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Abstract

The angular declination of a target with respect to eye level is known to be an important cue to egocentric distance when objects are viewed or can be assumed to be resting on the ground. When targets are fixated, angular declination and the direction of the gaze with respect to eye level have the same objective value. However, any situation that limits the time available to shift gaze could leave to-be-localized objects outside the fovea, and, in these cases, the objective values would differ. Nevertheless, angular declination and gaze declination are often conflated, and the role for retinal eccentricity in egocentric distance judgments is unknown. We report two experiments demonstrating that gaze declination is sufficient to support judgments of distance, even when extraretinal signals are all that are provided by the stimulus and task environment. Additional experiments showed no accuracy costs for extrafoveally viewed targets and no systematic impact of foveal or peripheral biases, although a drop in precision was observed for the most retinally eccentric targets. The results demonstrate the remarkable utility of target direction, relative to eye level, for judging distance (signaled by angular declination and/or gaze declination) and are consonant with the idea that detection of the target is sufficient to capitalize on the angular declination of floor-level targets (regardless of the direction of gaze).

Keywords

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Gaze Direction and the Extraction of Egocentric Distance

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Abstract

The angular declination of a target with respect to eye level is known to be an important cue to egocentric distance when objects are viewed or can be assumed to be resting on the ground. When targets are fixated, angular declination and the direction of the gaze with respect to eye level have the same objective value. However, any situation that limits the time available to shift gaze could leave to-be-localized objects outside the fovea, and, in these cases, the objective values would differ. Nevertheless, angular declination and gaze declination are often conflated, and the role for retinal eccentricity in egocentric distance judgments is unknown. We report two experiments demonstrating that gaze declination is sufficient to support judgments of distance, even when extraretinal signals are all that are provided by the stimulus and task environment. Additional experiments showed no accuracy costs for extrafoveally-viewed targets and no systematic impact of foveal or peripheral biases, though a drop in precision was observed for the most retinally-eccentric targets. The results demonstrate the remarkable utility of target direction relative to eye level for judging distance (signaled by angular declination and/or gaze declination), and are consonant with the idea that detection of the target is sufficient to capitalize on the angular declination of floor-level targets (regardless of the direction of gaze).

KEY WORDS: distance perception, angular declination, gaze direction, blind walking

Gaze Direction and the Extraction of Egocentric Distance

A fundamental aim in the study of visual space perception is the identification of the sources of information that support judgments of distance from oneself to objects in the world. *Angular declination*, or the angular direction of the target with respect to eye level (Ooi, Wu, & He, 2001), is a reliable source of information about distance in the intermediate distance-range (Cutting & Vishton, 1995). Accordingly, it plays an important role in several accounts for the perception of distance, particularly when objects can be seen or assumed to be resting on the ground (e.g., Durgin & Li, 2011; Ooi, Wu, & He, 2006; Sedgwick, 1983; Rand, Tarampi, Creem-Regehr, & Thompson, 2011; Wu, Ooi, & He, 2004). Recent studies from our laboratory have further shown that the egocentric distance can be extracted quite quickly when angular declination is informative (Gajewski, Philbeck, Pothier, & Chichka, 2010). Because of its reliability and speed of extraction, we have proposed a dynamic framework wherein angular declination is the primary functional cue when viewing time is limited to the timeframe of a typical eye fixation (Gajewski, Philbeck, Wirtz, & Chichka, 2014). Although additional sources of useful information can be extracted when viewing time is extended, these presumably influence the computation of distance from angular declination by supporting a more accurate representation of the ground surface (He, Wu, Ooi, Yarbrough, & Wu, 2004; Wu, He, & Ooi, 2008; Wu et al., 2004) and/or by providing a more elaborate representation of the scale of the contextual space (Gajewski, Wallin, & Philbeck, 2014). The weight of evidence suggests that angular declination is important at all timeframes when objects are resting on a level ground surface, but that this directional cue most completely drives localization performance when viewing time is limited. Because objects that require localization are often fixated, the angular declination *of the target* and the direction of gaze *to the target* typically provide the same angular value. Is the direction of gaze alone sufficient to support a judgment of distance? Real-world situations, such as navigating busy city sidewalks, arguably limit the time available to shift gaze toward objects that require localization. Are there systematic errors associated with judging the distance to objects that are not directly fixated?

The present study clarified the strong role for directional information in the distal localization of objects by determining the role for gaze direction in distance judgments. To begin, consider Figure 1, which depicts a situation where the observer is fixating a point on the ground in front of the target object. Regardless of the direction of gaze, angular declination is defined as the direction of the target with respect to a horizontal projection of eye level. As indicated by the figure, several pieces of information are needed to use target direction as a basis for judging distance. The target's direction is required along with a representation of the horizontal projection of eye level, and, even if the ground plane is level, a representation of the surface slant is required to define the target direction's point of intersection with the ground plane. Finally, because it is reasonable to assume that target direction is at least initially coded within a gaze-centered reference frame, the computation of distance from angular declination requires a representation of gaze direction (which itself must be based on the posture of the head). Of these, we have argued that target direction is the only source of information that must be extracted from the visual stimulus to support a judgment of distance based on angular declination (Gajewski et al., 2014). This conclusion is supported by the fact that response sensitivity is good (the slope relating response distance to target distance approaches one) even when illuminated targets on the floor are viewed in the dark (see also Philbeck & Loomis, 1997). A representation of eye level can certainly be derived from visual cues (e.g., Matin & Fox, 1989; Matin & Li, 1994; Wu, He, & Ooi, 2007) and there is evidence that visual cues to eye level are indeed used to judge distance (Grutzmacher, Andre, & Owens, 1997; Ooi et al., 2001). However, eye-level can be judged with relatively small constant error (about 2-3°) even when luminous targets are viewed in the dark (e.g., Stoper & Cohen, 1986), presumably because a stored representation of eye level can be built up from one's prior visual experience, body-based information, and gravity.[1] Similarly, distance judgments are more accurate when the ground is visible (e.g., Wu et al., 2004), but the computation of distance can be based on a stored representation of the ground plane when it is not visible (Ooi et al., 2006) or when the viewing duration limits the availability of cues needed to represent the ground accurately. Thus, target direction is the only visual stimulus value needed to compute distance from angular declination when the target can be assumed to be resting on a level ground plane.

<< Insert Figure 1 About Here >>

The first aim of the present article was to determine whether gaze declination, specifically, could support judgments of distance to ground-level targets. When targets are fixated, the direction of the target and the direction of gaze coincide, and, as a result, the two are readily conflated. In fact, Li and Durgin (2009; 2012; Durgin & Li, 2011) use the term *gaze declination* instead of angular declination, which is fitting when, as in their studies, targets are always fixated (see also Wallach & O'Leary, 1982). Indeed, the information sources available to support the determination of angular declination and gaze declination do typically overlap considerably. Because target direction is presumably encoded in a gaze-centered reference frame, the computation of angular declination must require a value for the direction of gaze.

[1] Based on these findings, we assume angular declination can be determined with respect to a nonvisual representation of the direction. Alternatively, in reduced-cue settings, target direction may be used more heuristically (i.e., higher indicates farther away). However, this would predict a strong reliance on direction as a relative cue. We have shown observers can sensitively judge the distance to floor-level targets even on the first trial (Gajewski et al., 2014).

Additionally, although the coding of gaze direction is thought to be supported by extraretinal signals (e.g., Bridgeman & Stark, 1991; Gauthier, Nommay, & Vercher, 1990; Skavensky, Haddad, & Steinman, 1972), the target object provides a retinal signal to its direction as well as to the direction of gaze. A specific ability for gaze declination to support distance judgments is of interest because it would compellingly add to the accumulating evidence in favor of the strong role for directional information in the distal localization of ground-level objects.

The second aim was to determine whether a benefit is derived from having the direction of gaze aligned with the direction of the target. Are fixated targets localized more accurately than those that are viewed extrafoveally? If gaze declination is itself a useful source of information about distance, it would be tempting to expect a benefit for fixated targets because, in that case, angular declination and gaze declination would each be similarly informative. However, we presume that the computation of angular declination always requires a value for the direction of gaze, whether the target is fixated or not. As a result, angular declination and gaze declination are best not thought of as distinct sources of information that are weighted and combined individually (we return to this issue in the General Discussion). Nevertheless, there are additional reasons one might expect an advantage for fixated targets when the viewing duration does not afford an eye movement. To begin, attention is typically coupled with the point of regard (e.g., Henderson, 1992; Hoffman & Subramaniam, 1995; Shepherd, Findlay, & Hockey, 1986). If the target appears outside the focus of attention, the probability of detection would certainly be expected to diminish. However, distance judgments for targets viewed in a fully-lit room with durations near each individual's threshold for detection (< 36 ms) demonstrated a sensitivity to distance comparable to those when illuminated targets were viewed in the dark with 3 seconds of viewing (Gajewski et al., 2014). In the former case, direction of gaze was uncontrolled and there was not sufficient time to execute an eye movement. In the latter case, the availability of cues other than angular declination was substantially diminished, but observers had enough time to direct gaze to the object. This outcome suggests that target detection is sufficient to support use of the angular declination cue, and therefore performance should not be expected to differ between fixated and peripheral targets if each are reliably detected.

On the other hand, performance in 2D task environments does suggest that objects are directionally localized more precisely (responses are more tightly clustered around the location of the target) when the observer's attention and/or direction of gaze is shifted toward the object (e.g., Adam, Ketelaars, Kingma, & Hoek; 1993; Adam, Paas, Ekering, & van Loon; 1995; Prinzmetal, Amiri, Allen, & Edwards, 1998; Tsal & Bareket, 1999; 2005; Uddin, 2006). Similarly, several investigations using 2D task environments suggest that there are biases that occur in the directional localization of peripherally viewed targets (e.g., Adam, Davelaar, van der Gou, & Willems, 2008; Bock, 1993; Fortenbaugh, Sanghvi, Silver, & Robertson, 2012). As previously indicated, distance judgments to illuminated targets viewed monocularly in the dark suggest that target direction is the only stimulus property that requires extraction for observers to be able to capitalize on the informativeness of angular declination. Because target direction is sufficient to support the use of this angular declination as a cue to distance for ground-level targets, any factor that governs the extraction of direction in 2D ought to similarly factor into the extraction of distance. If the direction of gaze and/or attention influence directional localization beyond their influence on the detection of targets when viewing time is limited, these would be expected to influence performance in the distance estimation task as well.

Experiment 1

Experiment 1 examined the roles for angular declination and gaze declination within the context of a limited-viewing-time paradigm. Brief viewing durations were considered important here because they exclude the possibility of an eye movement during stimulus presentation and provide a more controlled experimental focus on the directional signals arising from angular declination and gaze declination. In this 3D task setting, participants view targets through a shutter window that can provide brief (< 220 ms) glimpses of a real-world room environment and follow it up with a masking stimulus (see Pothier, Philbeck, Chichka, & Gajewski, 2009). Judgments of distance are then made by walking to the remembered location of the target with eyes closed (i.e., blind walking). Here, we compared performance between conditions that differed in terms of their visual cues to the angular direction of the target. A fixation point was always used to align the participant's gaze with the direction of the target in the shutter window before the viewing period was initiated (described below). As a result, gaze declination and angular declination always had the same objective value.

There were two viewing conditions. In the *Fixated-Target* condition, individually-set, near-threshold viewing durations were employed. Because the targets were always fixated, these durations were exceedingly brief. In fact, if the observer's gaze was not aligned with the target at the moment of the glimpse, the probability of detecting the target would have been markedly reduced. It is important to note that the speed of the window was expected to substantially reduce the observer's ability to extract additional sources of information (e.g., the texture gradient of the ground plane or other features of the room space), thereby providing a tighter focus on the angular declination cue. In the *No-Target* condition, the shutter window never actually opened. Participants were informed that viewing durations would at times be below their threshold for detection and that they should provide their best distance estimates even when did not see the target. Specifically, they were instructed to walk to the imagined location based on the knowledge that they were looking directly at an object placed on the floor even if the window opened and closed so quickly that they failed to detect the target.

In both conditions, the direction of gaze was aligned with the direction of the target so that gaze declination would be available as a source of information about target distance. In the Fixated-Target condition, the target was reliably detected, and so the angular declination of the target was available in addition to gaze declination. In the No-Target condition, the target itself was never seen, and so performance could only be based on gaze declination. It is important to note that gaze declination is one's representation of the direction of gaze with respect to the horizontal projection of eye level, and that in the present context this representation is likely supported by retinal as well as extraretinal signals. For example, features of the window, such as the frame, would occupy at least somewhat different regions of the visual field depending on the direction of gaze. Based on our previous work (Gajewski et al., 2010; Gajewski et al., 2014), the combined availability of angular declination and gaze declination in the Fixated-Target condition was expected to support a highly sensitive response (slope near 1) with some bias towards underestimation. If the target's angular declination is a crucial source of information, there should be an advantage for this condition (greater response sensitivity and/or less underestimation bias). In fact, gaze declination might not even be a source of information that observers use. In this case, sensitivity would be reduced to zero in the No-Target condition. However, if gaze declination is itself a useful source of information about target distance, then a sensitive response to distance would be observed even in the No-Target condition. In fact, if gaze declination is a powerful source of information, performance could be similar across the two conditions.

<< Insert Figure 2 About Here >>

Method.

Participants. Fourteen individuals from the George Washington University community participated in the experiment. All participants were 18 to 24 years of age, reported normal or corrected-to-normal vision, and were paid $10/hr or participated in exchange for course credit.

Stimuli. The targets were sheets of yellow foam laid flat on the ground and salient against bluish gray carpeting. They were created for 11 distances from 2.5-5.0 m with physical size varying with distance to hold angular size constant. These were cut to appear as horizontal bars and subtended approximately 0.67° x 4.94° visual angle. The testing environment was a laboratory space that extended 9.5 m in depth from the participant's viewing position. The visible space was mostly empty with lighting that was bright yet diffuse. A more cluttered environment would certainly add potentially useful sources of depth information. However, our specific focus here was on the factors that govern the extraction and use of angular declination.

Apparatus. A schematic of the apparatus is displayed in Figure 2. A liquid crystal shutter window (LC-Tec, Borlänge, Sweden) was used to control the duration of viewing of target objects placed within a real-world room scene. The shutter window could be made to transition from a semi-opaque (i.e., 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 multi-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). The field of view measured from the midline subtended approximately 65º x 60º (horizontal x 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 semi-opaque (closed) state.

To monitor and control the direction of gaze during each glimpse, participants wore a head mounted eyetracker (ISCAN ETL-500). The eyetracker employs two small video cameras, each mounted to a secure but lightweight headband. One camera captures a video image of the real-world scene; a second camera captures a video image of the eye as reflected from a small beamsplitter. The cameras were tethered to CPU with software that extracted gaze direction from the eye video and presented it as a small cross hair within the scene video, thus presenting to the experimenter the observer's point of regard in real time. The scene camera is positioned approximately 6 cm above the observer's eye level, which does create some parallax relative to the observer's view. We correct for this during the calibration procedure.

Design and Procedure. The experiment used a 2 (viewing condition) x 11 (distance) design with viewing condition (Fixated-Target and No-Target) and distance (2.5-5 m) manipulated within-participants and with order randomized. The viewing duration for the Fixated-Target condition was individually set based on a preliminary threshold setting procedure. Participants were presented targets with a sequence of trials descending from 100 ms and then ascending from 7 ms with the target fixated (see below). For purpose of threshold setting, yellow, red, and blue targets were employed. Participants indicated whether they saw the target and if so identified the color. Targets for these preliminary trials were presented at varied distances, but distance estimates were not requested. As with experimental trials, stimulus presentation was followed by the mask. Because our aim was only to employ a very fast duration that would still reliably support target detection (i.e., we were not interested in measuring a threshold per se), we used the fastest speed the target was detected in both runs (the mean duration was 14 ms). The viewing duration for the No-Target condition was 0 ms – in this case, the shutter window never really opened. Participants understood the viewing duration would at times be so brief that they would not even see the target.

Great care was taken to ensure that participants only saw the testing environment through the shutter window and during experimental trials. The experimenter provided instructions outside the laboratory and then ushered participants into the room with their eyes closed. The participants were set up with the eye tracker and it was calibrated with their backs to the stimulus environment. 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. At the beginning of each trial, the experimenter instructed the participants to open their eyes and aimed a laser pointer at the screen to the left so that the image of the red laser dot reflected into the beamsplitter (see Figure 2). It was adjusted to coincide with the direction of the target in the shutter window. Because the scene camera on the eyetracker is sensitive to infrared light that transmits even through the semi-opaque (closed) window, a faint image of the target could be seen by the experimenter in the video monitor. The experimenter used this image to align the red laser with the target location. The participants were instructed to direct their eyes to the location of the red dot. It should be noted that the virtual location of this dot was approximately 2 m in front of the shutter window (see Figure 2, right). We presume that providing the fixation dot prompted observers to converge at that location, which means the oculomotor posture of the eyes was never aligned with the target object's location at the moment of the glimpse. The stimulus cues to accommodation and convergence (monocular and binocular parallax, respectively) are nevertheless available during visual presentation (Foley, 1978), though these are relatively weak beyond 2-3 m (Cutting & Vishton, 1995) and thus were presumably not useful in our context.

The experimenter watched the scene monitor to confirm gaze was appropriately directed and then terminated the laser about 1 second before announcing 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. For the No-Target trials, the mask image was projected immediately. After the mask, the experimenter asked participants whether they saw the target. If they reported seeing the target, they were asked to estimate the distance using the blind walking response. If they reported not seeing the object, they were asked to walk to the imagined location based on the assumption that they were indeed looking right at the object at the time of the glimpse. The experimenter pushed the apparatus to the side, and participants walked in a darkened room with their eyes closed. Participants wore earplugs or hearing protectors to minimize spatial sound cues. Occasionally, participants failed to see the target in the Fixated-Target condition. When this occurred, the participants walked to the imagined location but the data were discarded and the trial was re-run later in the session.

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 examined the fixed effects of viewing condition and distance in a mixed model with intercepts and distance included as random factors. Parameter estimates for the fixed effects of distance and interactions with distance do generally correspond to the mean of the slopes and the slope differences between viewing conditions. This approach is well suited to analyses with a continuous independent variable and repeated measurements across observers. *Bias* represents the overall tendency toward under- or over-estimation. Tests were performed on the mean responses across target distances. In the text, we report bias as the percent signed errors averaged across the all target 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 standard deviations of each participant's judgments on a given experimental condition (normalized by target distance), here we employed a fine-grained set of distances without repetition as opposed to a small set of target 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. We have previously reported power analyses based on extant data and our own pilot studies (see Gajewski et al., 2014). These analyses suggested that differences between mean values of 10% of the target distance or greater are relatively common and that effect sizes with *d* values (Cohen, 1988) of 0.90 and higher are reasonably expected. 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. Effects of this magnitude are expected if the difference between slopes is 0.20 or greater. Sensitivity to distance has been shown to be high (slopes near 1) when targets are reliably detected, as in the Fixated-Target condition. When angular declination is not informative, as it is with eye-level targets, sensitivity is nearly lost (slopes approach 0; see Gajewski et al., 2010). If gaze declination is not itself useful for judging distance, sensitivity in the No-Target condition should be substantially diminished and the expected effect size would be relatively large. We tested at least 12 participants per group in all of the experiments reported. The multilevel model approach was used 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 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 used according to Morris and DeShon (2002).

<< Insert Figure 3 About Here >>

Results and Discussion

As can be seen in Figure 3, accuracy was not diminished in the No-Target condition. Sensitivity was actually greater in the No-Target condition than it was in the Fixated-Target condition, $F(1,278) = 9.24$, $p = .002$, $d = 0.72$. (Parameter estimates for Experiment 1 and all subsequent experiments are presented in Table 1.) Additionally, underestimation bias was greater in the No-Target condition than it was in the Fixated-Target condition, $F(1,13) = 7.80$, $p = .015$, $d = 0.75$. Precision did not differ between conditions, $F(1,13) = 2.58$, $p = .132$. The results of Experiment 1 clearly indicate that observers can make use of the directional cue to distance whether they see the actual target or not. Here, gaze declination was sufficient to support performance when the target could be assumed to be resting on the ground. It should be noted, though, that by controlling the direction of gaze with a fixation point, we provided a visual signal to target direction in advance of the glimpse. As a result, alternate interpretations for these data are possible. We are suggesting that the location of the fixation dot in the window at most served as a visual signal to gaze direction. In this case, the dot was of no additional use once extinguished. Alternatively, because the angular declination of the dot and the angular declination of the target are the same (see Figure 2, right), observers could have computed distance from the fixation dot in advance of the trial. Similarly, participants could have encoded the direction of the fixation dot into memory and used that as a basis for judging distance when the actual target was not seen. We view each of these possibilities as striking demonstrations of the potency of direction as a source of information about distance when coupled with the assumption that the object is on the ground. In the No-Target condition, neither the target nor the visual context could be seen, yet the angular declination of the fixation dot and/or the declination of gaze were at least as useful. In Experiment 2, an eyetracker was used to direct the participant's gaze to an object in the dark, with all vision obscured. In this Gaze-Direction-Only condition, participants could judge distance based solely on the declination of gaze, with gaze direction informed only by extraretinal signals.

Experiment 2

Method.

Participants. Fourteen new individuals from the George Washington University community participated in the experiment. All participants were 18 to 24 years of age, reported normal or corrected-to-normal vision, and were paid $10/hr or participated in exchange for course credit.

Stimuli & Apparatus. The set of distances and the apparatus were the same as Experiment 1, except that the shutter window was removed from the sliding stage and replaced with a cardboard box that surrounded the observer's face and obstructed their view. A small hole was cut in the box so that the scene camera on the eyetracker could capture an image of the room. The hole was approximately 1 square inch and positioned about 6 cm above eye level. The testing environment was the same laboratory employed in Experiment 1.

Design and Procedure. Because Experiment 2 was conducted as a supplementary condition for Experiment 1, distance was the only variable here. All participants judged the distance via blind walking with distance manipulated within-participants and with order randomized. The introductory procedure was the same as Experiment 1. That is, participants were similarly prevented from seeing the room and the procedure for setting up and calibrating the eyetracker was the same. In the experimental trials, participants never saw the room or the target. At the beginning of each trial, the participants were asked to open their eyes. The room was dark and a co-experimenter had a flashlight placed upside-down right on top of the target. This provided a dim source of light that was easily visible to the experimenter in the eyetracker's scene camera monitor, but was invisible to participants, whose vision of the darkened room was occluded by the box. The experimenter used this image in the monitor to guide the participants' gaze verbally. That is, the experimenter called out, "up, down, left, or right" until the point of regard indicated by eyetracker coincided with the dim flashlight image. In this way, the participants' gaze direction was manipulated without providing any vision of the environment. Once the target was "fixated", the experimenter called out "lock" to inform participants that they were at that time looking directly at the target. With gaze locked, the experimenter counted down 5 seconds out loud and then asked the participants to close their eyes and give their best estimate of the target distance based on the knowledge that they were looking directly at the object placed on the floor. As in Experiment 1, the apparatus was pushed out of the way and the participant walked in the dark with his or her eyes closed.

<< Insert Figure 4 About Here >>

Results and Discussion

As can be seen in Figure 4, there was a significant effect of distance, $F(1,13) = 6.53$, $p < .001$, and sensitivity compared favorably to that observed in Experiment 1 (see Table 1). Responses were statistically unbiased in Experiment 2: the mean error did not significantly differ from 0, $t(13) = 0.39$, $p = .70$. Accuracy clearly suggests that gaze declination informed only by extraretinal signals can be used as a source of information about distance, at least when the target can be assumed to be resting on the ground. However, performance was less precise here than it was in either of the two conditions of Experiment 1 (both *p*s < .001, see Table 1). The drop in precision in Experiment 2 is not surprising because performance in gaze-directed pointing tasks does suggest that the visual signal contributes to a more precise representation of gaze direction (e.g., Admiraal, Keijsers, & Gielen, 2003; Blouin, Amade, Vercher, Teasdale, & Gauthier, 2002; Bridgman & Stark, 1991). The high level of accuracy is striking. Intuitively, one would expect a less sensitive response and possibly a greater bias towards underestimation, given that fewer sources of information were available. How might we account for this aspect of our findings?

We have previously suggested that underestimation could at least partially be attributed to a lack of information about the scale of the space. When observers are afforded extended views of the target in its context, or if they are provided a visual preview of the room in advance, the bias towards underestimation is diminished (Gajewski et al., 2010; Gajewski et al., 2014), Presumably, a smaller space is assumed when the observer does not have the ability to visually extract a more elaborate representation of the target's context. However, because participants were if anything less familiar with the visual context in Experiment 2, this account would predict a greater bias towards underestimation in the Gaze-Direction-Only condition. Ongoing studies from our laboratory do suggest the possibility that assumptions about the scale of the space may indeed play a role in performance. We have found that distance judgments in indoor and outdoor environments differ even when the cues are similarly reduced by viewing targets through an aperture. This suggests the possibility that angular declination is weighted according to an assumed spatial scale because in both cases the actual context was visually obscured. Any account for the unbiased judgments in Experiment 2 would be speculative without further study, but one possibility is that the complete absence of visual information led the observers to respond more directly on the basis of the extraretinal signals and to be less influenced by assumptions about scale. Regardless, the important and critical conclusion to be derived from the experiment is not at all ambiguous: target direction is a potent cue to distance along the ground plane and observers can capitalize on this source of information in the complete absence of visual cues.

Experiment 3

Whereas Experiments 1 and 2 illustrate the utility of gaze declination as a source of information about distance, Experiment 3 addressed the question of whether there is a benefit associated with having the direction of gaze aligned with the target. Here, we compared blind walking performance when the target was fixated to that when the point of regard was above or below the object. Philbeck (2000) reported a study suggesting that foveated and extrafoveated targets are equally well localized. The aim of that study was to test varied accounts for response-dependent judgments of spatial extent (i.e., exocentric distance), though the task entailed blind walking only to one of two floor-level targets (i.e., the required judgment was egocentric).

However, recent findings suggest important aspects of the design likely limited the strength of conclusions drawn from that study. Gajewski et al. (2010) demonstrated a benefit associated not only with extended viewing but also of prior visual experience. Performance was better with brief (113 ms) viewing durations than when viewing time was extended (5000 ms), but only when the block of brief-viewing trials was administered first. Although we argue that angular declination drives performance when viewing time is limited, additional useful sources of information can be extracted when viewing time is more extended. Critically, these sources can be maintained in memory to enhance performance on subsequent trials when viewing time is limited. Philbeck (2000) employed 150 and 5000 ms viewing durations in blocks with block order counterbalanced, but the study was not designed to make strong tests on possible effects of block order. Performance in that study depended neither on viewing duration nor the point of regard when viewing time was limited. The fact that there was no effect of viewing duration suggests that observers might have been able to draw from prior experience to support their judgments of distance not only when viewing time was limited but perhaps also when the targets were not fixated.

The question addressed in Experiment 3 is strongly motivated by the primacy of angular declination and the idea that any factor that influences the extraction of direction ought to similarly influence the extraction of distance, particularly when the viewing duration does not afford the extraction of additional useful cues. The directional localization literature does suggest the existence of biases that could manifest as performance differences given the important role for directional information in distal localization. Investigators have reported data suggesting a peripheral bias in 2D localization tasks (e.g., Bock, 1993; Temme, Maino, & Noell, 1985). A bias of this kind would predict overestimation when the point of regard is below the target and underestimation when the point of regard is above the target. However, there are also investigators that have reported a foveal bias (e.g., Adam et al., 2008; Tsal & Bareket, 2005; Uddin, Kawabe, & Nakamizo, 2005). Biases of these kinds would predict underestimation when the point of regard is below the target and overestimation when the point of regard is above the target. Fortenbaugh et al. (2012) suggest that the latter should be expected when the stimulus configuration includes a border, as is typically the case with experimental paradigms run on computer monitors. Because our shutter window does provide a border, a bias, if any, would be expected towards the fovea. In addition to potential biases in directional localization that might be expected to influence distance judgments based on angular declination, performance in 3D task environments provide yet another basis for expecting a foveal bias. In reduced cue settings adjacent objects located at different distances from the observer can be judged to have the same distance, a phenomenon termed the *equidistance tendency* (Gogel, 1965). Critically, it has been shown that when one of two objects is fixated, the fixated object's distance is perceived more accurately and the perceived distance of the other is drawn toward the perceived distance of the fixated object (Gogel & Tietz, 1977; Wist & Summons, 1976). It is unclear whether a bias of this kind should be expected to manifest when direction provides a potent cue, but the possibility does compound the motivation for the question.

Method.

Participants. Fourteen new individuals from the George Washington University community participated in the experiment. All participants were 18 to 24 years of age, reported normal or corrected-to-normal vision, and were paid $10/hr or participated in exchange for course credit.

Stimuli & Apparatus. The stimuli and apparatus were the same as Experiment 1, except only 10 targets were employed (2.5-4.75 m) and testing occurred in a different laboratory environment. The room and lighting were matched closely to Experiment 1. The visible space was mostly empty but with bookshelves in the far left and right peripheries of the visual field. The room was also smaller, extending 7.4 m in depth from the participant's viewing position.

Design and Procedure. The experiment used a 3 (viewing condition) x 10 (distance) design with viewing condition (Fixated-Target, Above-Target, and Below-Target) and distance (2.5-4.75 m) manipulated within-participants and with order randomized. The viewing duration was 74 ms for all trials, which was selected to ensure targets were detected while also prohibiting the execution of an eye movement. The procedure was the same as Experiment 1, except that gaze was aligned with a non-target location on two-thirds of the trials. We opted to generate a fixation dot rather than verbally direct gaze because it is faster and more precise. Because the fixation dot was aligned with the target on only one-third of the trials, it was not predictive of the target's actual direction and therefore would not have been a reliable proxy for the target. Distances were computed in advance for locations that would correspond to 6° visual angle above and 6° visual angle below each target distance. The co-experimenter placed the target object and a secondary target to align gaze when the required point of regard was above or below the target. Once the participant's gaze was aligned, the experimenter cued the co-experimenter to remove the secondary target before administering the glimpse.

<< Insert Figure 5 About Here >>

Results and Discussion

As can be readily seen in Figure 5, performance was nearly identical in the Fixated-Target and Above-Target conditions. Viewing condition had an effect on sensitivity, $F(1,388)$ =

7.12, $p < .001$. Sensitivity was greater in the Below-Target condition than it was in the Fixated-Target condition, $t(388) = 3.57$, $p < .001$, $d = 0.79$. Sensitivity in the Above-Target condition did not differ from that of the Fixated-Target condition, $t(388) = 0.74$, $p = .461$. Viewing condition also had an effect on bias, $F(2,26) = 3.93$, $p = .032$. Performance was less biased in the Below-Target condition than in the Fixated-Target condition, $t(26) = -2.25$, $p = .033$, $d = 0.49$. Bias in the Above-Target condition did not differ from that of the Fixated-Target condition, $t(26) = 0.33$, $p = .745$. Viewing condition did not have an effect on precision, $F(2,26) = 0.40$, $p = .676$. In sum, while there were accuracy differences, they were not in the direction of diminished performance when the target was outside the fovea at the moment of the glimpse. That is, the pattern of results suggests a bias specifically when gaze is directed below the target as opposed to a cost associated with retinal eccentricity more generally. Importantly, the pattern is in accord neither with foveal nor peripheral biases in directional localization; each would predict distance judgments with an overall bias in one direction or another and for both extrafoveal positions. We thus considered yet another possibility. While there are data suggesting that angular declination is perceived accurately (Ooi et al., 2001; 2006), Li and Durgin (2009) suggest that gaze declination (angular declination to fixated target) is biased with a gain factor of about 1.5. If the declination of gaze, specifically, were biased by this amount, fixations below the target would always be associated with greater error. This would predict decreased sensitivity (greater underestimation for far targets), while the opposite pattern was observed here.

Experiment 4

Given that the pattern of results in Experiment 3 was not wholly expected, we ran an additional experiment with the same objectives but with a stronger manipulation of eccentricity, which in turn required a different design. Here, the angular separation between the target and the fovea at the moment of the glimpse was about 10.6° visual angle. Because angular differences between target locations decrease with distance, our testing environment afforded neither the ability to fixate below the nearest target distance nor above the farthest target distance. In the former case, the gaze would be directed too close to one's feet (obscured by the shutter window apparatus); in the latter case, the gaze would be directed at the back wall. As an alternate approach, we focused on two distances (2.75 and 4.50 m) with two gaze directions. In the Gaze-Near condition, gaze was directed at the 2.75 m location. In the Gaze-Far condition, gaze was directed at the 4.50 m location. This rendered a simple 2 x 2 design wherein each target distance was viewed foveally and extrafoveally.

Method.

Participants. Thirteen different individuals from the George Washington University community participated in the experiment. All participants were 18 to 24 years of age, reported normal or corrected-to-normal vision, and were paid $10/hr or participated in exchange for course credit.

Stimuli & Apparatus. The stimuli and apparatus were the same as Experiment 1, except only 6 targets were employed (2.50, 2.75, 3.00, 4.00, 4.50, and 5.0 m).

Design and Procedure. The experiment used a 2 (viewing condition) x 2 (distance) design with viewing condition (fixation at 2.75 m and fixation at 4.50 m) and distance (2.75 and 4.50 m) manipulated within-participants and with each of four conditions repeated three times. To obscure the focus on two distances, 4 filler distances were employed and these were used once in each viewing condition. The trial order was completely randomized. The procedure was otherwise the same as Experiment 3.

Results and Discussion

The results of Experiment 4 can be viewed either from the perspective of eccentricity (Target-Foveated vs. Extrafoveal) or from the perspective of gaze direction (Gaze-Near vs. Gaze-Far). Our primary analysis was from the perspective of eccentricity, though we discuss the data from both perspectives. To begin, viewing condition did not have an effect on sensitivity, $F(1,128) = 0.16$, $p = .691$, and, as can be seen in Figure 6 (left), underestimation was actually somewhat greater for foveated targets, $F(1,12) = 5.59$, $p = .036$, $d = 0.66$. This outcome is not wholly consistent with either a foveal or a peripheral bias. Close objects were judged further away when gaze was far, an outcome that would be expected with a foveal bias. However, far objects were judged as farther away when gaze was near, which would be expected with a peripheral bias. On the other hand, in contrast to Experiment 3, precision was greater in the Target-Foveated condition than it was in the Extrafoveal condition, $F(1,12) = 5.37$, $p = .039$, $d = 0.64$. Directional localization of targets has been shown to be less precise (indexed by absolute error) in the 6-12° target range, even when controlling for attention (Tsal & Bareket, 1999). It is therefore reasonable to suppose that acuity limits do indeed impact the precision of directional localization. That there was an effect of eccentricity on precision here but not in Experiment 3 suggests that the cost of peripheral viewing is not negligible at all eccentricities even though the targets were equally well detected. Presumably, the variability associated with the extraction of direction is larger than the variability associated with the computation of distance from direction (and the generation of a response), but this is true only when the target is viewed more peripherally.

<< Insert Figure 6 About Here >>

The filler trials provide the basis for a complementary analysis. Because these targets were never fixated, they could only be viewed from the perspective of gaze direction (Figure 6, right). Although gaze direction did not have an effect on sensitivity, $F(1,76) = 1.04$, $p = .311$, or bias, $F(1,12) = 0.00$, $p = 0.969$, the trends were consistent with the pattern observed in the primary data subset (i.e., close objects were judged further away when gaze was far and far objects were judged as farther away when gaze was near). There was no effect of viewing condition on precision, $F(1,12) = 2.79$, $p = 0.121$. The filler data also highlight the fact that observers discriminated the distances; responses were not clustered around two distances, as might be expected if the observers limited their responses in accord with the repeated distances. In sum, as in Experiment 3, the results of Experiment 4 do not align with any bias that would have been predicted by the directional localization literature. Further, the more eccentric targets were actually underestimated less, which suggests that there is no cost associated with viewing targets extrafoveally, at least in terms of accuracy.

General Discussion

By assessing the role for gaze direction, the results of the present study provide strong support for the idea that angular direction is a potent cue to distance when targets are seen or assumed to be resting on the ground. In Experiment 1, a fixation point was used to align gaze with the direction of the target in advance of the glimpse. In this context, there was no benefit associated with the viewing condition that allowed the participant to actually see the target. Performance in this case could only be supported by the extraretinal signal associated with gaze direction, by the visual cues to gaze direction (i.e., changes in the overall distribution of features in the visual field that depend on the direction of gaze), by remembering the direction of the fixation dot and using that to compute distance, or by some combination of all three. In Experiment 2, all sources of visual information were removed and observers continued to have a compelling response to distance: response sensitivity was high and judgments were unbiased. In this case, performance could only be based on the extraretinal signal to gaze direction. This outcome is empirically intriguing, to be sure, but it is also theoretically compelling in that it demonstrates that visual cues are not needed to make use of angular direction as a cue to distance. Theorists have suggested that the visible horizon is used as reference for making use of angular direction (Ozkan & Braunstein, 2010; Rand, Tarampi, Creem-Regehr, & Thompson, 2011; 2012), visual cues to eye level are generally thought beneficial, and a visual representation of the ground surface is important in existing theory (He et al., 2004; Wu et al., 2004). We show here that retinal and/or extraretinal sources of information about angular direction coupled with the assumption that the object is on the ground can support a well-constrained judgment of distance. It might fairly be argued that the results of Experiment 2 say more about mental imagery than they do about perception. Real-world situations do not require one to locate objects based solely on the direction of gaze. By our view, performance, even if based on mental imagery, provides a window into the knowledge structures available to the observer to support the perception of distance (i.e., knowledge about the relations between target direction, the horizontal projection of eye level, and the distance along the horizontal ground plane).

The data we have presented supports the idea that gaze declination itself can provide the basis for distance judgments. It would be intuitively appealing to expect fixated targets to be localized more accurately because target direction and gaze direction have the same objective value. In other words, angular declination and gaze declination might be thought of as two sources of information that can be combined in some way to derive a more accurate or precise representation of target distance. We suggest that this could only be the case if angular declination were computed with respect to a visual reference, such as a visual cue to eye level or the visible horizon. As previously discussed, if angular declination is computed relative to a nonvisual representation of the eye-level projection (i.e., derived from gravity and body-based sources of information), that angle can be partitioned into components that reflect the displacement of the target from the fovea and the displacement of the eye from straight ahead. By this account, angular declination and the direction of gaze are never completely separable. Much further research is needed, but we expect that the encoding of gaze direction should factor into the computation of angular declination similarly whether the target is fixated or not.

The results of the present study also provide little indication of a cost associated with viewing the targets extrafoveally. This outcome may be surprising given the diminished level of acuity when targets are more eccentric. These data are in accord with work by Rand and colleagues (Rand et al., 2011; 2012) showing that floor-level targets can be localized reasonably well even when viewed through blurred goggles. The practical import of these findings is that angular declination is a source of information that is useful even for individuals with low vision. Of course, the ability to finely resolve the target is only one issue. The dynamic framework suggests that any factor that constrains the extraction of direction ought to similarly constrain the extraction of distance. As a result, biases that occur in 2D localization tasks ought to have influenced judgments of distance accordingly. Based on the existing literature, we considered a peripheral bias to be most likely. However, it should be noted that the biases that do occur in 2D localization tasks have been shown to depend on a variety of stimulus parameters (Fortenbaugh et al., 2012), and the linkage between 2D biases and possible biases in 3D environments remains an important topic for future research. The overarching conclusion here, however, is that if the viewing duration supports target detection, whether fixated or more peripheral, the observer is able to make good use of the directional cue to distance.

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Table 1. Means and between-subjects standard errors for sensitivity (given by the slope relating response distance to target distance), bias (given by the percent mean signed error across distances), and precision (given by the standard errors of the estimates).

	Sensitivity	Bias	Precision
Experiment 1			
Fixated-Target	0.84 (0.06)	-21.5 (3.8)	0.43 (0.05)
No-Target	1.07 (0.10)	-16.4 (4.8)	0.48 (0.07)
Experiment 2			
Gaze-Direction-Only	0.88 (0.14)	2.5 (6.2)	0.97 (0.12)
Experiment 3			
Fixated-Target	0.79 (0.06)	-19.4 (4.8)	0.44 (0.07)
Above-Target	0.85 (0.10)	-20.2 (4.6)	0.46 (0.04)
Below-Target	1.09 (0.12)	-13.9 (5.1)	0.42 (0.03)
Experiment 4			
Target-Foveated	0.84 (0.10)	-18.7 (6.1)	0.33 (0.06)
Extrafoveal	0.81 (0.07)	-15.2 (5.1)	0.50 (0.09)
Gaze-Near (Filler Trials)	0.75 (0.13)	14.1 (7.3)	0.62 (0.10)
Gaze-Far (Filler Trials)	0.62 (0.06)	14.3 (5.5)	0.46 (0.06)

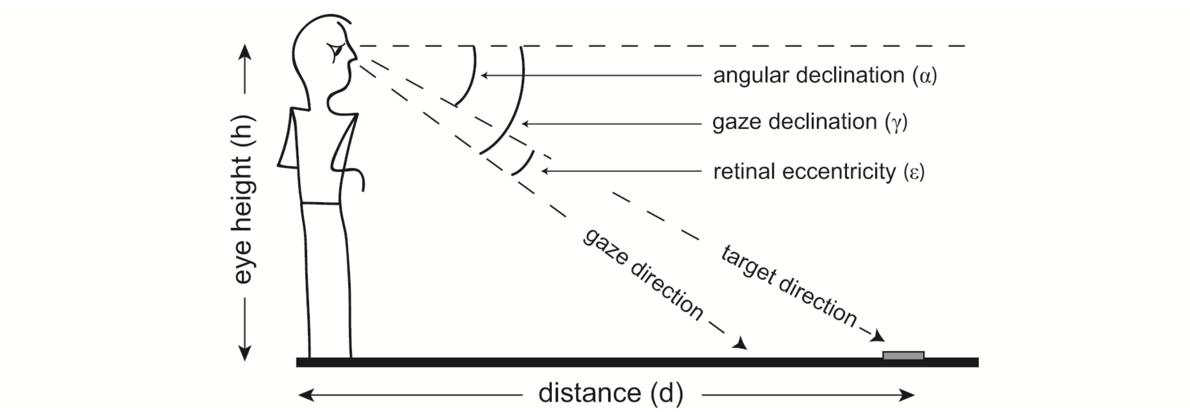

Figure 1. Angular declination (α) is the direction of the target with respect to the horizontal projection of eye-level. Distance along a level ground surface is given by a trigonometric function of angular declination and eye height, $d = h / \tan(\alpha)$. Gaze declination (γ) is the direction of gaze with respect to the horizontal projection of eye-level. When a target is fixated, angular declination and gaze declination have the same objective value. When the target is not fixated, as depicted above, angular declination is the difference between gaze declination and the retinal eccentricity (ε), which is the direction of the target with respect to the direction of gaze.

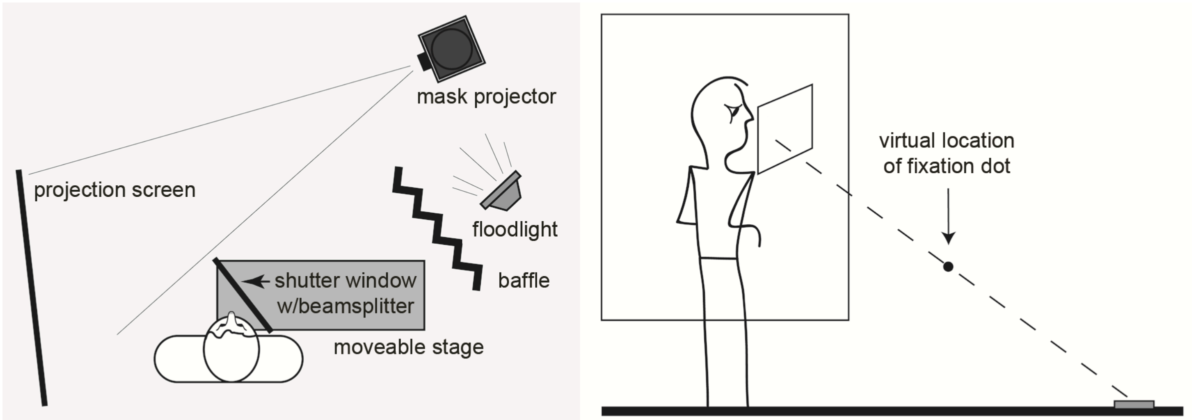

Figure 2. Overhead schematic of apparatus is presented on the left. The shutter window clears briefly to provide a view of a real-world room environment. When the shutter window returns to the opaque (light-scattering) state, a mask image is projected onto the projection screen to the observer's left, which is reflected in the beamsplitter. A laser pointer is aimed at the projection screen in advance of the trial to provide a fixation dot. The dot reflects into the beamsplitter in a location that can correspond to directional location of the target object when viewed through the shutter window (depicted on the right). The virtual location of the fixation dot depends on the distance from the observer to the projection screen (in the present case, about 2 m).

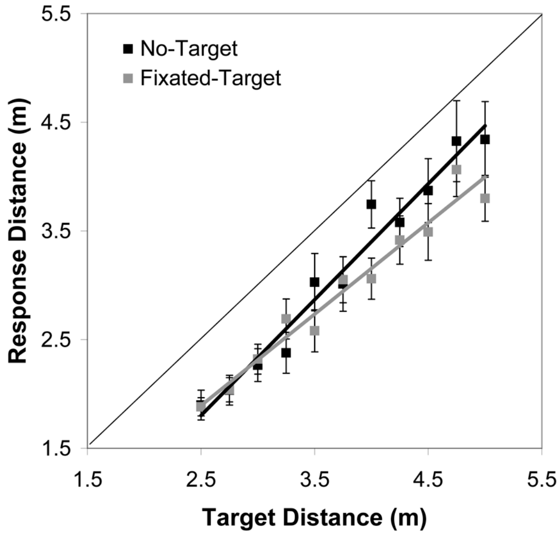

Figure 3. Mean walked distance to floor-level target locations as a function of target distance and viewing condition in Experiment 1. In the Fixated-Target condition, targets were viewed with near-threshold viewing durations. In the No-Target condition, gaze was directed to a target location but a target was never seen. Depicted are the means with between-subjects standard error bars and best-fitting lines for the fixed effects derived from the model.

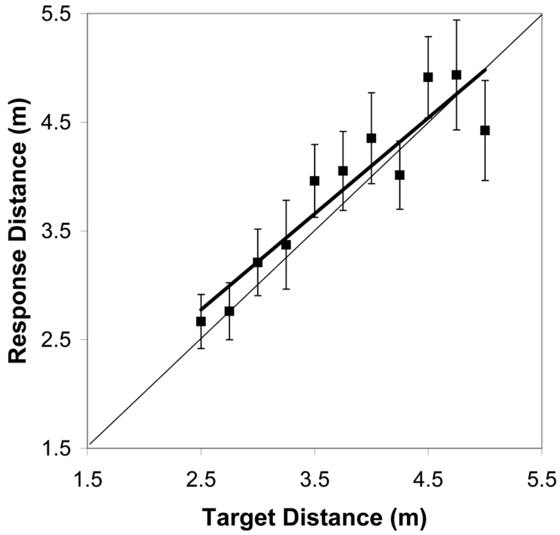

Figure 4. Mean walked distance to floor-level target locations as a function of target distance in Experiment 2. Here, gaze was directed to a target location in darkness and with vision obscured. Performance could only be based on extraretinal signals to target direction. Depicted are the means with between-subjects standard error bars and best-fitting lines for the fixed effects derived from the model.

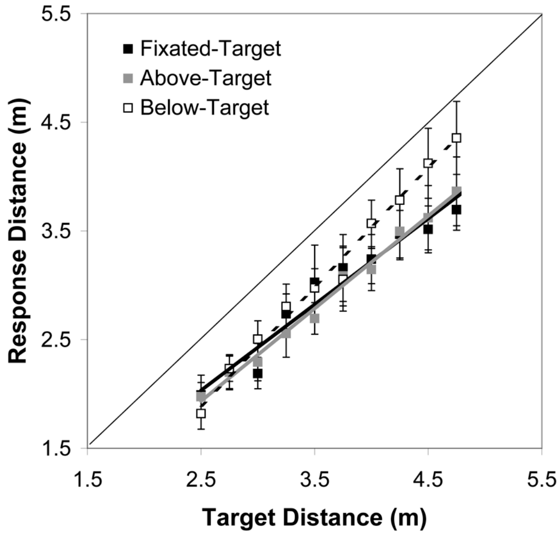

Figure 5. Mean walked distance to floor-level targets as a function of target distance and viewing condition in Experiment 3. Targets were viewed for 74 ms with gaze directed toward the target (Fixated), about 6° above the target, and about 6° below the target. Depicted are the means with between-subjects standard error bars and best-fitting lines for the fixed effects derived from the model.

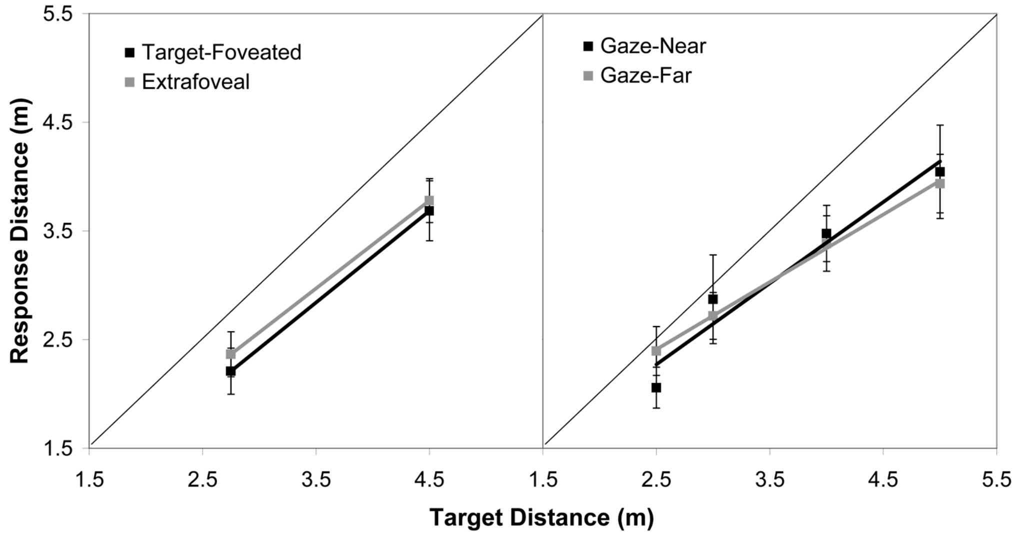

Figure 6. (Left) Mean walked distance to floor-level targets as a function of target distance and viewing condition in Experiment 4. Gaze was directed toward the 2.75 m or 4.50 m locations with the target then either fixated or about 10.6° in the periphery. (Right) Mean walked distance on filler trials when gaze was directed toward the 2.75 m and 4.50 m locations, Gaze-Near and Gaze-Far, respectively. Depicted are the means with between-subjects standard error bars and best-fitting lines for the fixed effects derived from the model.