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The Effects of Age and Set Size on the Fast Extraction of Egocentric Distance

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Abstract

Angular direction is a source of information about the distance to floor-level objects that can be extracted from brief glimpses (near one's threshold for detection). Age and set size are two factors known to impact the viewing time needed to directionally localize an object, and these were posited to similarly govern the extraction of distance. The question here was whether viewing durations sufficient to support object detection (controlled for age and set size) would also be sufficient to support well-constrained judgments of distance. Regardless of viewing duration, distance judgments were *more* accurate (less biased towards underestimation) when multiple potential targets were presented, suggesting that the relative angular declinations between the objects are an additional source of useful information. Distance judgments were more precise with additional viewing time, but the benefit did not depend on set size and accuracy did not improve with longer viewing durations. The overall pattern suggests that distance can be efficiently derived from direction for floor-level objects. Controlling for age-related differences in the viewing time needed to support detection was sufficient to support distal localization but only when brief and longer glimpse trials were interspersed. Information extracted from longer glimpse trials presumably supported performance on subsequent trials when viewing time was more limited. This outcome suggests a particularly important role for prior visual experience in distance judgments for older observers.

Keywords

Distance Perception; Aging; Visual Working Memory; Angular Declination; Blind Walking

The visual perception of any real-world environment is dynamic. Even when the observer and all the objects in the environment are stationary, frequent eye movements and deployments of attention are generally needed to extract behaviorally relevant information from the scene. As a result, there has been much interest in the temporal properties of stimulus processing in the domain of high-level vision. Limited-viewing-time paradigms have been used to study, for example, the time course for the activation of scene gist (e.g., Greene & Oliva, 2009; Joubert, Rousselet, Fize, & Fabre-Thorpe, 2007), the relative speeds of object detection and categorization (e.g., Grill-Spector & Kanwisher, 2005; Mack, Gauthier, Sadr, & Palmeri, 2008), and the time needed to form durable visual working

memory representations (e.g., Vogel, Woodman, & Luck, 2006). These investigations are valued in the field because they reveal the nature of the visual scene representation as it develops over the course of viewing as well as the processes that govern its formation. In contrast, visual space perception is most often studied under conditions that afford the observer sufficient time and attention to extract all the available cues. As a result, substantially less is known about the temporal constraints that govern the perception of egocentric distance. Filling this void is critical because there are a variety of common, real-world factors that can constrain the effective amount of time and attention available for localizing objects (e.g., high workload situations, fast-moving environments, normal aging, neurological disorders, etc.), and the consequences of mislocalizing objects under these situations can be dire. A better understanding of how objects are localized when viewing time is restricted is therefore of practical as well as theoretical significance.

To begin characterizing the dynamics of egocentric distance perception, we have conducted a series of studies using a limited-viewing-time paradigm in a real-world environment (Gajewski, Philbeck, Pothier, & Chichka, 2010; Gajewski, Philbeck, Wirtz, & Chichka, 2014). These studies have shown that the distance from oneself to a target object can be extracted quite quickly when the object is resting on the ground and in the intermediate distance range. In this case, *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 (Figure 1). Although distance judgments have been shown to improve when viewing time is extended to several seconds, a brief (9-220-ms) glimpse supports a sensitive response (i.e., slopes relating responses to target distances are near 1), typically with some underestimation. These findings have led to the development of a framework for the extraction of egocentric distance that posits a primary role for angular declination, particularly when viewing time is limited to the timeframe of a typical eye fixation (Gajewski, Philbeck, et al., 2014). We suggest that the extraction of distance is fast when angular declination is informative because target direction is the only stimulus property required to make use of the cue. As suggested by Figure 1, representations of the ground surface and the horizontal projection of eye level are also required to compute distance, but these need not be visually specified. In support of this, observers were found able to blindly walk to previously seen targets with a high degree of response sensitivity when illuminated targets were viewed in an otherwise dark room and assumed to be resting on the ground (Gajewski, Philbeck, et al., 2014; see also Philbeck & Loomis, 1997). Critically, Gajewski, Philbeck, et al. (2014) found a similar level of performance when observers viewed targets in a fully lit room with viewing durations that were just above their individual thresholds for detection (< 40 ms). Taken together, these results suggest that target direction is sufficient for capitalizing on the angular declination cue and that it is available as soon as the target is detected.

Our framework takes a strong stance on the sufficiency of target direction for judgments of distance based on angular declination, particularly when viewing time is limited. As suggested above, there are visual sources of information that would be expected to sharpen the computation of distance from angular declination. The ground plane is widely held to be an important reference for distal localization (e.g., Bian, Braunstein, & Andersen, 2005, 2006; Gibson, 1950, 1979; Sedgwick, 1986), and one theory, the sequential surface

integration process (SSIP) theory, suggests that a *visual* representation of the ground surface is critically important for computing distance from angular declination (He, Wu, Ooi, Yarbrough, & Wu, 2004; Wu, He, & Ooi, 2008; Wu, Ooi, & He, 2004). By this account, when the ground is not visible, as when illuminated targets are presented in the dark, performance reflects a bias to localize objects as if resting on an upwardly slanting surface (Ooi, Wu, & He, 2006; Wu, He, & Ooi, 2014; Zhou, He, & Ooi, 2013). Thus, even when a horizontal ground plane can be assumed, as it can be when indoors, the SSIP theory suggests that the extraction of visual cues to ground slant provides a source of information that plays a pivotal role in optimal performance based on angular declination.

Distance judgments are indeed subject to at least some systematic error with respect to the physical object locations when viewing time is limited to a single brief glimpse (most prominently, they exhibit underestimation). Increased access to visual cues to ground slant could be expected to reduce this error when viewing time is more extended. However, in our investigations we have found a greater impact of obscuring the overall context and very little impact of obscuring the nearby ground plane (Gajewski, Wallin & Philbeck, 2014a). By our view, this reduction in systematic error with increased viewing time is not primarily associated with an improved representation of ground slant. Although linear perspective cues provided by walls in indoor environments may enhance one's representation of ground slant, they might alternatively influence performance by informing the observer of the size and shape of the space. Indeed, judgments of distance have been shown to depend on the setting in which the target is viewed, even when the cues and the time available for their extraction are abundant (Lappin, Shelton, & Rieser, 2006; Witt, Stefanucci, Riener, & Proffitt, 2007). In fact, Witt et al. (2007) found that judgments differed for targets viewed from the long versus the short end of a hallway, which had the very same visible ground surface. These authors suggested, among other accounts, that differential cues to eye level might factor into performance between settings. Rand and colleagues (Rand, Tarampi, Creem-Regehr, & Thompson, 2011) have also demonstrated that distance judgments are influenced by the visible horizon, such as by the edge that forms the meeting between the floor and a back wall in a room environment.

The precise elements of visual context that play a role in distal localization and the mechanistic basis for their influence remain to be investigated. However, distinguishing any one account is outside the present focus because our tests suggest useful contextual information is of limited availability when viewing time is limited to the timeframe of a typical eye fixation. To begin, we have found performance with 9-ms glimpses to be undistinguished from performance with 175-ms glimpses (Gajewski et al., 2010). In contrast, that study demonstrated a substantial improvement (53% less underestimation) when viewing was relatively unlimited (around 5 sec) relative to when viewing was limited to 113-ms glimpses. Subsequently, relative to performance with very brief (36 ms) glimpses, we have shown a modest improvement (23% less underestimation) when viewing was relatively long (220 ms) but still insufficient for the execution of an eye movement (Gajewski, Philbeck, et al., 2014). The scene perception literature provides clear evidence that global image properties can be extracted quite quickly (e.g., Greene & Oliva, 2009), so it is reasonable to assume that some additional sources of useful information would be extracted even within the limited timeframe. However, we have suggested that target

prioritization plays a role in limiting the contextual information that is generally extracted with brief glimpses (Gajewski, Philbeck, et al., 2014; Gajewski, Wallin, & Philbeck, 2014a). To support any level of performance, the target must first be detected and directionally localized, which presumably requires at least a shift of attention to the target at the onset of viewing. Even when viewing time is relatively unlimited, the first saccade is almost always toward the target object (Gajewski, Wallin, & Philbeck, 2014a). In addition, performance was completely undistinguished from one block of trials to the next when the viewing durations were 100 ms within each block (Gajewski et al., 2010), an outcome that suggests observers were never able to extract additional useful information within this time frame. Thus, we suggest that observers are primarily occupied with directional localization when viewing time is limited.

Factors that Govern the Directional (2D) Localization of Objects

The reliability of angular declination as a distance cue, coupled with its speed of extraction, suggests an important bridge between 3D space perception and the visual cognition literatures that predominantly consider the processing of 2D stimuli: To the extent that target direction is a 2D stimulus property that is informative about target distance, any factor that constrains the extraction of directional information about objects is expected to similarly constrain the extraction of distance. Here, we considered the roles for two factors that are known or can fairly be expected to constrain the time course for extracting target direction -- i.e., the viewing time needed to localize an object in 2D.

First, displays of multiple objects that each potentially require a response are known to increase visual working memory load, which is capacity-limited (e.g., Irwin & Andrews, 1996; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). Critically, even when the number of items in the display is within the limits of one's capacity, there is evidence that the viewing time needed to form durable visual working memory representations, a process termed *consolidation*, increases with the number of items in the display (e.g., Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011; Gegenfurtner & Sperling, 1993; Jolicœur & Dell'Acqua, 1998; Vogel et al., 2006). Of particular interest here, Vogel et al. (2006) have shown that the effect of set size on memory displays of colored squares depends on the delay between onset of the stimulus and onset of the mask. That is, longer delays are required to reach asymptotic performance when there are more items in the display. Because the sensory representation is particularly susceptible to the disruption of masking (Averbach & Coriell, 1961; Coltheart, 1980; Di Lollo, 1980; Irwin & Yeomans, 1986), this outcome suggests a capacity-limited process is also needed to preserve or firm up perceptual representations of objects that are inherently fragile and susceptible to interference.

It is fair to note that Vogel et al. (2006) tested memory for object color as opposed to memory for the directional locations of the object more specifically. Although consolidation rates have not similarly been determined for objects that differ only in terms of location, there is some indication in the literature that the locations of objects might be extracted more efficiently than their other features. Sagi and Julesz (1985), in particular, described a study wherein the delay between stimulus and mask required to support accurate detection of targets in a field of distractors did not depend on set size. This was not the case when the

task required discriminating the orientations of the targets, which were diagonal line segments. Critically, the time course for target localization in this task setting followed that for detection, suggesting to the authors that the localization of targets could be done in parallel. However, subsequent works have provided bases for qualifying or rejecting the claim that localization is exceptionally efficient (e.g., Dukewich & Klein, 2009; Folk, Egeth, and Kwak, 1988; Green, 1992; Saarinen, 1996). In fact, Folk et al. (1988) found that the time needed to detect even a small number of items did depend on set size. (This was evidenced by numerosity judgments, which Sagi and Julesz also used to measure detection rates.) Nevertheless, even if the locations of objects can be encoded with high efficiency, outside the laboratory and in real-world task settings, task-relevant objects are most typically individuated by some feature other than location. That is, it is important not only to know which locations are occupied by objects but also which objects occupy these locations. In Vogel et al.'s 2D task environment, the viewing time needed to detect and remember the colors of the objects depended on the number of items that needed to be remembered. We assume the viewing time needed to directionally localize a set of objects individuated by color is well represented by performance in their task.

The second factor considered here is age. There are several age-related changes that would generally be thought to impact the ability to quickly extract visual information from a stimulus, whether presented on a 2D display or in a view of a real-world environment. To begin, there are optical changes, such as senile miosis, that can substantially reduce the amount of light transmitted to the retina (summarized in Sekuler & Sekuler, 2000). Decreased visual information processing speed and increased visible persistence (and temporal integration) associated with age have been shown to limit performance when viewing time is limited (DiLollo, Arnett, & Kruk, 1982). Indeed, processing speed is thought to be a primary factor in general age-related cognitive decline (e.g., Salthouse, 1996). Of particular relevance here, the viewing duration required to adequately perform the useful field of view task, a speeded task that measures directional localization with and without attentional load, has been shown to increase with age (Lunsman et al., 2008). Thus, age-related changes are clearly expected to have an impact on the viewing time needed to detect and directionally localize objects in a real-world environment.

Overview of the Present Study

We began our investigation with the expectation that viewing durations that afford the detection of (and memory for) the objects should also afford the extraction of their directions, and that these, in turn, should be sufficient to support well-constrained judgments of egocentric distance. As indicated above, the viewing duration required to support detection of a target for localization can reasonably be expected to depend both on the age of the observer and the number of task-relevant objects that are displayed. In the experiments reported here, viewing durations were set for each observer and each set size. Based on our prior work reviewed above, we suggest that viewing durations long enough to support the detection of the object, regardless of age or set size, should be long enough to support a sensitive response to distance (i.e., with slopes relating response distance to target distance near 1 and significantly greater than 0). Further, although performance may not be strictly accurate, we expected little or no benefit associated with giving the observer additional

viewing time so long as the viewing durations remained in the range of a typical eye fixation.

On the other hand, there are bases for predicting costs with age and set size even given a strong role for angular declination. Specifically, the encoding of distance might take longer than the time needed to detect and encode the objects and their directions into memory. To be clear, we are not testing the idea that distance might be encoded automatically (e.g., Hasher & Zacks, 1979; Naveh-Benjamin, 1987). Instead, we begin with the assumption that even the encoding of simple objects in 2D displays consumes central processing resources (Jolicœur & Dell'Acqua, 1998; Stevanovski & Jolicœur, 2007) and consider the possibility that the encoding of distance might be even more expensive. This would be expected if distance were best computed from angular declination for each target prior to or during consolidation. In this case, distance might be thought of as a feature that adds to the object's processing load. Although the need to encode multiple (i.e., additional) object features does not appear to impact consolidation, neither in terms of its central processing requirements (Stevanovski & Jolicœur, 2011) nor its rate (Woodman & Vogel, 2008), these studies do suggest that features are not all consolidated with equal efficiency. Greater dual-task interference (Stevanovski & Jolicœur, 2011) and slower consolidation rates (Woodman & Vogel, 2008) have been observed in tasks that required memory for object orientation versus memory for color. If distance increases the processing load, performance would be expected to suffer when the viewing duration is set for detection because the viewing time should fail to support the needed additional processing.

Similarly, here, we test the idea that there should be no costs of age over and above those costs already measured in 2D task environments. That is, we expect that accounting for the difference in the viewing time needed to detect and remember the set objects and their directional locations should adequately account for the viewing time needed to localize the set of objects in 3D. On the other hand, if distance does increase processing load during consolidation, as considered above, age would be expected to have an impact over and above its impact on directional localization. Older adults have shown greater and more sustained *attentional blink* (e.g., Lahar, Isaak, & McArthur, 2001; Maciokas & Crognale, 2003), a phenomenon of rapid serial visual presentation tasks that is commonly attributed to consolidation failure (e.g., Chun & Potter, 1995; Ptito, Arnell, Jolicœur, & MacLeod, 2008; Vogel & Luck, 2002). Thus, if distance is a feature that increases processing load, the cost of encoding multiple distal objects into memory could reasonably be expected to compound with age.

Experiment 1

In Experiment 1, we compared blind walking distance judgments across younger and older adults for two set sizes (Single- vs. Multi-Object). Participants always walked to a single target. In the Multi-Object condition, 3 *potential* targets were presented, but the *actual* target for that trial was not identified until after the viewing period was terminated by a masking stimulus. The critical viewing durations were set to be near each observer's detection threshold for each set size (near-threshold).¹ As indicated above, the near-threshold durations employed here were presumed sufficient to support the durable encoding of target

direction, and expected to depend on age and set size. The question was how well these durations would support performance in the distance estimation task when multiple objects were presented as opposed to just a single object. To address this issue, a control condition for each set size employed a longer viewing duration, well above the near-threshold durations. If the near-threshold duration is sufficient for the extraction of target direction, and the extraction of target direction is sufficient for the observer to capitalize on angular declination as a cue to distance, then giving the observer additional viewing time should not be beneficial. Alternatively, if distance increases processing load such that distal targets are encoded into memory less efficiently, additional viewing time should prove beneficial in terms of accuracy and/or precision, particularly for older observers and/or when multiple objects are presented.

Method

Participants—Sixteen older adults (aged 65-83 years) recruited from the Washington, DC metropolitan area were paid \$10/hour for their participation. Two groups of 16 younger adults (aged 18-24 years) participated in exchange for course credit. (Younger Group A and Younger Group B were tested with different viewing durations in the control conditions, as elaborated in the Procedure section.) Color vision and visual acuity were screened using the Optec Vision Tester. Far visual acuity was at least 20/70 for all participants, though acuity was somewhat diminished for older adults relative to both younger-adult groups, even with corrective lenses ($p < .001$). Older adults were screened using the Mini-Mental State Examination (MMSE, Folstein, Folstein, & McHugh, 1975). A score of 23 (out of 30) or lower is generally considered indicative of cognitive impairment; all participants scored 27 or greater in Experiment 1. In addition, perceptual/cognitive tests were included as baselines for comparing the groups. The Digit and Spatial Spans (Wechsler Memory Scale III, 1997) were employed to index short-term memory ability. On the Digit Span test, Younger Group A outperformed the other two groups (both $p < .05$); the Older Group's performance did not differ from Younger Group B's ($p = 1.00$). On the Spatial Span test, the Older Group scored significantly lower than Younger Groups A and B (both $p < .001$). Younger Group A scored marginally higher than Younger Group B, $t(30) = 1.98$, $p = .057$. Although age differences were anticipated on the span tests (e.g., Hester, Kinsella, & Ong, 2004), we found that all participants could report three or more objects in each of these tests. The Digit-Symbol Coding test (Wechsler Adult Intelligence Scale IV, 2008) was also included as a measure of processing speed. The Older Group scored lower than Younger Groups A and B (both $p < .001$); the younger two groups did not statistically differ on this measure, $t(30) = 0.72$, $p = .478$. These data are summarized in Table 1.

Stimuli and Apparatus—Targets were thin rectangular sheets of foam (red, blue or yellow) placed on the floor. These were created for 6 distances (2.5-5.0 m) and were sized so that each target subtended approximately 0.67×4.94 degrees of visual angle -- i.e., physical

¹Our interest was in performance at the briefest duration that would support reliable detection of the target(s). Threshold durations are by definition associated with a detection rate that is typically below 100%. As elaborated in the Methods section, our procedure aimed to minimize the possibility of considering responses to targets that were actually not detected, which would be expected to occur 25-50% of the time with traditional approaches. We use the term near-threshold to highlight the fact that our durations are close to but above the more standard threshold durations.

size varied systematically with distance to hold angular size constant. Although the relative angular size of the target across trials does not contribute to performance when angular declination is informative (Gajewski, Philbeck et al., 2014), we held angular size constant to maintain tighter control over the available stimulus information. On trials with 3 potential targets, each was a different color and distance, with color and distance randomly paired. To provide stimulus variation, the objects were placed in configurations derived from 1 of 2 sets of distances (2.5, 3.5, and 4.5 m, or 3.0, 4.0, and 5.0 m), and with each potential target in a different lateral location (left, right, and center). To avoid presenting targets in an orderly, diagonal column, the middle item was never placed in the center. (An example is depicted in Figure 1.) Selection of color and placement of single targets were similarly constrained. The targets were presented within a largely empty laboratory (9 × 11 m with the back wall 8.0 m from the observer's initial viewpoint) and illuminated indirectly by a photo flood light.

Viewing durations were controlled by a liquid crystal shutter window (LC-Tec, Borlänge) with a field of view that subtends about 65° × 60° (horizontal × vertical). The shutter window can transition between clear and semi-opaque (light-scattering) states quickly to provide glimpse durations as brief as 9 ms (see Pothier, Philbeck, Gajewski, & Chichka, 2009, for a report on the timing characteristics). A colored checkerboard mask image was projected onto a screen to the observer's left, which appeared straight ahead from the participants' perspective when reflected by a beamsplitter positioned at a 45° angle along with the shutter window. A mechanical shutter exposed the mask immediately after the smart window "closed". Head motion was controlled via chin rest, set to maintain participants' natural standing eye height. The support for the shutter window and chinrest was wheeled to allow the apparatus to be cleared for walking.

Design and Procedure—Set size (Single- vs. Multi-Object), viewing duration (Fast vs. Slow), and target distance (2.5-5.0 m) were varied within participants with trial order completely randomized. Viewing durations for the Fast-Single and Fast-Multi conditions were set for each individual based on a speed-setting procedure (described below). Viewing durations for the Slow-Single and Slow-Multi conditions were multiples of each condition's corresponding Fast duration. For the Older Adult Group and Younger Group A, the Slow durations were 4 times the Fast durations (capped at 548 ms). Although the differences between the Fast and Slow viewing durations were proportionate between these two groups, we anticipated longer threshold durations for the Older Adult Group, which translated into correspondingly longer durations for that group's Slow conditions. To preview our results, we found a high overall level of performance in the Older Adult Group. As elaborated below, this outcome could be expected if this group were especially able to extract more contextual information (i.e., information about the ground plane or the size of the setting) from their longer glimpse durations in the Slow conditions. We therefore subsequently ran a second group of younger adults with their Slow durations set to approximate the Slow durations of the Older Adults. Younger Group B's Slow durations were 11 times greater than their Fast durations.

Each session was comprised of a set of speed-setting trials followed by the blind walking trials. Care was taken to ensure that participants only saw the laboratory through the shutter

window during speed-setting and experimental trials. Viewing was binocular in all cases, and participants wore hearing protectors to minimize auditory cues.

Speed Setting Procedure: The aim here was to determine the fastest duration that would support detection of the target(s) on every trial. The Fast (near-threshold) viewing durations for Single- and Multi-Object conditions were determined for each individual using the method of limits with two runs that each consisted of an ascending and a descending series of trials. When there was a single target object, participants reported whether or not they saw the target. If they saw the target, they also reported its color (red, yellow, or blue). When there were 3 target objects, participants reported whether or not all were seen. If they saw all 3 targets, they reported the order of the colors in the configuration from left to right. The speed for each condition was the average of the first and last durations that supported detection (and correct naming of colors) in the ascending and descending series, respectively. Our procedure was relatively coarse-grained and the viewing durations on experimental trials were adjusted when targets were missed (see below). For ease of exposition, we refer to these as near-threshold durations, though, as indicated above, we acknowledge that this may overestimate somewhat the detection thresholds that might be measured using a different methodology. Our approach has the virtue of minimizing contamination of distance judgments by guessing when targets are not detected.

Experimental Trials: Participants began each trial with their chin in the chinrest and the smart window “closed”. The experimenter gave a verbal warning prior to opening the window. The smart window then opened to provide a glimpse of the laboratory and target(s) ranging from 13-548 ms, depending on the participant and condition. After the window closed, the masking image was presented for 1 s. The experimenter then verified that the participant had detected the object(s) and called out a color to specify the walking target for the trial. At that point, the object(s) were removed, the participants donned a blindfold, and the chinrest was pushed aside. Participants then attempted to walk to the specified target without vision. Although the targets could be positioned slightly left or right of center, participants were informed of our particular interest in target distance. The experimenter measured the walked distance and guided participants back to the observation location, without providing error feedback. Although infrequent, if the observer failed to detect the target, the trial was re-run later and the duration of subsequent Fast trials was increased by about 5 ms. Misses occurred on 8% of the Fast trials on average (across Experiments 1 and 2).

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 used 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 overestimation. Tests were performed on the mean

responses across distance. In the text we report bias (mean signed 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 (for further discussion, see Gajewski, Philbeck et al., 2014). Statistical tests for bias, precision, and the threshold viewing durations were performed using the mixed models approach with random intercepts.

Results

Near-threshold Viewing Durations—Two near-threshold viewing durations were calculated for each participant during the speed-setting procedure (one for each set size) and adjusted as needed on experimental trials. For the present analysis, the mean durations used during successful Fast-Single and Fast-Multi trials (i.e., trials where the target was actually detected) were considered the near-thresholds for Single and Multiple objects, respectively (see Table 2). There was a main effect of set size: Near-threshold durations were greater for multiple objects than single objects, $F(1,45) = 24.71, p < .001$. There was also a main effect of group, $F(2,45) = 34.50, p < .001$. Near-threshold durations were greater for the Older Adult Group compared to Younger Group A, $t(45) = 7.22, p < .001$, and Younger Group B, $t(45) = 7.17, p < .001$. However, the two younger groups did not statistically differ, $t(45) = 0.05, p = .962$. Finally, there was a significant group $\times$ set size interaction, $F(2,45) = 10.00, p < .001$, indicating an effect of set size for the Older Adult Group, $t(45) = 6.52, p < .001$, but not for the two younger groups (both $ps > .27$).

Sensitivity—Performance as a function of distance, viewing condition, and group is depicted in Figure 2. As can be seen, participants generally exhibited good response sensitivity -- there was a significant main effect of distance, $F(1,45) = 428.31, p < .001$. Effects of group and viewing condition are generally indicated by interactions with distance. There was an effect of set size on sensitivity that depended on group (i.e., a group $\times$ set size $\times$ distance interaction), $F(2,1038) = 4.72, p = .009$. For Younger Group B, sensitivity was diminished with the larger set size, $t(1038) = -2.68, p = .007$. In contrast, for Younger Group A and for the Older Adult Group, sensitivity did not vary with set size, $ps > .11$. There were no other effects on sensitivity and no other interactions (all $ps > .16$). Parameter estimates for Experiment 1 are presented in Table 2.

Bias—As can be seen in Figure 2, there was a main effect of set size: underestimation was generally greater with single targets than with multiple targets, $F(1,135) = 39.71, p < .001$. However, there was also a set size $\times$ group interaction, $F(2,135) = 4.87, p = .009$. Greater underestimation with single targets was observed in the Older Adult Group, $t(135) = 5.89, p < .001$, as well as Younger Group A, $t(135) = 3.54, p < .001$. This same pattern was observed in Younger Group B, though the effect did not reach the level of statistical significance, $t(135) = 1.49, p = .140$. Underestimation bias was also somewhat greater at Slow durations, but this trend did not reach the level of statistical significance $F(1,135) = 3.66, p = .058$. In fact, this effect was driven by Younger Group B. There was a significant interaction between group and viewing duration, $F(2,135) = 5.01, p = .008$, with an effect of viewing duration observed in Younger Group B, $t(135) = -3.59, p < .001$, but not in the Older Adult Group or Younger Group A, $ps > .45$. Overall bias did not significantly differ

between the groups, $F(2,45) = 2.67$, $p = .080$. There were no other effects or interactions, p s $> .41$.

Precision—The precision of performance indexed by the SEEs is depicted in Figure 3. To begin, all main effects were statistically significant. Precision was greater (i.e., SEEs were lower) when there was a single target than when there were multiple potential targets, $F(1,135) = 4.71$, $p = .032$. Precision was greater when the viewing duration was slow compared to when it was fast, $F(1,135) = 4.84$, $p = .030$. There was also a main effect of group on precision, $F(2,45) = 11.79$, $p < .001$. Younger Group A was more precise than Younger Group B, $t(135) = -2.08$, $p = .039$, and the Older Adult Group, $t(135) = -4.84$, $p < .001$. Younger Group B was more precise than the Older Adult Group, $t(135) = -2.76$, $p = .039$. There were no interactive effects on precision (p s $> .51$).

Discussion

The primary question addressed in Experiment 1 was whether near-detection-threshold viewing durations adjusted for age and set size would be sufficient to support well-constrained judgments of distance. As would generally be expected, the viewing time needed to detect and remember the objects was greater when multiple objects were presented, particularly for the Older Adult Group. Of interest here was whether additional viewing time would be needed to durably encode distance from direction. Accuracy for the most part did not depend on viewing duration. A viewing duration effect was observed with Younger Group B, but this was in the opposite direction that would be predicted (i.e., greater underestimation with the longer viewing duration). On the other hand, precision was greater overall when the viewing duration was longer. This outcome suggests that the representation of distance does improve to some degree when processing is not disrupted. It is important to note, however, that the effects of viewing duration did not depend on set size. Indeed, there was little evidence suggesting that increased set size was detrimental to blind walking performance at all, at least for the set sizes we tested. The results of Experiment 1 therefore suggest that most of the required processing is accomplished in the time needed to detect and encode the directions of the objects.

The most salient outcome from Experiment 1 was the clear benefit associated with having multiple objects, and this benefit was realized despite the fact that the target was not revealed until after the stimulus and mask, meaning that the locations of the objects needed to be encoded and maintained in memory. There are several possible bases for this effect. First, one could argue that viewing durations were longer in the multiple object condition, and that this afforded the extraction of cues to ground slant, which in turn supported a better judgment of distance (see He et al., 2004; Wu et al., 2004). However, the viewing durations in the Slow-Single conditions were the same as (or greater than) those in the Fast-Multi conditions and a reduced tendency to underestimate with multiple-objects was observed in all three groups even in these cases (p s $> .05$). Thus, the additional viewing time in the multiple object conditions was not instrumental to the benefit.

A second possibility is that the directions of the objects were encoded more accurately in the multiple object condition, and this in turn supported better judgments of distance. There is

evidence that the locations of objects in 2D task environments are encoded in visual working memory as configurations (Jiang, Olson, & Chun, 2000). Although there is debate about the role for configural representation when location information is task irrelevant (Jaswal & Logie, 2011), there are accounts that suggest the coding of absolute position as well as of the configuration as a whole when location is task relevant (Boduroglu & Shah, 2014). If these types of information are each available when multiple objects are presented, it is conceivable that errors of directional localization might be reduced relative to the case where just a single object with only its absolute location is represented.

A benefit of this kind would depend on the nature of the bias that would be expected for the directional localization of single targets. The literature provides bases for expecting foveal and peripheral biases, depending on stimulus configuration (Fortenbaugh, Sanghvi, Silver, & Robertson, 2012). That is, within a retinotopic reference frame, errors in directional localization can be toward or away from the center of vision. Interestingly, the benefit of multiple objects observed here is not in particular accord with the correction of any of three types of directional error. First, if a foveal bias were more pronounced when the objects are presented one at a time, the distribution of target directions would be more compressed relative to when presented as a configuration. A multiple-object benefit would therefore be predicted in the direction of increased response sensitivity with increased set size. Second, our previously reported data examining performance as a function of the target's retinal eccentricity suggests, if anything, a peripheral bias, and this was most prominent for far targets (Gajewski, Wallin, & Philbeck, 2014b). If this bias were corrected by the availability of a configural representation, we would expect a decrease in response sensitivity. Third, if target directions were unbiased, the configural representation, if beneficial, would simply have reduced the noise. In this case, we would expect an increase in precision with increased set size. Instead, the compelling effect of set size in Experiment 1 was a reduction in the overall underestimation bias when there were multiple objects presented: the only effect on sensitivity was the decrease observed with Younger Group B, and precision generally *decreased* with increasing set size.

A final possibility is that the target directions were equally well represented in single- and multiple-object viewing conditions but that the computation of distance from direction was enhanced when multiple objects were presented simultaneously. Specifically, with the presentation of multiple objects, *relative* angular declination takes on a stronger role in determining distance. In this case, the observer can take into account the distance that would be assigned to all the objects, even those that are not by the target object. Informal observations were consistent with this possibility. Older adults, in particular, were at times observed pausing at non-target locations on the way to a more distal target, which suggests that they maintained all the object locations in memory throughout the course of the trial. A relative angular declination account for the benefit would be consistent with decreased underestimation. Because change in angular declination per unit of distance decreases with distance, underestimation implies greater error in the differences between the angular declinations of the objects (see Figure 4). It is possible that the configural representation supports performance similarly. In this case, underestimation would also imply greater errors in angles between the directions of the objects themselves. Critically, it is not the representation of direction that improves but the computation of distance from direction.

A notable outcome that remains to be considered, however, is the relatively high level of performance observed in the Older Adult Group. This outcome was unanticipated, though it should fairly be noted that Bian and Andersen (2013) have also found older adults to be less prone to underestimate in distance judgment tasks, at least outdoors and with relatively long viewing durations. In our study, older observers were less precise, but they were remarkably accurate (as measured by bias and sensitivity). One possibility was that this group's longer near-threshold durations supported better performance. Contrasts between the older group's performance in the Fast conditions and Younger Group A's performance in the Slow conditions provide little support for this conclusion. The older adult group was marginally less biased with single targets, $t(135) = 2.47$, $p = .073$, and significantly less biased with multiple objects, $t(135) = 2.47$, $p = .015$. The corresponding contrasts for response sensitivity revealed no significant differences ($ps > .13$).

Another possibility we considered was that the additional viewing time provided to the older adults in the Slow conditions might have allowed them to extract useful information that could be deployed on subsequent trials even when viewing time was more limited. Past work has shown that visual information extracted from longer viewing durations (i.e., 5-15 seconds) can be maintained in memory to support performance in subsequent trials involving brief glimpses (Gajewski et al., 2010; Gajewski, Philbeck et al., 2014). The viewing durations here, capped at 548 ms, were relatively brief. However, these more extended glimpses may have afforded the observer a better sense of the room scale, which we have suggested is an important factor in the present task environment (Gajewski, Wallin, & Philbeck, 2014a). Also, prior visual experience may provide access to an elaborated representation of the scene that can be used to integrate target information when it becomes available during subsequent brief glimpses. It should be noted that a benefit of this kind would be expected to also impact performance in Younger Group B, given that their Slow viewing durations were set to match the Older Adult Group's. Although this group did underestimate less than Younger Group A, the difference did not reach the level of statistical significance and their overall pattern of results was not nearly as clean nor as compelling as the Older Adult Group's (see Figure 2).

Experiment 2

One aim of Experiment 2 was to determine whether age-related performance differences would persist within a block design that minimized the potential for accumulating visual experience with the task environment. One possibility is that older adults in Experiment 1 benefited from having the longer glimpse trials interspersed. Since a benefit was not strongly realized by the group of younger adults with matching slow durations, this possibility suggests a more important role for visual context in the older adult group. On the other hand, the striking older adult performance could also reflect a difference in response calibration and/or path integration ability. Walking to a previously viewed object with eyes closed requires not only an accurate perception of (and memory for) the object's location, but also the ability to keep up with how far one has traveled at every step along the way. If the older adults were prone to underestimate their walked distances, their responses could have been correspondingly greater even without age-related differences in judged target distance. To test for potential between-group differences in calibration and/or path integration ability, we

included a block of extended viewing trials at the end of the session. If older adults are differentially calibrated, their response should be greater when viewing time is limited as well as when viewing time is extended. If accuracy differences between age groups are eliminated or reversed here when viewing time is limited, and there is no difference between groups when viewing time is extended, it would suggest older observers derived some benefit from the longer glimpse trials in Experiment 1.

Although prior visual experience might have elevated older-adult performance in Experiment 1, this possibility does not diminish the fact that they were able to extract target distances from brief glimpses (55 and 129 ms on average for single and multiple targets, respectively). Everyday, real-world performance is often accomplished with some knowledge of or familiarity with context, so the results reported thus far are of practical significance regardless. Critically, we argue that even a confirmed role for prior visual experience in Experiment 1 does not undermine the test of our hypothesis that the encoding of direction is sufficient to support a well-constrained judgment of distance. A sensitive response to distance would not be expected to depend wholly on prior visual experience. Because target direction must be extracted anew on every trial, even perfect knowledge of the setting would be of limited use in the constraining of distance judgments. Further, based on prior research (Gajewski, Philbeck et al. 2014; Gajewski, Wallin, & Philbeck, 2014a), we suggest that the extraction of context primarily reduces underestimation. Experiment 2 nevertheless provides an opportunity to put our hypothesis to further test. Here, we addressed the question with a block design and with the longer glimpse durations eliminated. As a result, the primary focus was placed on the age $\times$ set size interactions. If encoding of distance from direction increases the processing load (and this cost was counteracted in performance by a benefit of prior visual experience in Experiment 1), then older adults would be expected to underperform relative to younger adults most particularly when multiple objects are presented. If target detection is generally sufficient to support well-constrained judgments of distance, then both age groups should perform similarly regardless of set size.

Method

Participants—Twenty-eight older adults (aged 65-90 years) participated in exchange for \$10/hour. Twenty-eight younger adults (aged 18-25 years) participated in exchange for partial university credit. The screening tests and inclusion criteria were the same as in Experiment 1. Visual acuity was significantly greater for younger adults than older adults, $t(54) = 4.35$, $p < .001$. Here, all older adults scored 25 or greater on the MMSE. The Older Group scored lower than the Younger Group on the Digit-Symbol Coding test, $t(54) = -7.15$, $p < .001$, and the Spatial Span test, $t(54) = -6.49$, $p < .001$, but not on the Digit Span test, $p = .345$. These data are summarized in Table 3.

Stimuli and Apparatus—The apparatus and stimuli were the same as in Experiment 1, except that Experiment 2 was conducted in a different laboratory, which was about 5×11 m and extended 9.5 m from the observer viewpoint.

Design and Procedure—Set size (Single- vs. Multi-Object) and target distance (2.5-5.0 m) were varied within participants with block order (Single Block First vs. Multi Block First) and age (Older Adults vs. Younger Adults) varied between participants. All participants were run at their near-threshold durations set for each condition. Target distance was randomized within each block.

The procedures were identical to that of Experiment 1, except here the speed setting procedure was modified for the Multi-Object condition. Three objects (two same color, one different) were placed on the floor and participants were instructed to name the colors. This eliminated the need to report colors in a spatial order. The blind walking trials employed 3 different-colored targets, as in Experiment 1. In addition, at the end of the session, a final block of trials was run at 5000 ms to permit a comparison between groups at a viewing duration that presumably provided ample time to extract and process the available distance information. This block, included solely to assess for potential between-group response biases, contained only a single target and consisted of one trial for each of the 6 possible target distances in random order. For this block, there were no main effects or interactions involving group and block order, and this held true across the sensitivity, bias, and precision analyses ($p > .25$). The means for the slope, bias, and SEE were 1.01, -9% , and 0.33 m.

Results

Near-threshold Viewing Duration—There were main effects of age group and set size. Near-threshold viewing durations were greater for Older Adults than they were for Younger Adults, $F(1,52) = 47.41$, $p < .001$, and greater when there were multiple potential targets than when there was just a single target, $F(1,52) = 14.11$, $p < .001$. There was also a significant set size $\times$ block order interaction, $F(1,52) = 6.16$, $p = .016$. The near-threshold viewing durations were greater for multiple objects than for single objects when the Multi-Object condition was the first block, $t(52) = 4.41$, $p < .001$. There was no effect of set size when the Single-Object condition was administered in the first block, $p = .37$. The effect of set size on near-threshold viewing durations was somewhat greater for the Older Adult Group, but the age group $\times$ set size interaction did not reach the level of statistical significance, $F(1,52) = 3.40$, $p = .071$. There were no other effects or interactions (all $p > .23$). Parameter estimates for Experiment 2 are presented in Table 4.

Sensitivity—Performance as a function of distance, viewing condition, age group, and block order is depicted in Figure 5. Again, participants generally exhibited good response sensitivity: there was a significant main effect of distance, $F(1,52) = 412.24$, $p < .001$. Age group and set size each significantly interacted with distance. Sensitivity was greater for the Younger Adult Group than the Older Adult Group, $F(1,52) = 7.01$, $p = .011$, and greater when there were multiple potential targets than when there was just a single target, $F(1,552) = 5.21$, $p = .023$. However, there was a set size $\times$ block order $\times$ distance interaction, $F(1,552) = 4.21$, $p = .041$. Sensitivity was greater for multiple potential targets than for single targets when the Single-Object block of trials was administered first, $t(552) = 3.07$, $p = .002$. There was no effect of set size on sensitivity when the Multi-Object block was administered first, $t(552) = 0.16$, $p = .87$. The effect of set size on sensitivity also depended on age, $F(1,552) = 3.92$, $p = .048$. For the Older Adult Group, sensitivity was greater for multiple potential

targets than for single targets, $t(552) = 3.01, p = .003$. For the Younger Adult Group, there was no effect of set size on sensitivity, $t(552) = 0.22, p = .83$. There were no other main effects or interactions ($ps > .35$).

Bias—As in Experiment 1, there was a main effect of set size: underestimation bias was greater in the Single-Object condition than it was in the Multi-Object condition, $F(1,52) = 25.64, p < .001$. There were no other main effects or interactions ($ps > .11$).

Precision—The precision of performance indexed by the SEEs is depicted in Figure 6. There was a significant age group $\times$ block order interaction, $F(1,52) = 4.68, p = .035$. It was a crossover interaction, though neither difference was statistically significant. The Younger Adult Group was not significantly more precise when the Single-Object condition was administered first, $t(52) = -1.13, p = .265$, and the Older Adult Group was marginally more precise when the Multiple-Object condition was first, $t(52) = 1.93, p = .059$. The effect of set size on precision depended somewhat on block order, but this did not reach the level of statistical significance, $F(1,52) = 3.26, p = .077$. There were no other main effects or interactions (all $ps > .24$).

Discussion

The results of Experiment 2 provide continued support for the idea that target detection is sufficient to support the use of direction as a cue to distance. The interactive effect of age and set size on response sensitivity was in the opposite direction that one would predict if there was an additional cost of encoding multiple target distances -- response sensitivity was greater for older adults when multiple objects were presented. Older adult performance was not specifically diminished with the larger set size when any of our measures of interest were considered.

The results of Experiment 2 also provide continued support for the multiple object benefit. Underestimation was clearly more substantial when there was a single target object than when there were multiple potential targets. Responses were again less precise in the Multiple-Object condition, though this was the case only when multiple objects were administered first. To assess the potential role for viewing duration in the multiple object benefit, we performed supplemental analyses on first block summary scores. In Experiment 1, mean levels of performance were shown not to depend on the mean viewing durations employed. Of specific interest here was whether individually-set viewing durations might have played a role in the multiple object benefit. First block performance was the focus here because there would be no possible contribution of carryover effects. As a result, age group and set size were both between-subjects variables with each subject contributing a near-threshold viewing duration, a slope relating response distance to target distance, and a percent mean signed error (PMSE). To begin, viewing duration did not significantly correlate with slopes, $r(56) = -.145, p = .286$, and it did not significantly correlate with PMSEs, $r(56) = -.213, p = .115$. Because viewing duration depended on age group and set size in our primary analyses, we considered the possibility that the effects of set size might be diminished if viewing duration were included in regression models for slopes and PMSEs. The results of these two sets of analyses are presented in Table 5. In accord with our

primary analyses, the initial regression analyses indicated significant effects of set size in the model predicting slopes as well as the model predicting PMSEs. The addition of viewing duration as a predictor improved the fit of neither model: $R^2 = .006$, $p = .545$, and $R^2 = .046$, $p = .085$, for the models predicting slopes and PMSEs, respectively. Critically, when viewing duration was included as an additional predictor in each of these models, the effects of set size remained significant. Thus, Experiments 1 and 2 indicate robust benefits of set size that do not depend on viewing duration.

Although block order was not a manipulation of interest, at least one element of the set size effect depended on block order: response sensitivity in the Single-Object condition was diminished relative to that in the Multi-Object condition only when the Single-Object condition was in the first block. One possibility is that information extracted from the presentation of multiple objects might be maintained and subsequently deployed. For example, the arrangement of objects may to some degree enhance perception of ground slant, which theorists suggest is important for accurate localization (He et al., 2004; Wu et al., 2008; Wu et al., 2004). Because viewing duration has not been shown to be a factor in these experiments, an enhanced perception of ground slant would not likely be derived from ground surface information (such as the texture gradient). Rather, the arrangement of the objects themselves may improve the representation of ground slant. Multiple objects contribute multiple angular declination values, which could constrain the computation of target distance within the Multi-Object block based on the relative angular declinations of the objects. However, the availability of multiple angular declination values might additionally inform ground slant, which could be useful if maintained in memory from one block to the next. Another possibility is that performance is enhanced by the relative angular declinations available in the first block with multiple objects, and the associated level of performance alters the calibration of responses in the second block. These possibilities are not mutually exclusive.

Finally, the results of Experiment 2 do provide a clear contrast to Experiment 1 in terms of older adult performance. The Older Adult Group's underestimation bias was at least as great as Younger Adult Group's, and sensitivity was relatively diminished. It should be noted that the groups performed equally well on the extended viewing trials administered at the end of the session. Although the possibility remains that younger and older adults were differentially calibrated in Experiment 1, this outcome does not favor such an account. The contrast between experiments suggests that older adults likely were extracting some additional useful information during the longer glimpse trials of Experiment 1 that supported performance on brief glimpse trials when they were interleaved. The contrast further suggests that older adults may rely more heavily on experience derived from prior viewing episodes.

General Discussion

The primary aim of the present study was to test the role for angular direction in the extraction of distance to floor-level targets. Specifically, our expectation was that if the viewing duration, controlled for age and set size, were sufficient to support the detection of and memory for the objects, it would also be sufficient to support a well constrained

judgment of distance. The prediction was based on the idea that detected and remembered objects would be directionally localized, and that directional localization is sufficient for distal localization when the object can be assumed to be resting on the ground. The overall pattern of results was in agreement with this expectation: sensitive responses to distance were observed in all groups and all viewing conditions in the present study (i.e., the mean slopes were always significantly greater than 0). However, performance differences between groups, viewing conditions, and experiments suggest some qualifications on the sufficiency of direction as a useful cue to egocentric distance.

To begin, our guiding framework posited that any factor that influences the extraction and memory for the directions of the objects should be expected to similarly influence the extraction and memory for their distal locations. A benefit of increased set size would be consistent with this expectation if the availability of a configural representation supported a more accurate encoding of the directions of the objects. The results from both experiments conclusively demonstrate a benefit associated with the presentation of multiple objects. Diminished underestimation was the more dominant pattern in the data, and this outcome is better explained by the use of angular declination as a relative cue to distance. Gajewski, Philbeck et al. (2014) have suggested an account such as this to explain enhanced performance from one trial to the next when single targets are presented. Above we suggest the directions are encoded with similar accuracy with single and multiple objects but that the computation of distance from angular declination is improved when multiple angular declination values are mutually constraining. An alternate possibility is that multiple objects constrain the magnitude of underestimation more directly. If a 4 m object were to be judged to be 3 m when presented singly, that same judgment would force the 3 m object to be judged to be 2 m when the full set is presented. The observer might simply realize that the 3 m target could not be that close, forcing a reappraisal of the other object distances. A bias reduction could thus result without considering the relative angular declinations, necessarily. Future work will be needed to tease apart these possibilities, but each possibility suggests that the distances to the objects are judged with respect to one another when presented as a set. In this sense, the direction of a single target object is less adequate than that same direction in the context of two others.

Despite the fact that there was a benefit associated with the presentation of multiple objects, a cost of encoding efficiency for location might still have been observed. That is, the viewing time needed to extract distance might have exceeded the viewing time needed to detect and remember the objects, and, if so, the cost of cutting viewing time short would be expected to increase with set size. The results from Experiment 1 did not support this hypothesis. Accuracy (measured by sensitivity and bias) did not improve at all with additional viewing time. It is interesting to note that response precision was greater with longer viewing durations. This outcome might be taken to suggest that the representation of distance is well constrained upon detection but becomes more definite with additional viewing time. However, the effect of viewing duration on precision depended neither on age nor set size, which would be expected if the encoding of distance from direction were to add a cost of efficiency. It thus seems more likely that the additional viewing time supported the extraction of some additional information about the scene context, such as about the ground surface or the size and shape of the room. It would be fair to note that the possibility that

benefits were being carried over from longer-viewing-duration trials might render the lack of viewing duration effects noninformative. We instead suggest that the information that would be maintained in memory in support of subsequent performance would be information about the greater scene context (as opposed to information about the targets themselves). This information would be equally useful for single- and multiple-object trials, and as a result, a cost for encoding multiple object distances ought not to be obscured. The overall pattern of results suggests that distance can be derived from direction quite efficiently.

A potential concern with the present paradigm and the conclusions we have drawn centers on our speed-setting procedure. In particular, our procedure was not criterion free, and thus the possibility exists that observers were less willing to report that they had detected the target(s) during the speed-setting procedure when they were older and/or when multiple objects were presented. If true, the viewing durations determined for subjects in these cases could have been inflated. By our view, it was critically important that localization performance was measured for targets that were most certainly detected. By this specification, criterion-free threshold-measuring techniques are less useful because they typically define thresholds in terms of stimulus values that sometimes result in guessing. Guessing would inject some bias and variability into the data that would be difficult to tease apart from responses based on legitimately-perceived targets. In the current studies, we aimed to circumvent such issues so as to focus on the localization of presumably detected targets. Nevertheless, a potentially fruitful line of future research would involve measuring localization performance at criterion-free threshold viewing durations. Admittedly, research of this kind would present practical challenges. Most notably, obtaining reliable estimates of criterion-free detection thresholds typically requires a large number of trials; this can be readily accomplished with stimuli presented on a computer screen, but is more challenging when objects must be manually placed on the floor by a team of research assistants and when older adults are required to stand for longer periods of time. Assuming these practical challenges could be surmounted, however, this method would provide a means of testing the possible impact of differing detection criteria between older versus younger adults.

Here, despite using methods that may not have been completely criterion-free, performance in the speed-setting tasks provided interesting outcomes that echo the claim that the extraction of distance from direction is quite efficient. Although the average detection threshold duration for multiple objects was longer than the duration required for a single target, the difference was more pronounced for older adults and was not at all compelling for younger adults. Indeed, younger adults needed less than 40 ms to detect and encode the set of 3 potential targets in our study. In contrast, participants in Vogel et al.'s (2006) study needed around 200 ms to reach asymptotic performance level with the same set size. Even older adults in the present study encoded the larger set size more quickly (129 ms and 74 ms on average in Experiments 1 and 2, respectively). The differences between task environments prohibit a direct comparison -- we used color naming (versus change detection) and our configurations were likely less random. Although speculative, it is possible that distance is so efficiently extracted from direction that the encoding of target direction is actually facilitated by the presentation of targets at varied distances (as opposed to having them all appear at the same distance, as they would on a computer screen). Xu and Nakayama (2007) have shown enhanced visual working performance for targets presented in

3D on two different vertically oriented surface planes. Clearly, the difference between 2D and 3D paradigms is provocative and suggests an avenue for future research.

Finally, our investigation also highlights the effect of age on judgments of distance when viewing time is limited. Not surprisingly, detection thresholds were longer for the older adults than for younger adults, confirming that younger participants can extract direction more quickly. Critically, younger adults were more accurate than older adults in judging distance, but only when brief glimpses were isolated. On the one hand, these findings suggest that armed with a reasonable representation of context, older adults are not impaired relative to younger adults. This lack of impairment is not surprising to us given that extraction of direction was considered to be the most crucial aspect of the extraction of distance, and all the impairments associated with the extraction of direction were presumably controlled for by the speed-setting procedure. On the other hand, these findings add to previous work showing that prior visual experience plays a role in shaping distance judgments made on the basis of brief glimpses (Gajewski, Philbeck et al., 2014). The fact that older adults did so well at brief glimpses, specifically when they had access to richer visual experience afforded by randomized inclusion of longer viewing durations, suggests that memory gained from past glimpses plays an especially important role for older adults in perceiving distances. We suggest that without prior visual experience, observers must relate the target's direction to a location in an abstract representation of the setting. As indicated in Figure 1, this requires stored information (general knowledge) about one's eye level, the geographic slant of ground surfaces, and the relationship between the direction to ground targets and distance. Our recent work suggests information about the scale of the space might also be important (Gajewski, Philbeck et al., 2014; Gajewski, Wallin, & Philbeck, 2014b, see also Lappin et al., 2006; Witt et al., 2007). Prior visual experience affords the generation of an episodic representation that includes many of these elements. Future research is required, but the present study suggests that older adults rely more wholly on having such a representation in place.

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Figure 1.

The distance to a target object resting on the ground is trigonometrically related to the angular declination of the object, the angle swept from eye level to the line of sight to the target (left). A photograph of a sample configuration for multiple object trials (right).

Figure 2.

Response distance in Experiment 1 depicted as a function of target distance by set size and viewing duration. Set size was either a single target (1) or multiple candidate targets (3). Viewing duration was either Fast (threshold duration) or Slow (a multiple of the threshold duration). Performance for Older Adult Group, Younger Group A, and Younger Group B are shown separately on the left, middle, and right, respectively.

Figure 3.

Precision was analyzed in terms of SEEs. Experiment 1 SEEs are shown by set size, viewing duration, and group. Error bars show the standard error of the means.

Figure 4.

Depicted are the directional projections of targets placed at 3, 4 and 5 m (the red, blue, and yellow rectangles, respectively) for an observer with an eye height of 1.6 m. The red, blue, and yellow circles represent the directional projections that would correspond to the response distances for each when underestimation is constant (1 m). As indicated, the relative angular declinations (RADs) between the distal locations decrease with increasing distance. As a result, the differences between the RADs for the targets versus those for the responses also increase with constant underestimation. In addition, the configural angles (i.e., the angles of the triangle formed by connecting the directional locations of the objects) derived for the actual objects differ substantially from those implied by the underestimated responses. Thus, responses that account for the RADs and/or the configural angles would be expected to diminish the bias towards underestimation. Critically, this type of error reduction requires the computation of each distance to take the computation of each of the others into account.

Figure 5.

Response distance in Experiment 2 depicted as a function of target distance by set size and block order. Set size was either a single target (1) or multiple candidate targets (3). Viewing duration was threshold for all groups and conditions. Performance when multiple targets were presented first is shown on the left; performance when single targets were presented first is shown on the right.

Figure 6.

Precision was analyzed in terms of SEEs. Experiment 2 SEEs are shown by set size, group, and block order. Error bars show the standard error of the means.

Table 1

Means and Standard Deviations of Participants' Demographic Information and Test Scores, Experiment 1

Variable	Younger A ^a		Younger B ^b		Older ^c	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Age (years)	19.6	1.6	19.3	0.9	73.5	6.0
Acuity	20/22	1.2	20/20	0.7	20/33	1.7
Digit Span	21.8	3.3	18.7	3.4	18.7	2.9
Spatial Span	19.1	3.5	16.9	2.6	13.9	1.7
Digit Symbol Coding	87.0	11.5	84.5	7.8	57.1	11.6

^a
n=16 (10 female, 6 male)^b
n=16 (9 female, 7 male)^c
n=16 (12 female, 4 male)

Table 2

Means and standard errors for viewing durations (ms), sensitivity (given by the slope relating response distance to target distance), bias (given by the percent means signed error across distances), and precision (given by the standard errors of the estimates).

	Viewing Duration	Sensitivity	Bias	Precision
Younger Group A				
SingleFast	21.3 (0.9)	0.65 (0.07)	−24.4 (4.0)	0.34 (0.04)
MultiFast	32.5 (3.0)	0.79 (0.08)	−18.8 (4.2)	0.42 (0.05)
SingleSlow	81.4 (3.6)	0.70 (0.06)	−23.2 (3.9)	0.27 (0.03)
MultiSlow	128.3 (12.1)	0.77 (0.09)	−17.6 (4.3)	0.35 (0.03)
Younger Group B				
SingleFast	20.8 (1.1)	0.90 (0.10)	−8.8 (6.0)	0.51 (0.06)
MultiFast	33.5 (3.1)	0.80 (0.10)	−5.2 (5.0)	0.53 (0.05)
SingleSlow	205.1 (10.2)	0.92 (0.08)	−13.3 (4.8)	0.35 (0.03)
MultiSlow	397.6 (26.6)	0.66 (0.06)	−12.2 (4.2)	0.44 (0.03)
Older Group				
SingleFast	55.2 (6.0)	0.88 (0.09)	−10.1 (5.8)	0.54 (0.09)
MultiFast	129.1 (19.6)	0.90 (0.13)	0.3 (5.7)	0.70 (0.11)
SingleSlow	217.4 (24.5)	0.93 (0.10)	−9.8 (6.5)	0.57 (0.08)
MultiSlow	413.0 (35.1)	0.93 (0.11)	−1.4 (6.1)	0.61 (0.07)

Table 3

Means and Standard Deviations of Participants' Demographic Information and Test Scores, Experiment 2

Variable	Younger ^a		Older ^b	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Age (years)	19.2	1.5	70.2	6.6
Acuity	20/20	1.2	20/29	1.7
Digit Span	17.9	3.4	17.0	4.1
Spatial Span	18.0	3.1	12.9	2.7
Digit Symbol Coding	91.2	14.0	62.7	16.1

^a
n=28 (22 female, 6 male)^b
n= 28 (15 female, 13 male)

Table 4

Means and standard errors for viewing durations (ms), sensitivity (given by the slope relating response distance to target distance), bias (given by the percent means signed error across distances), and precision (given by the standard errors of the estimates).

	Viewing Duration	Sensitivity	Bias	Precision
Multi Block First				
YoungerSingle	29.2 (2.0)	0.95 (0.12)	−23.7 (5.1)	0.50 (0.05)
YoungerMulti	39.8 (4.6)	0.85 (0.07)	−13.6 (4.6)	0.55 (0.07)
OlderSingle	49.6 (4.5)	0.69 (0.09)	−27.7 (4.9)	0.27 (0.03)
OlderMulti	80.4 (12.0)	0.81 (0.09)	−17.9 (7.1)	0.46 (0.08)
Single Block First				
YoungerSingle	27.4 (1.9)	0.82 (0.12)	−23.5 (5.7)	0.45 (0.05)
YoungerMulti	29.5 (2.1)	0.94 (0.08)	−19.4 (5.8)	0.42 (0.06)
OlderSingle	61.9 (5.2)	0.46 (0.10)	−42.4 (6.7)	0.54 (0.13)
OlderMulti	68.3 (7.4)	0.79 (0.10)	−29.8 (8.1)	0.52 (0.07)

Table 5

Summary of hierarchical regression analyses predicting slopes and percent mean signed errors (PMSEs) for first block performance in Experiment 2.

Model	Predictor Variables	b	SE	<i>t</i>	<i>p</i>
Slope #1	(Constant)	.46	.10	4.81	< .001
	Age Group	.36	.13	2.68	.010
	Set Size	.35	.13	2.61	.012
	Age Group $\times$ Set Size	-.31	.19	-1.65	.106
Slope #2	(Constant)	.53	.15	3.48	.001
	Age Group	.32	.15	2.13	.038
	Set Size	.37	.14	2.66	.010
	Age Group $\times$ Set Size	-.32	.19	-1.67	.101
	Viewing Duration	-.001	.002	-.61	.545
PMSE #1	(Constant)	-42.29	6.11	-6.92	< .001
	Age Group	18.86	8.64	2.18	.034
	Set Size	24.43	8.64	2.83	.007
	Age Group $\times$ Set Size	-14.64	12.22	-1.20	.236
PMSE #2	(Constant)	-29.29	9.51	-3.08	.003
	Age Group	11.63	9.41	1.24	.222
	Set Size	28.30	8.75	3.23	.002
	Age Group $\times$ Set Size	-15.95	12.00	-1.33	.190
	Viewing Duration	-.21	.12	-1.76	.085