu, 2004; Wu, He, & Ooi, 2008). These researchers suggest the ground plane forms a crucial reference plane for localizing objects (see also Bian, Braunstein, & Andersen, 2005; 2006; Gibson, 1950; 1979; Sedgwick, 1986). Critically, He and colleagues proposed that an accurate representation of ground surface depends on a *sequential surface integration process* (SSIP), wherein information about the nearby ground surface provides a kind of anchor for the integration of information about farther regions of the ground surface. The idea is that the immediate ground surface can be more accurately represented because the nearby distance and depth cues are more reliable. An accurate representation of the immediate ground surface then provides an important constraint on the development of a ground representation at further distances where the cues become less reliable. In support of this idea, Wu et al. (2008) have shown that if a task biases participants' initial attention toward distances lying beyond the immediate ground surface, the accuracy of distance judgments suffers, presumably because the crucial information from the immediate ground plane has not been selected or picked up. Their model is agnostic about whether selection can be accomplished covertly or if saccadic eye movements are required. However, if important distance cues require deployments of attention and/or eye movements, then performance most certainly should depend on the duration of viewing allowed.

Our framework takes the SSIP account as a starting point because it suggests a special role for angular declination (see also Durgin & Li, 2011; Li & Durgin, 2012) and because it makes predictions for how performance might be expected to change as viewing time

affords the accumulation of additional cues. Consider the scenario that is illustrated in Figure 1, adapted from Ooi, Wu, & He (2006). The distance, D , to an object resting on the ground is specified by a trigonometric function of eye height, h , and the angular declination of the object with respect to eye level, α , assuming, that is, that the ground plane is accurately represented. As can be seen, the angular declination of an object can correspond to several different distances, depending on the perception and/or representation of the surface slant, η . Ooi et al. have described an internally-specified “intrinsic ground plane”, characterized by a tendency to perceive illuminated targets visible below eye level as increasingly elevated with distance, even when resting on the ground (as though the ground had non-zero slant). These findings suggest that there are internal determinants of perceived distance that do not arise from vision of the target. In well-lit viewing conditions, these internal determinants, or perceptual biases, are thought to play a small role in the perception of distance, at least for relatively nearby objects (e.g., within 6 m), presumably because the ground surface is perceived and represented more accurately.

Ooi and colleagues have not fleshed out a time course in their account beyond the idea that selection processes may be involved. We extend their account with the suggestion that any condition that limits the duration of viewing will effectively create a reduced-cue viewing context, even when multiple reliable cues are present. When the viewing duration is limited, only those cues that have been extracted will be effective. The remaining cues would, in effect, be entirely absent, and in this case a greater influence of the perceptual biases is expected. Critically, predictions about the time course depend wholly on the information that the observer must extract from the environment. While judgments of eye level can be influenced by visual cues (e.g., Matin & Fox, 1989; Matin & Li, 1994; Wu, He, & Ooi, 2007), eye level is judged with relatively small constant error (about $2\text{--}3^\circ$) even in the dark (e.g., Stoper & Cohen, 1986). Like Ooi and He (2007), we assume that angular declination can be computed with respect to a stored representation of eye level built up from the sum of one’s visual experience and body-based information. To capitalize on angular declination, then, the line of sight must be referenced to a location on the ground surface. We argue that angular direction is the only external source of information that must be extracted to make use of the angular declination cue. When the target is viewed in the dark, or, as we argue, when viewing time is limited, distance is computed as though with respect to an abstract representation of a slanted or upward-curving ground surface. Performance improves when cues are more abundant and the duration of viewing affords the extraction of all available cues.

According to the SSIP account, the additional cues primarily afford a more accurate representation of surface slant, which in turn affords more accurate localization of the target distance at its observed angular declination (Ooi & He, 2007). Critically, an important role for angular declination is suggested by this account whether the ground plane is visible and accurately represented or not, provided the object can be assumed to be resting on the ground. In contrast, Mon-Williams and Bingham (2008) have suggested that the role for angular declination is substantially diminished when other cues are available. Their task involved targets presented above the ground at multiple heights in near space (20 – 80 cm) in the light and in the dark (so that support surfaces could not be seen). While we do not

assume our framework should necessarily generalize to that configuration, the idea that angular declination might receive less weight as additional cues come on-line is not out of accord with our predictions. The difference is in the assumed role for visible surfaces. While these investigators acknowledged that angular declination might predict performance at each given height, responses were not well predicted by angular declination when assessed independently of the height of the target, at least when targets could be seen resting on a horizontal surface. As a result, Mon-Williams and Bingham (2008) argued that angular declination and the accompanying surface cues cannot be disentangled. This conclusion was derived in a context designed to prevent assumptions about target height that are critical to the use of angular declination for deriving egocentric distance (Cutting & Vishton, 1995). In fact, angular declination was rendered completely uninformative about distance when the targets were viewed in the dark. In contrast, Ooi et al. (2001; 2006; Wu, He, & Ooi, 2013) have conducted a series of studies using a paradigm in which the required response included a judgment of target height above the ground as well as distance. Illuminated targets were presented in the dark at one of two or three heights. Errors in the judgment of distance were often made but the combined judgments generally suggested accurate perception and use of angular declination. Thus, in the absence of *visual* cues to height, the observer *assumed* some height and the accompanying distance judgment was constrained by this assumption. By our view, angular declination itself is strictly the angular direction of the target with respect to eye level, but effective use of the cue requires at least an assumption about the height of the object even when the ground plane (or support surface) is not visible. When available, additional cues may indeed receive some share of the relative cue weightings. However, when one can see or assume the height of the object, the accumulated evidence suggests that these additional cues influence the computation of distance based on angular declination, rather than completely dominating it.

The present study bolstered support for the dynamic framework by testing predictions made by two of its three primary assumptions. First, we propose that the dominance of the angular declination cue is linked with its reliability as well as its speed of extraction. When floor-level targets are employed, the cue value for angular declination is highly informative about distance. Because a reasonably accurate representation of direction can be encoded as soon as the target is detected (e.g., Adam, Davelarr, van der Gouw, & Willems, 2008; Adam, Paas, Ekerling, & van Loon, 1995; Tsal & Bareket, 2005), extraction of the angular declination cue value should be correspondingly fast. The angular declination of targets can be extracted just as quickly when presented at or near eye level, but in this case angular declination is not informative and as a result a similarly accurate representation of distance does not develop until other useful sources of information have had time to be extracted. When angular declination is informative, as it is with floor-level targets, its reliability coupled with its speed of extraction render all remaining cues superfluous in brief time frames. It is only with extended viewing that additional useful cues become available. It is important to note that we do not suggest that angular declination alone supports an *accurate* representation of distance, strictly speaking. Rather, we assume and test the hypothesis that angular declination alone supports the best representation of distance when viewing time is limited to the time frame of a typical eye fixation.

To be fair, the apparent dominance of angular declination at brief viewing durations could be linked entirely to its speed of extraction, and in that case it would not be considered dominant in the traditional sense. However, even at longer viewing durations, angular declination is arguably the most reliable egocentric distance at intermediate distances (e.g., between about 2 and 30 m; Cutting and Vishton, 1995). We suggest that angular declination is quickly extracted because target direction is available when the viewing conditions afford target detection. Other cues, such as monocular parallax (stimulus to accommodation) and binocular parallax (stimulus to convergence), are similarly rooted in directional information and thus could *potentially* be available upon target detection; the fact that vergence latencies (presumably based upon binocular parallax) average around 200 ms (Yang, Bucci, & Kapoula, 2002) indicates that these forms of parallax are certainly available within the time frame of an eye fixation. The difference is that the reliability of these cues is known to be substantially diminished beyond 2–3 m (Cutting & Vishton, 1995; Sedgwick, 1986).

Several other cues could play less direct roles in judgments of egocentric distance, either by supporting a better representation of the ground plane or by providing information to scale one's sense of the space. Binocular disparity is one cue that might be expected to play such a role. Although the time course for stereoscopic judgments can be quite protracted (e.g., McKee, Levi, & Bowne, 1990), observers likely have at least some sensitivity to binocular disparity within the time frame of an eye fixation (e.g., Hess & Wilcox, 2006; Harwerth, Fredenburg, & Smith III, 2003; Uttal, Davis, & Welke, 1994), particularly in contexts that provide additional cues (e.g., Bradshaw, Hibbard, & Gillam, 2002; Richards, 1977). While recent findings suggest that binocular viewing can improve depth discriminations even in the intermediate distance range (Allison, Gillam, & Vescillio, 2009), judgments of egocentric distance to ground-level targets in indoor and outdoor settings do not suffer under monocular viewing conditions (Bian & Anderson, 2012; Philbeck & Loomis, 1997). Given these findings, the presence of binocular information is not expected to have a noticeable impact on performance in our contexts, regardless of viewing duration.

Texture gradients and linear perspective cues should be useful because of the importance of the ground plane discussed above. However, we suspect these are partially or fully unavailable during brief viewing durations because critical regions of the scene are too far removed from the fovea (thus requiring an eye movement to resolve critical details) and/or because the attentional priority of the target prohibits the extraction of these sources in the allowed time frame. Because the target object is arguably the most task-relevant element of the scene, we assume it receives attention whether the viewing duration affords an eye movement or not. As a result, other potentially informative regions of the scene are likely outside the focus of attention, which would be expected to delay extraction (Posner, Nissen, & Ogden, 1978). While global image properties can be extracted quickly (Greene & Oliva, 2009a), the nearby ground plane presumably requires a more local level of analysis and texture pattern discriminability has been shown to suffer outside the locus of attention (e.g., Barbot, Landy, & Carrasco, 2012).

In sum, we hypothesize that angular declination is dominant because it is extracted quickly *and* because it is reliable. That being said, it is fair to note that our approach to assessing dominance differs from the approach of creating cue conflicts to determine which cue is

used preferentially (e.g., Cornilleau-Pérès, Wexler, Droulez, Marin, Miège, & Bourdoncle, 2002; Greenwald, Knill, & Saunders 2005; Marlow & Gillam, 2011; Uomori & Nishida, 1994). By that approach, our framework would posit that a plethora of cues might be extracted, even within the limited time frame, but that angular declination is the most reliable cue and therefore it is given the most weight. Above we name sources of information besides angular declination expected to be operative in our task environment. (Dynamic cues, such as motion parallax or optic flow, we would exclude here because they entail changes of perspective and necessarily extend over time.) To claim dominance, then, angular declination would have to be put into competition with each of these and shown to win out. Our approach to the problem was to compare performance when cues were provided in addition to angular declination. If the additional sources of information are quickly extracted and useful, there ought to be an associated performance benefit. If angular declination is informative and additional cues provide no functional advantage, we argue that angular declination can rightly be considered the dominant source of information. A potential challenge to our approach is that the cue weights can be expected to change in the context of other cues (see Mon-Williams & Bingham, 2008). If the additional cues are informative, the weight on angular declination could in principle be reduced to the point that it is no longer given as much weight as one or more of the other cues, even if there is no change in performance. In this light, cue conflict is preferred because it provides the only window to cue preference (i.e., the actual weighting). By our view, however, the precise weight on each of the cues is of less interest than the utility of adding sources of information. Whether the weights change or not, if nothing is gained by the addition of cues, our conclusion is the same. While we suspect that both approaches under most circumstances ought to converge on a similar conclusion, the fact that they need not do so suggests that an alternate term might fairly be adopted. Henceforth, we use the term *primary* as opposed to dominant to mean we test the idea that angular declination is the most functionally important cue when viewing time is limited.

The focus of the present study was to characterize the role for angular declination in judgments of distance to floor-level targets (2.5–5 m) using a limited-viewing-time paradigm. Experiments 1 and 2 determined whether performance would be supported by the *relative* angular sizes of the targets and *relative* angular declinations of the targets across trials, respectively. Experiment 3 compared performance with brief viewing durations to that in a reduced cue setting (glowing targets in a dark room), a context where angular declination is arguably the only reliable cue to egocentric distance available. Experiment 4 compared performance between two viewing durations -- one that was just above the threshold for target detection and one that was just below the latency for a typical saccade. If angular declination is the primary functional source of information, two general patterns are expected. First, observers should have a sensitive response to distance. That is, performance might not be entirely accurate, but response distances should significantly increase with target distance. Second, there should be no benefit associated with providing additional cues or additional time to extract other cues.

The present study also bolstered support for the dynamic framework by testing a prediction made by its third primary assumption, the idea that visual information extracted from prior

episodes plays an important role in performance when viewing time is limited. Familiarity with the stimulus and task environment has been shown to greatly enhance the extraction of distance when viewing time is limited (Gajewski et al., 2010). The familiarity acquired does not appear to be related to practice because there was no benefit associated with performing a second block of trials at the same 100-ms viewing duration. A competing hypothesis is that the benefit of experience derives entirely from motor recalibration (e.g., Durgin, Pelah, Fox, Lewis, Kane, & Walley, 2005; Philbeck, Woods, Arthur, & Todd, 2008; Rieser, Pick, Ashmead, & Garing, 1995). Experiment 5 compared performance on limited-viewing-duration trials when prior experience was controlled – one group was familiarized only visually with a preview of the room and the other was familiarized only with the walking distances (i.e., providing exposure to walking without optic flow). If visual memory supports performance, there should be a benefit of the former but not the latter. If a motor recalibration account is best, the opposite pattern should be observed.

Experiment 1

The aim of Experiment 1 was to determine the role for relative angular size in performance when angular declination is informative. It is not uncommon for researchers to employ targets of constant physical size when asking observers to judge the distance to floor-level targets. In this case, judgments of distance could be supported by the relative angular size of the target from one trial to the next. When angular size was held constant by systematically varying physical size with distance, Gajewski et al. (2010) found that the distance to eye-level targets could not be extracted as quickly as the distance to floor-level targets. However, reasonably good performance was observed with eye-level targets when physical size was constant, suggesting that relative angular size is a useful source of information, at least when angular declination is not informative. The question here is whether relative angular size contributes when angular declination is informative. If angular declination is the primary cue when targets are floor-level and viewing time is limited, then the availability of the relative angular size cues should not be advantageous. If performance at brief durations is supported by the relative angular size of the target across trials when angular declination is also informative, there should be a benefit associating with holding physical size constant.

Methods

Participants—Twenty-four individuals from the George Washington University community participated in the experiment. All participants were 18 to 35 years of age, reported normal or corrected-to-normal vision, and were paid \$10/h or participated in exchange for course credit.

Stimuli—The targets were sheets of yellow or magenta foam that were laid flat on the ground, eliminating cast shadows. Both colors were highly salient against gray carpeting. Targets were created for 11 distances from 2.5–5.0 m such that the physical size varied with distance. These were cut to appear as horizontal bars and subtended approximately 0.67×4.94 degrees visual angle. Because the objects were rectangular, the short sides of these stimuli did project to the observer with some amount of “keystoning” and thus provided some linear perspective information. However, the depth dimension was kept small to

minimize the contribution of this cue. The testing environment was a laboratory space that extended 7.4 m in depth from the participant's viewing position. The visible space was mostly empty but with bookshelves located in the far periphery of the visual field. The lighting was bright yet diffuse.

Apparatus—A liquid crystal shutter window (LC-Tec, Borlänge, Sweden) was used to control the duration of viewing of a target objects placed within a real-world room scene. The shutter window could be made to transition from a translucent (but completely light-scattering) state to a transparent state and back again very quickly and reliably (within 1–2 ms of the intended duration). Shutter timing was previously calibrated by monitoring the output of a phototransistor, which was exposed to an infrared laser through the shutter window when the window became transparent (see Pothier et al., 2009). The masking stimulus was a colored checkerboard pattern projected by an LCD projector onto a screen positioned to observer's left. Because the mask image needed to be reflected into a beamsplitter positioned in front of the shutter window, the shutter window and beamsplitter were each positioned at about a 45° angle. As result, the apparatus obscured a greater portion of the ground surface on the left (about 1.8 m) than on the right (about 0.8 m).¹ The field of view measured from the midline subtended approximately 65° × 60° (horizontal × vertical). The shutter window and beamsplitter were mounted to a sliding stage equipped with a chinrest. Mask presentation was controlled with a mechanical shutter that opened for 1 second as the shutter window returned to the translucent (closed) state.

Design and Procedure—Participants completed two blocks of trials: one block with physical size held constant (relative angular size informative) and one block with physical size varying systematically (relative angular size not informative). Target color varied only between blocks. Block color and order were counterbalanced. In this experiment, all trials employed a 74-ms viewing duration. The selection of viewing duration was somewhat arbitrary, though it was considered safely above the threshold for detecting the target and safely below the time needed to launch an eye movement (see Experiment 3).

Before testing, the experimenter provided instructions outside the laboratory and then ushered participants into the room with their eyes closed. Great care was taken to ensure that participants only saw the testing environment through the shutter window and during experimental trials. With the room darkened, the participants opened their eyes and the experimenter used a flashlight to orient them to the apparatus and guide their chins into the chinrest. As part of the orientation, the flashlight was also used to show participants the general region in the window where they could expect to see the target. At the beginning of each trial the eyes were closed and the lighting was turned on manually. The experimenter then instructed the participant to open the eyes, and announced the impending opening of the shutter window with a “ready, here we go”. Immediately after the shutter window closed, the mask was projected and reflected onto the beamsplitter directly in front of the shutter.

¹We ran a control study to determine whether the field of view of the window would have an impact on performance. One group (n = 12) viewed targets through the window while another group (n = 8) was provided a full view. In both cases, head was held stationary and the viewing duration was around 5 seconds. Blind walking performance did not significantly differ on any of the measures of interest (all $F_s < 1$). Responses were somewhat oversensitive (slope = 1.24), there was a modest bias toward underestimation (−9%), and precision was quite compatible across conditions (SEE = 0.36 m).

After the mask, participants estimated distance using the blind walking response. Participants closed their eyes while the experimenter pushed the apparatus to the side, and then walked in a darkened room with their eyes closed. Participants wore earplugs or hearing protectors to minimize spatial sound cues. Experimental trials were preceded by a demonstration trial with a target placed at 4 m but with no response required. The viewing duration for the demonstration was about 100 ms and was intended to prepare the participant for the speed of the shutter window.

Data Analysis—Accuracy was examined in terms of sensitivity and bias. *Sensitivity* represents the degree to which response distance differs systematically with differences in the distance of the target. In the text we report the means for the slopes relating response distance to target distance as an index of sensitivity. It is important to note, however, that statistical tests were not performed on the slopes per se. We employed a mixed models approach with intercepts and distance included as random factors. Parameter estimates given by the model for the effects of distance and interactions with distance do generally correspond to the mean of the slopes and the differences between slopes across individuals. *Bias* represents the overall tendency toward under- or over-estimation. Tests were performed on the mean responses across distance. In the text we report bias (mean error) as a percentage of the mean of the actual distances. Finally, we examined the *precision* of responses, which was given by the standard errors of estimate (SEEs) for the best-fitting lines relating distance estimates to target distance. While it may be more common to measure variable errors as the normalized standard deviations of each participant's judgments on a given experimental condition, here we employed a fine-grained set of distances without repetition as opposed to a small set of distances with each distance measured multiple times. As a result, it was not possible to use the more common method of calculating variable errors. Our data fit well to a linear regression model and given those assumptions the SEE is a reasonable proxy for variable error. Statistical tests for bias and precision were performed using the mixed models approach with random intercepts.

Power and Effect Size—Differences between mean values across conditions observed in our pilot studies and in the literature tend to be 10% of the target distance or greater (e.g., Philbeck, Behrmann, Levy, Potolicchio, & Caputy, 2004; Philbeck & Loomis, 1997; Wu et al., 2004). These data suggest effect sizes with d values (Cohen, 1988) of 0.90 and higher are reasonably expected. While traditionally these would be considered large effects, in the domain of space perception these would generally be considered moderate. Effects of these magnitudes given the distance range used in the present study (2.5–5 m) would correspond to mean differences of around 37 cm or greater (only slightly larger than the size of the average human foot). The practical significance of a slope difference can similarly be determined. Effects of similar magnitudes are expected if the difference between slopes is 0.20 or greater. If the slope differed by this amount from one condition to the next while maintaining the same overall mean, the mean absolute error across distances would be around 20 cm or greater. Power analyses show that there is an 80% chance of detecting effects of these magnitudes (within-groups, two-tailed, $\alpha = .05$) when there are 12 participants. We tested at least 12 participants per group in the all of the experiments reported. The multilevel model approach was employed in the present study because it

requires fewer assumptions and because it is the most appropriate way to compare slopes. In the text we report d values for effect sizes of based on the differences between the slopes, the means, and the SEEs because they are intuitive and familiar for readers of most disciplines. These were typically for within-participant differences; where appropriate, correction for dependence among means was employed according to Morris & DeShon (2002).

Results and Discussion

As can be seen in Figure 2, sensitivity was high and performance was very similar across viewing conditions. There was a trend toward greater sensitivity in the constant physical size condition when it was administered in the second block, $t(476) = 1.85$, $p = .07$, $d = 0.52$; sensitivity was also somewhat greater in the varied physical size condition when it was administered in the second block, though this difference did not approach statistical significance ($p = .50$). Critically, sensitivity did not differ between conditions when first-block performance was compared directly ($p = .76$). The overall mean slope was 0.90. Bias and precision were also not differentiated by the informativeness of the size cue ($ps > .19$); the means for these were -16% and 0.46 m, respectively. Thus, there was no indication that angular size contributes when angular declination is informative. This outcome is consistent with the idea that angular declination is the primary cue when floor-level targets are employed and viewing time is limited.

Experiment 2

The aim of Experiment 2 was to determine the strength of angular declination as an absolute cue² to egocentric distance on the very first trial. Much past work suggests that angular declination operates as a cue to egocentric distance -- it varies systematically with the distance to floor-level targets and thus in principle can support egocentric distance judgments. However, all existing empirical studies supporting this idea have presented multiple stimulus distances to each participant. In our own studies, Experiment 1 and those reported in Gajewski et al. (2010), we observe a strong relationship between target distance and response distance (slopes near 1) even with the most fleeting of glimpses (as brief as 9 ms). However, response sensitivity can reasonably be thought of as an index of one's ability to tell the differences between the object distances. Participants may develop a relatively coarse representation of the target's distance on the first trial, with additional trials then providing cues to relative distance, such as the angular declination of the target relative to that of the preceding trial (Gogel, 1968; 1969). At the extreme, observers could simply note that the target was higher or lower in their field of view compared to previous trials, and in this case a sensitive response would still be expected. It is unlikely that observers are completely insensitive to the egocentric distance information provided by angular declination and extract only the relative depth order of stimuli across trials without any information about scale. Even if observers did extract only the relative depth order, in the

²Bingham and his colleagues have argued that the term "absolute" should not be used in connection with distance information because it unreasonably implies an absolute level of accuracy and precision (Bingham, 1993; Bingham & Pagano, 1998). Instead, they prefer the less restrictive term "definite distance information". We use "absolute cue" here to emphasize that the cue is based on the momentary information provided by a single object, as opposed to information specifying the relationship between two or more stimuli (either simultaneously or successively presented).

absence of other cues, they still know the object is on the floor and in a room-sized environment, and thus a definite scale of some kind can reasonably be assumed (see Bingham & Pagano, 1998). Nevertheless, observers may be substantially better able to judge the differences between distances based on the differences between their angular declination values than they are able to associate a definite distance to a target based on its angular declination. Given the proposed role for angular declination in our framework, it is of interest to know how constrained the perception of distance is when observers have only one angular declination value at their disposal.

Method

Participants—Seventy-two new individuals from the George Washington University community participated in the experiment. All participants were 18 to 35 years of age, reported normal or corrected-to-normal vision, and were paid \$10/h or participated in exchange for course credit.

Stimuli & Apparatus—The stimuli and apparatus were the identical to Experiment 1, except that only four distances were employed (2.75, 3.50, 4.25, & 5.00 m), the targets were always yellow, and the targets were always of constant angular size (physical size varied systematically with distance).

Design and Procedure—Here, we compared performance on the very first trial to that on three subsequent trials with targets presented at four distances. The small number of trials and distances allowed for a complete crossing of distance and trial number, with all 24 of the possible distance orders being presented to three participants apiece. This design yielded 18 observations per distance by trial number combination and was intended to best match the statistical power of the previous experiment. Critically, the first trial was the participant's very first glimpse of the room and target. In Experiment 1, participants began with a practice glimpse to ensure they were prepared for the speed of the window. Here, we also gave them a demonstration trial through the window, but we presented them with a target letter "X" in a circle on a poster board. This ensured that they were looking in the correct region of the window when the trials began (roughly centered on the target range) and that they were prepared for the viewing duration, but in this case they did not get a preview of the room or target. Thus, the very first trial was quite literally their very first trial. On every trial the experimenter asked the participant to confirm that he or she had indeed seen the target. Three participants were replaced because they failed to see the target on the first trial. The viewing duration was 74 ms and the procedure was otherwise identical to Experiment 1.

Results and Discussion

Performance as a function of distance and trial number is displayed in Figure 3. It is important to note that because each participant can only have one distance for each trial number, each distance was presented to a different set of participants for each trial number. Thus, the fixed effect of distance on trial 1, for example, is the model fit across four sets of participants. There are several key findings. To begin, there was a reliable effect of distance on the first trial (estimated slope = 0.67), $t(138) = 5.32$, $p < .001^3$. Participants are thus getting some information about distance from the very first glimpse. There was, however, an

effect of trial number on sensitivity, $F(3,138) = 3.23, p < .05$. Sensitivity was least on the first trial, but it was only significantly diminished relative to the third trial (estimated slope = 1.18), $t(138) = 2.90, p < .01$. These differences were accompanied by a trend toward greater underestimation from one trial to the next, $F(3,209) = 2.60, p = .05$. In fact, performance on the first trial was not significantly biased (estimated error = -6% , $p = .07$). This outcome highlights the need to consider bias as well as sensitivity. Our early pilot studies with reduced cues (eye-level targets of constant angular size) showed a similar pattern across a range of viewing durations. At brief viewing durations the mean response was very close to the mean target distance but sensitivity was very low. As viewing duration increased, sensitivity increased but the underestimation bias did as well. With much longer viewing durations the bias then began to diminish.

The overall pattern of results here sharpens our understanding of the role for angular declination in performance. Performance on the first trial suggests angular declination does provide an absolute cue to egocentric distance (or more precisely, it can be used to derive a definite distance), though responses were less sensitive and somewhat less constrained (as indexed by the lower R^2 value) when only one cue value is available. That performance improves over 1 or 2 additional trials suggests that the relative angular declinations of the targets across trials does indeed provide some useful information over and above the cue value available on a single trial. It might be noted that the observed performance changes could be attributed to practice. This would be the case, for example, if participants were not attentionally prepared to get the most out of their first glimpse but were more prepared on subsequent glimpses. However, because observers were given a demonstration trial and were included only if they reported having seen the target on all trials, we think it is reasonable to conclude that the availability of multiple angular declination values multiply constrains the computation of distance across trials. Further research will be needed to elucidate a precise mechanistic account. Nevertheless, the overall pattern reinforces the idea that angular declination plays an important role when viewing time is limited and it provides a more nuanced picture of the role for angular declination in distance perception.

Experiment 3

The aim of Experiment 3 was to determine whether there are sources of information other than angular declination that can be extracted when viewing time is limited. We argue that limiting viewing time creates a situation that is not unlike a reduced-cue context wherein angular declination is the only useful cue one is able to extract. To test this hypothesis, we compared performance with an illuminated target in an otherwise dark room to that when the room was fully lit and viewing time was limited. In the illuminated target condition (Dark), viewing time was 3 seconds but viewing was monocular. In the fully lit viewing condition (Light), viewing was binocular but viewing time was only 74 ms. Thus, in the

³Because performance on each trial number is assessed with a different group of participants for each distance, the parameter estimates for the slopes by trial number are not reported as mean slopes. The reported parameter estimates differ slightly from the slopes of the mean distances by trial number because the mixed model considers the within-subject correlations in the generation of the estimates. In addition, the present approach does not afford the computing of effect sizes in a way that is consistent with the rest of the report. Given primary interest in the degree to which distance predicts performance on the very first trial, we ran simple linear regression models with each trial number considered in isolation. Reliable effects of distance were observed in all cases (all $ps < .01$) and the coefficients of determination (R^2) were .12, .34, .56, and .43, for trials 1–4, respectively.

former case observers had plenty of time to extract the available cues, though angular declination was arguably the only functional cue available. In the latter case, multiple cues were available, but observers had limited time to extract these additional cues. Because prior studies have shown no benefit of binocular viewing for floor-level targets with extended viewing durations (Bian & Andersen, 2012; Philbeck & Loomis, 1997), a benefit of binocular viewing was not expected with limited viewing time. Nevertheless, to contrast performance in the fully lit viewing condition to that in a decidedly reduced-cue context, we chose to allow binocular viewing in the Light viewing condition but not in the Dark. If performance at brief durations is supported by sources of information other than angular declination, there should be a benefit associating with viewing targets that are fully lit even with viewing time limited. Philbeck and Loomis (1997) showed very similar levels of blind walking performance when illuminated targets were viewed in a dark room versus when targets were viewed in a well-lit room, even with a viewing duration of around 10 seconds. Ooi et al. (2006) observed some bias in the judgments of the distance to illuminated targets in the dark, but performance still suggested a sensitive response to distance. Thus, our expectation was that there would be no benefit associated with the fully lit viewing condition.

Method

Participants—Twenty-eight new individuals from the George Washington University community participated in the experiment. All participants were 18 to 35 years of age, reported normal or corrected-to-normal vision, and were paid \$10/h or participated in exchange for course credit.

Stimuli and Apparatus—The illuminated targets were presented using a yellow electroluminescent panel with variably sized cutouts used to control the angular size of the target. Targets were created for 11 distances from 2.5–5.0 m such that they all subtended approximately 1.1×1.6 degrees visual angle. The physical sizes of the targets were constrained by the size of the panel, which was small relative to Experiments 1 and 2. Because they would appear smaller placed flat on the ground, we opted to place them angled so that they were perpendicular to the direction of gaze. When illuminated targets were employed, black velvet was draped to remove reflections from the floor and wall surfaces. Targets for the fully lit viewing condition were cut pieces of yellow foam identically sized and positioned. The testing environment was a different laboratory space that extended 9.5 m in depth from the participant's viewing. This space did not have bookshelves in the periphery, but was otherwise similar to that used for Experiments 1 and 2. The lighting and apparatus were also the same.

Design and Procedure—Participants completed two blocks of trials: one block with illuminated targets in a darkened room and one block with targets viewed in a fully lit room. Block order was counterbalanced with 14 participants per group. Participants wore an eye patch on their left eye in the darkened room condition. Because the experimenter and apparatus were to the right of the observer, leaving the right eye uncovered allowed the experimenter to see that the participant's eye was open prior to administering the glimpse. A demonstration trial was administered only before the fully-lit block of trials because only

these trials employed brief viewing durations. The design and procedure were otherwise identical to Experiment 1.

Results and Discussion

As can be seen in Figure 4, while there was a sensitive response to distance was observed in both viewing conditions, there was at least a modest benefit associated with the fully lit viewing condition. Sensitivity was greater in the fully lit viewing condition (slope = 0.78) than it was in the dark with illuminated targets (slope = 0.67), $F(1,556) = 4.02$, $p < .05$, $d = 0.32$, but there was no effect of block order on sensitivity nor a block-order interaction ($ps > .19$). The bias towards underestimation was marginally greater in the dark with illuminated targets (–30%) than in the full lit viewing condition (–25%), $F(1,26) = 4.09$, $p = .05$, $d = 0.39$, but there was no effect of block order on bias nor a block-order interaction ($ps > .59$). The effect of viewing condition on precision depended on block order, $F(1,26) = 12.02$, $p = .01$. When the fully lit condition was administered first, responses were more precise in the dark (SEE = 0.33 m) than the light (SEE = 0.56 m), $t(26) = 4.41$, $p < .001$, $d = 1.01$. When the illuminated target condition was administered first, there was no effect of viewing condition ($p = .63$, SEE = 0.39). These outcomes suggest that observers are in fact getting at least some additional useful information in a well-lit (but briefly-glimpsed) environment relative to a dark environment with a glowing target glimpsed for 3 sec. The sensitive response to distance in the dark suggests that angular declination is a very important source of information; however, the results are not consistent with the prediction that angular declination may be the *only* useful source of information extracted when viewing time is limited. Several possibilities exist, including visual cues to eye level, information that supports a representation of the ground surface, and information that supports a representation of the scale of the space. It is critical to note, however, that the benefit observed is really very small relative to what we observe with more extended viewing durations. Thus, the extraction of the additional useful cues continues beyond the time frame of an eye fixation.

Experiment 4

The aim of Experiment 4 was to determine the within-fixation dynamics of perceived distance to floor-level targets. The results of Experiment 3 suggest that sources of information other than angular declination are extracted when viewing time is limited, but it is unclear how quickly these other sources become available. Here, we compared performance between two viewing durations -- one that was just above the threshold for detection (Suprathreshold) and one that was just below the latency for a typical saccade (220 ms). We suggest that when the viewing is limited to a duration that just exceeds one's threshold for detection, the observer should have extracted target direction and should thus be able to make use of the angular declination cue. If so, a sensitive response to distance should be observed and performance should at least compare favorably to that observed in Experiment 3 with illuminated targets in the dark. If the additional sources of information are extracted as quickly as target direction, there should be no effect of viewing duration and performance at both durations should compare favorably to the fully lit condition of Experiment 3. If the additional sources of information accumulate over the course the time

frame of a typical eye fixation, then there should be a benefit for the longer viewing duration.

Method

Participants—Twenty-eight new individuals from the George Washington University community participated in the experiment. All participants were 18 to 35 years of age, reported normal or corrected-to-normal vision, and were paid \$10/h or participated in exchange for course credit.

Stimuli and Apparatus—Eleven yellow targets of constant angular size were employed for distances from 2.5–5 m, as in the varied physical size condition of Experiment 1. The testing environment was the same as Experiment 3.

Design and Procedure—Participants completed two blocks of trials: one block with the short, suprathreshold viewing duration and one block with the longer (220 ms) viewing duration. Block order was counterbalanced with 14 participants per group. The suprathreshold setting procedure was performed at the beginning of the session, regardless of block order, and eliminated the need for a demonstration trial. The design and procedure were otherwise the same as Experiment 1.

The suprathreshold duration was set for each individual based on a method of limits procedure for detecting objects through the shutter window. Participants reported whether or not they saw a given targets presented on the floor of the room, but for these trials a walking response was not requested. Here, to increase our certainty that the target was truly detected, we also varied the color of the target (red, yellow, or blue) and had participants report the color when they said they saw the target. The procedure entailed one descending run beginning at 105 ms and one ascending run beginning at about 7 ms. The suprathreshold duration for each participant was the duration they could detect and correctly name the color on two consecutive trials of a given duration during the ascending series. To yield a conservative threshold (one that would support detection close to 100% of the time), we employed only red and blue targets on the ascending series, which were somewhat less salient than the yellow target that would ultimately be used for the walking trials. The run speed (mean = 36 ms) was thus considered near but just above threshold for detection. The longer viewing duration was set on the basis of a pilot study we ran in which observers outfitted with an eyetracker simply directed their gaze to the targets as soon as they could be seen through the shutter window. The saccade latency in this task exceeded 220 ms on about 95% of the trials.

Results and Discussion

As can be seen in Figure 5, while a sensitive response to distance was observed in both viewing durations, there was at least a modest benefit associated with the longer viewing duration. There was no effect of viewing duration on sensitivity, $F(1,556) = 2.81, p = .09$ (long vs. short viewing duration slopes were 0.92 vs. 0.83, respectively). However, underestimation bias was greater in the fast, suprathreshold condition (–26%) than it was in with the longer viewing duration (–20%), $F(1,26) = 9.24, p < .01, d = 0.57$. There were no

reliable differences in precision between the longer viewing duration ($SEE = 0.37$ m) and the fast, suprathreshold condition ($SEE = 0.45$ m), $F(1,26) = 3.64$, $p = .06$. There were no effects of block order any of the three measures and no block-order interactions (all $ps > .13$). The pattern of results is consistent with the idea that viewing durations that afford target detection are sufficient to support the use of angular declination as a cue to distance. Performance in Experiment 4 was generally quite similar to that observed in Experiment 3. Comparing the illuminated target performance when that condition was administered first to the suprathreshold condition when it was administered first revealed no significant differences (all $ps > .24$). Comparing performance with the longer viewing duration when that condition was administered first to the 74-ms condition in Experiment 3 when it was administered first revealed no significant differences (all $ps > .08$). The results of Experiments 3 and 4 converge on the idea that angular declination is a very important cue, perhaps still the most important, though additional sources of useful information appear to be extracted even in the time frame of a typical eye fixation. Again, it is critical to note that while performance did improve across the viewing durations, it did not improve to the level we have observed with viewing durations that are more extended (e.g., 1200–5000 ms). In these cases, we observe slopes of around 1.2 and biases of around -5% .

Experiment 5

The results reported thus far suggest an important role for angular declination when viewing time is limited, though it does not appear to be the only functional cue as suggested by the prediction that angular declination is primary. Because other sources of visual information appear to be coming on-line even at the earliest stages of viewing, it will be necessary to determine the sources of information that are important and how these sources of information interact with and/or support the use of angular declination as a cue to distance. Experiment 5 takes a decidedly different tack on this question by leveraging the fact that prior experience is important. Specifically, the fact that performance at brief viewing durations improves when preceded by a block of extended viewing trials suggests that observers are extracting additional useful visual information in the first block, and that this information supports the extraction of visual information when viewing time is limited (see Gajewski et al., 2010). The availability of a visual memory representation from prior viewing episodes could support performance by exerting a top-down influence on the extraction of cues or by providing a spatial structure into which new cues may be integrated as they become available.

We acknowledge that it is notoriously difficult to definitively tease apart perceptual and post-perceptual sources of block order effects. Nevertheless, one particular type of post-perceptual processing that could play a role is motor recalibration. Participants presumably acquire a more accurate representation of distance in the first block when the viewing duration is extended than when it is brief. Their perception of distance is less biased towards underestimation and as a result they walk farther on average. This exposes them to more walking without optic flow, a situation known to result in overwalking aftereffects in blind walking tasks (e.g., Durgin et al., 2005; Philbeck et al., 2008; Rieser et al., 1995). When the brief trials are in the second block, performance may be better than when they are first because the observers have experienced more of this motor recalibration after the block of

extended viewing trials. This is not an entirely satisfying account because it suggests recalibration only matters when the percept is degraded – performance on the extended viewing trials was the same whether there were administered in the first block or the second. Another possibility is that observers develop a memory for the distribution of their responses in the first block when viewing time is extended and they adjust their responses accordingly when viewing time is subsequently limited. In either case, a more compelling test of the idea that the benefit has a visual basis is required.

Experiment 5 examined the benefit of two kinds of previews on blind walking performance with a brief viewing duration (74 ms) relative to a third no-preview condition. That is, there were three groups of participants and each walked blindly to briefly glimpsed targets, but the groups differed in terms of their prior experience. The *visual preview* group received a 15-second visual preview of the room. The framework we are developing predicts a specific role for visual information extracted from extended viewing of the task environment in the facilitation of performance with brief glimpses. There are several sources of potential useful information. Visual information that would support a more accurate representation of the ground surface would presumably be useful given the prominent role of the ground surface in theory of distance perception (e.g., Bian et al., 2005; Wu et al., 2008). In Experiment 3, a sensitive response to distance was observed in the dark, which suggests that observers can capitalize on angular declination without visual cues to eye level, though performance might be expected to improve with the availability of those cues. There is recent work suggesting that the visible horizon (the edge where the floor and back wall meet) is an important reference when the true horizon is not visible (Rand, Tarampi, Creem-Regehr, & Thompson, 2011). Finally, the underestimation bias with brief glimpses has generally been more substantial than would be predicted by the SSIP theory alone – slant errors primarily predict changes in sensitivity. In addition, participants after brief glimpse trials often remark that the room was bigger than they thought. Acquiring a sense of the room space could be important for scaling judgments of distance based on the angular declination cue. Thus, assuming any or all of these sources of information are useful but cannot be readily extracted during brief glimpse trials, a 15-second preview should prove beneficial.

The *walking preview* group participated in a directed-walking task before they completed their blind walking trials with the shutter window. In this preliminary task, the experimenter led them while they walked all eleven distances without vision. Thus, this group was given a preview of the responses required for the blind walking portion of the session but no visual input. If motor recalibration or memory for the distribution of responses can account for the facilitation provided by the extended viewing trials, there should be a benefit associated with this preview condition.

Method

Participants—Seventy-two new individuals from the George Washington University community participated in the experiment. All participants were 18 to 35 years of age, reported normal or corrected-to-normal vision, and were paid \$10/h or participated in exchange for course credit.

Stimuli and Apparatus—Eleven yellow targets of constant angular size were employed for distances from 2.5–5 m, as in the varied physical size condition of Experiment 1. The apparatus and testing environment were the same as Experiments 1 and 2.

Design and Procedure—The critical blind walking trials were preceded by 1 of 3 preview conditions, manipulated between participants. Participants in the visual preview group viewed the room freely for 15 seconds while standing at the starting position used for the experimental trials. Viewing was of the room without the target object and without the shutter window, though we requested participants to keep their head position steady. Participants in the walking preview group were lined up at the starting position in a darkened room. Using a flashlight, they were given a moment to observe their feet at the tapemark before each trial, but they never saw the room. The experimenter led them by the elbow to walk the distances that corresponded to each of the target locations (randomized order). While they were walking, the participants repeated a string of four random digits out loud to interfere with counting steps. The experimenter told them when to stop and after a brief pause asked the participant whether the walked distance was shorter or further than the previous trial. This response coupled with digit repetition was intended to encourage them to attend to their walking but without giving it a number. The no-preview group advanced directly to the block of blind walking trials. The procedure for these trials was the same Experiment 1, except participants were given a string of four random digits to repeat out loud as they were walking. This element was included primarily to further reduce the possibility that verbal coding of responses from the walking preview condition would influence subsequent blind walking performance, but was used consistently for all three groups.

Results and Discussion

As can be seen in Figure 6, preview condition did have an impact on performance. The focus of our analysis was on contrasts between the no-preview condition and each of the two preview conditions in turn. There were no effects of preview condition on sensitivity (both $ps > .18$); the mean slope was 0.94. The bias toward underestimation was greater in the no-preview condition (mean error = -16%) than in the visual-preview condition (mean error = -5%), $t(75) = 2.05$, $p < .05$, $d = 0.57$. The bias was diminished in the directed-walking preview condition (mean error = -7%), but this difference did not reach the level of statistical significance ($p = .11$). There were no effects of preview condition on precision (both $ps > .18$); the mean SEE was 0.49 m.

The results of Experiment 5 provide a clear demonstration of the fact that visual information extracted from a prior episode can facilitate performance when viewing time is limited. We presume there are useful sources of visual information that can be extracted from a 15-second preview but not from a brief glimpse, and that a memory representation built from these sources provides a structure for the integration of incoming sources of information during brief glimpse trials (an idea developed further in the General Discussion). It is important to note that the useful information extracted must be about the room space, whether it is the ground surface that is useful or the size of the room, because observers were not exposed to the targets during the preview. The results with directed-walking

preview were suggestive if not compelling. The trend suggests walking experience may help calibrate the responses made when viewing time is limited to some degree. The contributions were isolated in this study, however, so the trend does not take anything away from the fact that the visual preview was beneficial. In addition, if it is a sense of room size that is important, walking around in the space could provide this information non-visually and thereby play a role other than motor recalibration.

General Discussion

The present study employed a limited-viewing time paradigm to address fundamental questions about the time course for the extraction of distance information. Primarily, the experiments tested a provocative hypothesis about the role for angular declination in the perception of distance; namely, that angular declination is the only functional cue extracted within the time frame of a typical eye fixation when to-be-localized targets are floor-level and outside of one's immediate space. While the overall pattern of results did not support this very prediction, the experiments do call attention to the importance of angular declination and provide a particularly clear characterization of its role in distance judgments. Good sensitivity to distance was observed when relative angular size was rendered noninformative and when viewing duration was just above one's threshold for detection. Further, performance at the suprathreshold duration was well matched to that when the illuminated target was viewed in the dark, a context where angular declination was arguably the only functional cue available. Whether primary or not, we argue that the importance of angular declination hinges on the fact that it is both quickly extracted and reliable in the manipulated distance range. Angular direction of the target below eye level is informative because it changes systematically with changes in distance. Assuming angular declination can be encoded relative to an abstract representation of eye level, target direction is the only external source of information needed to capitalize on the angular declination cue when the target is thought to be resting on the ground. Given that a target's direction is at least coarsely encoded when it is detected (Adam et al., 2008; Adam et al., 1995; Tsal & Bareket, 2005), the duration of viewing required to observe a sensitive response to distance logically coincides with the duration required to detect the object. The present study confirmed that angular declination is available and can operate as a cue to distance as soon as the target is detected.

The idea that detection supports at least some degree of localization when the target can be assumed to be resting on the ground has implications that cut across domains, such as visual space perception and scene perception. A number of factors will govern the probability of detection, such as brightness of lighting and the contrast between target and surround (Barlow, 1958; Watson, 1986), and as a result these will influence perception of distance on the very first glimpse. If the room is so cluttered or the color and texture of the floor is such that the object evades detection, it will not be localized. Indeed, if our target were a letter T embedded in a field of Ls, it could take several hundred milliseconds to find, but our data suggest that once the target is found, it provides information about distance virtually instantaneously. In sum, everything we know from the vast psychophysical literatures on detection and visual search becomes immediately relevant for distance perception. Any factor that constrains the finding of targets in 2D arrays must similarly constrain the

extraction of distance. We know there are important early stages of processing that segregate objects from backgrounds in scenes (Neider & Zelinsky, 2006; Wolfe, Oliva, Horowitz, Butcher, & Bompas, 2002) and that the visual system can efficiently extract loosely bound clusters of features that serve as candidate objects for attentional selection (Wolfe & Bennett, 1997). The present data suggest these are highly relevant to the perception of target distance.

While the present study does highlight an important role for angular declination, the data refute the primary role that we expected based on our pilot work in conjunction with some existing literature (Gajewski et al., 2010; Ooi et al., 2006; Philbeck & Loomis, 1997). The present results suggest the perception of distance is dynamic even within the time frame of a single eye fixation. While the benefit is small compared to that observed with 5 seconds of viewing in our earlier study (Gajewski et al., 2010) and even relative to what we observed in here with a 15 second preview, the observer is getting something useful with a 74 or 220 ms glimpse that they are not getting with an illuminated target in the dark. The nature of the information that accumulates over the brief time scale and its role in performance is unclear. At this point we can only speculate based on our phenomenological impression of viewing the stimuli through the window at various durations. At the suprathreshold duration, the stimulus appears as a yellow bar against a featureless surround. This subjective impression is in accord with the fact that performance at this duration is not unlike that with a lit target in the dark. The most notable feature that appears to become available as the viewing duration increases to 74 ms is the high-contrast, low-spatial-frequency junction between the dark floor and the white walls. Observers could use linear perspective provided by this junction to develop at least a coarse representation of the size and shape of the space, and we articulate a role for this kind information in a framework discussed below. However, at this stage, a visible horizon is also available and this has been shown to influence distance judgments (Rand et al., 2011). When the duration is extended further to 220 ms, the additional viewing time does seem to afford a better sense of the ground plane, though this sense seems more a function of low-spatial-frequency changes in the lighting across the surface than high-spatial-frequency elements of the surface (carpet grain). It is unclear the degree to which this information would support a more accurate representation of surface slant. Additional work will be needed to distinguish between these possibilities.

A Framework for the Dynamic Perception of Distance

Performance even at very brief viewing durations indicates a high degree of sensitivity to distance, though it is marked by a bias towards underestimation. This generates a glass half empty, glass half full kind of story. On the one hand, our data suggest that a very large portion of the job can be done extraordinarily quickly. On the other hand, there is important information that accumulates within the time frame of an eye fixation and beyond. This suggests that the perception of distance is dynamic, even in static scenes viewed with head position stable.

The dynamic framework leads one to ask at least three fundamental questions. First, what useful sources of information are observers failing to get when viewing time is limited? The leading candidate based on existing theory is information about the nearby ground plane.

When other cues are unavailable or unreliable, angular declination coupled with the intrinsic ground plane support a sensitive response to distance. Performance is thought to be improved by a more accurate representation of the ground surface, which presumably requires attention to the immediate ground plane where distance cues are generally more reliable (He et al., 2004). The increased sensitivity we have observed with longer durations is consistent with this idea because extended viewing does seem to benefit the farther distances more specifically. However, with brief viewing durations we do also see underestimation more generally. We suggest that a benefit of extended viewing is that it supports a more accurate perception of the scale of the space and/or of the room itself. A better representation of the ground surface would certainly be expected to enhance one's representation of the size and shape of the room. A better representation of the room could then influence performance by providing a framework for integrating other cues.

The second question, then, is: how are the additional sources of information integrated? The data reported here and previously by Gajewski et al. (2010) strongly implicate a role for a memory representation of some kind. Performance on limited-viewing trials was markedly improved by a 15 second preview of the room, suggesting that observers have the ability to draw support from prior viewing episodes. Current models of scene perception suggest a scene representation is built up over a sequence of fixations (e.g., Hollingworth & Henderson, 2002). Relatively abstract, short-term visual memory representations are available for the 2–3 most recently fixated objects in a scene (Hollingworth, 2004); information about objects fixated earlier during scene viewing must be retrieved from long-term memory (Hollingworth, 2003; 2005). A role for memory even within the time frame of a few fixations suggests that the on-line benefit of extended viewing and the benefit of extended viewing on subsequent brief-glimpse trials ought to have similar if not identical bases. We presume that the information sources that support the benefit of extended viewing also support the facilitation during subsequent brief glimpse trials (i.e., cues to the ground slant and room scale). Above, we suggested that a memory representation built from the prior views can be used as structure for integrating the sources of information that become available during the glimpse. By this view, an enhanced memory representation of the ground plane and of the room space can be used as a frame of reference for establishing the target object's location in distance as provided by angular declination.

A role for a memory representation has intuitive appeal, too, particularly with blind walking, because the responses are made after vision has terminated and must therefore be controlled by a memory representation. It is often assumed that judged distance based on the memory representation reflects the initial visually perceived distance, with virtually no bias accrued in the transformation from perceived distance to memory (Loomis & Philbeck, 2008). Loomis and colleagues (Loomis, Lippa, Klatzky, & Golledge, 2002) have posited a memory representation termed a *spatial image* that coincides with one's percept of the distal object's location and persists when vision is terminated. This representation is thought to control the blind walking response, and it is thought to be the representation that is updated as one moves about in the world. Based on evidence that linguistic and visual input can modify a spatial image similarly (Avraamides, Loomis, Klatzky, & Golledge, 2004; Loomis et al., 2002; Loomis, Klatzky, Avraamides, Lippa, & Golledge, 2007), it has been suggested that

the spatial image may be an amodal representation and one that could fairly be considered a component of a situation model. A situation model is a representation of the current state of an evolving situation as it is described in a narrative (for review, see Zwaan & Radvansky, 1998). It captures spatial information, including the locations of objects relative to a protagonist, and it is thought to apply to observers in real-world settings (Magliano, Radvansky, & Copeland, 2007). Clearly, additional empirical work is required, but we posit an important role for a representation of this kind in the dynamic perception of target distance.

A benefit of the present framework is that it can accommodate what would ordinarily be termed perceptual and post-perceptual accounts for the benefit of prior visual experience. In the former case, the availability of the structural representation at the moment of the glimpse affords an immediate grounding of the object's location in distance and therefore supports a more accurate percept. In the latter case, a biased perception of target distance may arise on the basis of the brief glimpse with the bias corrected by knowledge of the room scale in much the same way that the spatial image is updated with changes in the observer's position or based on linguistic input. The visual percept is fleeting and not maintained across eye movements (Irwin, 1991; 1992; Irwin, Yantis, & Jonides, 1983; McConkie & Zola, 1979; O'Regan & Lévy-Schoen, 1983; Rayner & Pollatsek, 1983), and as a result the spatial image must be the phenomenological basis for perceived distance when vision is terminated. Because the correction could be accomplished implicitly or explicitly, there may be little basis for distinguishing between perceptual and post-perceptual accounts for the benefit of prior visual experience. In either case, performance suggests that useful information about distance is extracted and facilitative, and, perhaps of greatest ecological importance, it can be used to control appropriate spatial actions.

Future Directions

There are many avenues for future research suggested by the integrated framework we are proposing. Normal viewing often requires localization of objects that are more extended above the ground plane (e.g., tables and chairs) or are supported by surfaces that are substantially above the ground plane (e.g., toasters and blenders resting on counter tops). There is evidence that the angular declinations of the points of ground contact would play a role in localizing such objects (Bian & Andersen, 2010; Meng & Sedgwick, 2001); however, the impact of these object properties on the time course for the extraction of distance is not known. Our framework strives to incorporate what is known about eye movement behavior, though much work is needed to flesh out the relative contributions of covert and overt attentional selection. Finally, we have suggested that object detection is all that is needed for one to capitalize on the angular declination cue. In addition to stimulus properties (e.g., brightness and contrast), the present theory thus suggests that characteristics of the observer are important to consider, such as changes in perceptual processing speed attributed to cognitive aging. These are all topics of current investigation.

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Figure 1.

The distance to a target object resting on the ground is trigonometrically related to angular declination below eye level but depends on the perception and/or representation of surface slant.

Figure 2.

Mean walked distance to floor-level targets as a function of target distance and the physical size of object in Experiment 1. The targets were of constant size or were varied to hold angular size constant. Size was blocked such that either the varied-size trials were administered first (left) or the constant-size trials were administered first (right). Figures include best-fitting regression lines through the average data. Depicted are the means with standard error bars and best-fitting lines for the fixed effects derived from the model.

Figure 3.

Mean walked distance to floor-level targets as a function of target distance and trial number in Experiment 2. The viewing duration was 74 ms. Figure includes best-fitting regression lines through the average data. Depicted are the means with standard error bars and best-fitting lines for the fixed effects derived from the model.

Figure 4.

Mean walked distance to floor-level targets as a function of target distance and the viewing condition in Experiment 3. The illuminated targets were monocularly viewed in a darkened room (Dark) for 3 seconds and standard targets were viewed binocularly in a well lit room (Light) for 74 ms. Viewing condition was blocked such that either the Dark trials were administered first (left) or the Light trials were administered first (right). Depicted are the means with standard error bars and best-fitting lines for the fixed effects derived from the model.

Figure 5.

Mean walked distance to floor-level targets as a function of target distance and the viewing condition in Experiment 4. Standard targets were at each participant's brief (Suprathreshold) and long (220 ms) viewing duration. Viewing duration was blocked such that either the Suprathreshold trials were administered first (left) or the 220-ms trials were administered first (right). Depicted are the means with standard error bars and best-fitting lines for the fixed effects derived from the model.

Figure 6.

Mean walked distance to floor-level targets as a function of target distance in Experiment 5. A block of blind walking trials with a viewing duration of 74 ms was preceded by a 15-second visual preview of the room (Visual Preview), a set of directed-walking trials (Walking Preview), or no-preview control (None). Depicted are the means with standard error bars and best-fitting lines for the fixed effects derived from the model.