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Mobility-Related Gaze Training in Individuals With Glaucoma: A Proof-of-Concept Study

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Purpose: Older adults with glaucoma show inappropriate gaze strategies during routine mobility tasks. Furthermore, glaucoma is a risk factor for falling and colliding with objects when walking. However, effective interventions to rectify these strategies and prevent these adverse events are scarce. We designed a gaze training program with the goal of providing proof-of-concept that we could modify mobility-related gaze behavior in this population.

Methods: A total of 13 individuals with moderate glaucoma participated in this study. We taught participants general and task-specific gaze strategies over two 1-hour sessions. To determine the efficacy of this gaze training program, participants performed walking tasks that required accurate foot placement onto targets and circumventing obstacles before and after training. We used a mobile eye tracker to quantify gaze and a motion-capture system to quantify body movement.

Results: After training, we found changes in the timing between gaze shifts away from targets relative to stepping on them ($P < 0.05$). In the obstacle negotiation task, we found a greater range of gaze shifts early in walking trials and changes in the timing between gaze shifts away from obstacles after training ($P < 0.05$), each suggesting better route planning. A posttraining reduction in foot-placement error and obstacle collisions accompanied these changes ($P < 0.05$).

Conclusions: Our results demonstrated that it is possible to modify mobility-related gaze behavior and mobility performance in older adults with glaucoma.

Translational Relevance: This study provides proof-of-concept for a gaze training program for glaucoma. A larger, randomized controlled trial is warranted.

Introduction

Glaucoma is a leading cause of irreversible vision loss, which is projected to affect over 110 million people worldwide by 2040.[1] The progressive increase in visual field loss can negatively impact the quality of life of people afflicted with this eye disease.[2,3] Given the importance of vision in guiding walking,[4–7] it is not surprising that those with glaucoma have problems with mobility.[8–10] In fact, people with glaucoma are at high risk for bumping into objects or experiencing an unintended fall to the ground.[2,3,8,10–15] Despite increased rates of object collisions and falls, and the high prevalence of this eye disease, effective interventions for older adults with glaucoma are limited. In the absence of a cure, strategies to improve function often are geared towards the remaining visual field, either through expanding or enhancing it,[16,17] or teaching the individual to use it more effectively.[18–20] Other strategies also may involve relying on alternative sensory feedback.[21] However, research on their effectiveness is scarce.

Recently, using tasks that simulate everyday walking experiences, we discovered significant differences in gaze behavior in older adults with moderate levels of glaucoma compared to normally-sighted controls.[22,23] When precise foot placement was required, those with glaucoma looked away from targets earlier relative to stepping on them.[23] This correlated with greater visual field loss and increased foot-placement error. Interestingly, an early gaze transfer strategy and increased foot-placement variability differentiate older adults at high versus low risk of falling.[4,24,25] This gaze behavior also suggests that older adults with glaucoma prioritize the planning of future steps over execution of the current step. When having to circumvent obstacles, those with glaucoma directed gaze closer to their current position and made a greater number of fixations to the obstacles.[22] Despite the latter, these individuals made contact with obstacles to a much greater extent than controls. This new understanding of how older adults with glaucoma allocate gaze during natural motor behaviors provides a potential avenue for intervention.

Orientation and mobility (O&M) instruction aims to preserve independence of travel by teaching individuals with low vision to ambulate and negotiate the environment safely and independently.[18,19] O&M training focuses on general strategies, such as identifying objects in the distance and systematically scanning the environment to locate hazards rather than on task-specific situations. It is prescribed most often for those with severe visual impairment despite the fact that mobility deficits are present among individuals with moderate visual field loss levels. While there is extensive anecdotal evidence, limited empirical research for the effectiveness of O&M visual efficiency training is available, particularly for those not dependent on a long cane, and there are no standardized methods of assessment.[18,20] Furthermore, the spatial-temporal relationship between gaze and environmental hazards or desired step locations is not emphasized at a step-to-step level.

Gaze training has emerged as a beneficial strategy for motor skill learning,[26,27] and results in normally sighted older adults at risk for falls suggest that it may improve foot-placement accuracy during walking.[28] Computer-based visual search training recently has been evaluated as a technique to improve mobility performance in individuals with low vision.[29,30] However, this technique does not consider task-specific (i.e., mobility-related) gaze strategies that may prove even more effective.

We provide proof-of-concept of whether mobility-related gaze behavior is modifiable in older adults with glaucoma. To accomplish this, we taught older adults with glaucoma general and task-specific gaze strategies over two 1-hour sessions. To determine the efficacy of the training, participants performed mobility tasks that required accurate foot placement onto particular ground targets and avoiding collisions with obstacles before and after gaze training. We found significant changes in gaze behavior after training that were accompanied by improvements in mobility performance, including reduced foot-placement error and obstacle collisions. Our results suggest that it is possible to train gaze, that gaze training may be a viable option to improve mobility of older adults with glaucoma, and that a randomized controlled trial is warranted.

Methods

Participants

We recruited 13 individuals with glaucoma through two ophthalmology clinics. The Office of Research Ethics at Simon Fraser University approved the procedures, and all participants provided informed written consent before performing the experiments. This research adhered to the tenets of the Declaration of Helsinki.

An ophthalmologist had previously diagnosed all participants with glaucoma based on visual field loss on repeated testing. This included a glaucoma hemifield test outside of normal limits and retinal nerve fiber layer (RNFL) loss. A standard spectral-domain optical coherence tomography test assessed the latter. To be eligible, participants met the following inclusion criteria: a Humphrey visual field mean deviation worse than −2 dB on the 30-2 threshold test or −1.5 dB on the 24-2 threshold test in both eyes, habitual binocular acuity better than 0.4 logMAR (20/50 Snellen equivalent), absence of another visual disease that could affect the visual field (e.g., cataracts, macular degeneration), aged 60 years or older, able to understand instructions in English, no neurologic (e.g., Parkinson's disease, stroke) or musculoskeletal (e.g., arthritis) disorders that could affect balance or gait, ability to walk without assistance (or mobility aid) for >5 minutes, and >26 on the Mini-Mental State Exam.

Visual Assessment

We obtained visual field scores from the participant's ophthalmologist. Different ophthalmologists used different test procedures. Eight of the 13 participants were assessed with the SITA-Fast central

24-2 threshold test (size III Goldmann white target and background luminance of 10.03 cd/m^2) using a Humphrey visual field analyzer (model HFA-II 750; Carl Zeiss Meditec, Inc., Dublin, CA). The remaining four participants were assessed with the SITA-Fast central 30-2 threshold test. For consistency, all 30-2 scores were converted to 24-2 scores by eliminating the six additional peripheral points used in the former test, though we did not use visual field scores in any analyses. We calculated integrated visual field scores using the binocular best location method, which involves selecting the best eye value for each total deviation location, and then averaging these values to obtain a mean deviation score.[31] We also determined the location of visual field loss for each eye, where loss in a particular hemifield required having a cluster of $\geq$3 points depressed below the 5% level on the pattern deviation plot.

The Early Treatment of Diabetic Retinopathy Study (ETDRS) chart assessed habitual binocular visual acuity at a distance of 4 m. We terminated the test when a minimum of three letters on a line could not be read. We used the logMAR value of the row in which they identified more than three letters correctly and, if applicable, subtracted 0.02 logMAR units for every letter identified on a subsequent row.

We assessed binocular contrast sensitivity using the Melbourne Edge Test at a distance of 40 cm.[32] Participants identified the orientation of an edge in a series of test circles with progressively declining contrast (scored between 1 and 24 dB). We terminated the test when the participant reported two orientations in a row wrong. The dB value of the lowest contrast test-patch that the participant could correctly identify represented the participant's contrast sensitivity (where lower scores indicated worse performance).

Design

We sought to determine the feasibility and effectiveness of teaching people with glaucoma where and when to look during common mobility tasks. We assessed gaze behavior and mobility performance before and after a gaze training protocol. Gaze training occurred immediately after the baseline session and again at home between the two sessions. The average time between the pretraining and posttraining sessions was 7.7 ± 2.0 days (average time between the home-based training session and posttraining was 3.2 ± 1.5 days). In each case, training lasted approximately 1 hour and consisted of three components: general gaze strategies, task-specific training, and cognitive (or dual-task) training. We increased training complexity slowly and progressively at the same rate for all participants. We also provided participants with pamphlets after the first training session with written instructions about the general gaze and task-specific training strategies and encouraged them to review the details throughout the week.

Gaze Training

To teach participants general gaze strategies, such as visual scanning techniques and how to visually manage an environment, we created an obstacle course inside the lab, which contained various terrain, obstacles, landmarks, and targets. An orientation and mobility specialist (KTZ) provided guidance on this component. We taught participants how to conduct a gridline scan of the area, similar to the dynamic scanning method.[18,33] This common O&M training component involved a systematic scan back-and-forth and up-and-down to learn the layout of the environment. Participants identified and located hazards, areas of interest, and a safe, clear path. For the first few practice trials, we used a pointing stick to outline the gridline pattern they should use. We blocked the participant's vision of the obstacle course with a board before starting each practice trial. On some trials, we gave them an object to locate. Once we withdrew the board, they began their scan, which a researcher timed. Specifically, we timed how long it took the participant to correctly identify object location(s), with the goal of reducing the scanning time to under four seconds. We chose four seconds because it was enough time to fully scan the environment, but not too long to be unrealistic in real-life situations. Participants performed this task at least 12 times but did not actually walk through the course at this point. After the task-specific training (described below), participants walked through the mobility course. This gave them the opportunity to practice the general gaze and task-specific gaze strategies at the same time. We blocked their vision and changed the position of objects in the course at the beginning of each trial. Before walking, we informed them about the end goal and whether to identify a particular object.

For the task-specific gaze training component, we taught strategies to ensure accurate foot placement onto a particular ground target and to safely avoid colliding with obstacles. We previously identified glaucoma-related changes in gaze behavior on these types of mobility tasks,[22,23] which guided the training.

To teach accurate foot-placement control, we showed participants narrated videos that demonstrated two different gaze strategies: one of an "expert," where gaze is transferred once heel contact has been made on the target (referred to as a late gaze transfer), and one of a typical person with glaucoma,[23] where gaze is transferred to the next target before the step on the current target (referred to as an early gaze transfer). We also verbally explained what the videos showed and provided a rationale for why these strategies are beneficial. Past research has demonstrated the effectiveness of using videos of inappropriate and appropriate gaze behavior for a specific task.[26–28]

Participants practiced the late gaze transfer strategy while stepping to the center of two targets (width, 15 cm; length, 30 cm). First, we instructed the participant to scan the environment systematically. This included a saccade to each target (i.e., from targets one to two) and a gridline search of the area enclosing the targets. We instructed them to walk, stepping on the first target with their right foot and the second target with their left foot, with no steps in between, as accurately as possible. We told them to follow gaze behavior as shown in the video: saccade to the first target during the approach, maintain gaze on it until the heel contacts it, then immediately shift gaze to the next target. We used a laser pointer for the participant to fixate on to encourage the correct strategy in approximately 25% of these trials. Participants practiced with one target before progressing to two targets.

To teach safe obstacle avoidance, we again started with narrated videos. This included various videos of an "expert" navigating around multiple obstacles without bumping into them. The video emphasized that knowing where the obstacles are located is important, but that looking at the gap between them (approximately two steps before crossing through) is critical for safe passing, since we tend to walk in the direction we are looking.[34–36] Subsequently, participants practiced circumventing two obstacles in the travel path (3.5 cm diameter poles with a height of 165 cm), which were or were not staggered in the direction of travel, depending on the walking trial. We instructed participants to begin with a gridline scan of the area to identify any obstacles and areas of concern. To train safe gap detection, we changed the size of the obstacle gaps in the medial-lateral direction for each trial. We started with wide gaps, and gradually made them narrower when the participant did not contact the poles, and increasingly wide again if they contacted a pole. This was to help participants learn the gap distance (threshold) they needed to rotate their bodies to avoid collision. When the two obstacles were staggered, we instructed participants to fixate on the obstacle closer to them until they were within a step or two of it, then saccade to the second obstacle, and then make another saccade to the gap between the obstacles before passing between them. We instructed them to look frequently towards the end goal as they passed between the obstacles to encourage longer gaze distances.

For the cognitive (dual-task) training component, we added a secondary task to perform while performing the mobility tasks. This additional task required participants to list words that started with a given letter. This simulates the situation of having a conversation with someone while walking.

For the home-based component of the training, the same researcher visited each participant in their own home between the two testing sessions. During this one-time visit, we used objects in the participant's home (e.g., doorframes, chairs, kitchen items, and so forth) to create an obstacle course that challenged precision walking and obstacle avoidance. Participants practiced the gaze strategies taught in the lab to scan the environment and navigate through the course. Object positions and end goals changed throughout the session.

Further details regarding the gaze training program are available from the corresponding author upon reasonable request.

Pregaze and Postgaze Training Assessment

To determine whether we could train gaze successfully for everyday mobility situations, we tested participants on precision walking[23] and obstacle negotiation[22] tasks. We maintained similar lighting levels across trials and tasks. The precision walking task involved walking across a 6 m path and stepping to the center of four sequential targets (width, 15 cm; length, 30 cm) without stopping. We positioned the first target 1.5 m in front of the participant and set the anterior–posterior distance between targets to 70% of the participant's leg length. We randomly varied the positions of the middle two targets by 5 cm in either the anterior–posterior or medial–lateral direction trial-to-trial. This ensured the use of continuous visual information to accurately step to the center of the targets and prevented memory-guided foot placement. Participants always stepped on the first target with their right foot. A wooden board blocked participant's vision before the start of each walking trial.

In the obstacle negotiation task, participants walked across a 4.5 m long and 1.25 m wide path, trying to avoid four black vertical poles (height, 165 cm; diameter, 3.5 cm) and then walk through an "end gate" that consisted of two blue vertical poles (height, 25 cm; diameter, 6 cm). Obstacles were spaced 60 cm apart from each other in the anterior–posterior direction, but we randomly varied the medial–lateral positions of the obstacles and end gates trial-to-trial in one of four predetermined arrangements. We also blocked participant's vision with a wooden board before the start of each walking trial. Together, these actions ensured that the task was visually-guided and not based on memory. We designed each configuration such that there always was a clear path to get from the beginning to the end gates. We instructed participants to walk at a self-selected pace, navigate through the course by taking the simplest/safest route possible, not contact the obstacles, and not have any part of their body go outside of the lateral walkway borders. An experimenter demonstrated the task to ensure participants understood the instructions.

Participants performed the precision walking and obstacle negotiation tasks under three conditions in a randomized order: single task, counting dual task, and visual search dual task. These dual tasks were different than the one practiced as part of the gaze training procedure so that the training task did not bias performance after training. Participants completed 12 trials of each condition, resulting in a total of 36 trials for each task (72 walking trials overall). Participants wore their habitual vision corrective lenses, if applicable, for the duration of the experiments. In the single task condition, participants performed the task by itself. This served as a baseline condition to which we could compare performance during dual tasks. In the counting dual task condition, we provided participants with a random two-digit number (ending in 0 or 5) between 50 and 100 to count backwards from in serial fives. A researcher recorded the number of correct responses for each trial. In the visual search dual task condition, we instructed participants to remember the locations of four black shapes (13 cm, all dimensions) printed on white tiles (20 × 15 cm) laid out on the floor. At the end of each trial, we asked them to identify the location of one shape. The shapes consisted of a square, circle, triangle, and cross. We used the same spatial positions for each trial, but altered the configuration (i.e., the particular location of a given shape) to one of four randomly selected sequences at the beginning of each trial. This task purposely forced participants to look away from the targets or obstacles, simulating real-life situations where one has to monitor walking direction and identify landmarks. We instructed participants to stop walking after stepping off the fourth target or past the blue end gates. We recorded the number of correct responses for each trial as a metric for visual search performance.

Before testing on the mobility tasks, participants counted and performed visual search trials without walking to establish baseline performance. To assess baseline counting performance, participants counted backward by fives for 10 seconds for six trials while standing. We calculated the number of correct responses during the baseline and dual task situations, then divided these values by their respective trial duration. To assess baseline visual search performance, participants observed shape configurations while standing for 5 seconds (the typical duration participants could see the shapes during walking based on previous pilot testing). We then blocked the participant's view and asked them to identify the location of one randomly selected shape. They performed this for 12 trials. We calculated the proportion of correct responses for the baseline and dual-task trials and normalized these to trial duration. For the counting and visual search tasks, we calculated a dual task cost (DTC) using the following formula: (dual task − single task)/single task.[37] A negative value indicated worse performance in the dual task condition.

Gaze and Kinematic Data Collection

During the mobility tasks, we recorded gaze data using a high-speed, head-mounted eye tracking system (model H6-HS; Applied Science Laboratories, Bellerica, MA). The system tracked rotation of the left eye at 120 Hz, and recorded video data through a head-mounted (obstacle negotiation task) or stationary (precision walking task) camera at 30 Hz. The system software overlays 2D gaze (pixel) coordinates on the 30 Hz video, with gaze position represented by an intersection of vertical and horizontal crosshairs. We calibrated the eye tracker using the system's standard 9-point calibration method. To obtain kinematic data, we recorded, at 120 Hz, the position of motion-capture markers located on the head, chest, and bilaterally on the forefoot, midfoot, and heel with two Optotrak Certus cameras (Northern Digital, Inc., Waterloo, Canada) that were synchronized with the eye tracker.

Table 1. Summary of Outcome Measures to Demonstrate Proof-of-Concept

	Precision Walking Task	Obstacle Negotiation Task
Primary gaze measure	HC-interval	Interval: saccade away from obstacle relative to passing it
Secondary gaze measures	TO-interval	Gridline scan metrics Spatial and spatial-temporal gaze distances Proportion of fixations (and durations) to obstacles, route-planning regions, shapes
Primary mobility measure	Foot-placement error	Obstacle collisions
Secondary mobility measures	Foot-placement error variability Gait speed	Path choice Gait speed

HC, heel contact; TO, toe-off.

Gaze and Kinematic Measures

The measures used in this study are based on our previous work.[22,23] We filtered the gaze and kinematic data from the precision walking and obstacle negotiation tasks with a Butterworth low-pass filter at 15 or 6 Hz, respectively, before any analysis. With the gaze data, we first identified saccade onset and offset times and fixation durations using the 120 Hz gaze data. Eye velocities that exceeded and then fell below 100°/s for a minimum of 16 ms defined onset and offset times, respectively. We classified fixations as stable gaze on a location for >66 ms.

Table 1 summarizes our measures. For the precision walking task, we quantified the timing of gaze shifts relative to initiating or completing a step based on the kinematic and gaze data, which we refer to as the heel-contact (HC)-interval and toe-off (TO)-interval.[23,38] The HC-interval represents the time a saccade is made away from a target relative to the time heel contact is made on that same target. A negative value indicated a saccade away from the target before heel contact. This represented our primary measure of gaze behavior in this task, since it relates directly to what participants were taught and is related to foot-placement accuracy. The TO-interval represented the time a saccade is made towards a target relative to toe-off to step towards that target. A negative value indicated that the saccade towards the target occurred before the toe is lifted off the ground to step towards that target. Since some participants made multiple fixations towards the same target, we used the last fixation in the sequence to the target in these calculations. The local maximum vertical velocity of the mid-foot marker and local minimum anterior–posterior acceleration of the toe marker defined heel contact on and toe-off from each target, respectively.[23]

For the obstacle negotiation task, we quantified the proportion of fixations (and fixation durations) to route planning locations (gap between obstacles, ground regions, end goal region), obstacles (or end gates), and, in the case of the visual search dual-task condition, shapes. Participants rarely, if ever, fixated outside of these areas. We also quantified the time interval between a gaze shift away from an obstacle and the time at which the chest moved past the obstacle (i.e., the gaze-obstacle-crossing interval). If a participant fixated an obstacle more than once, we used the last gaze shift away from the obstacle in this calculation. A negative interval indicated gaze transfer away before walking past the obstacle. This represented our primary measure of gaze behavior in this task, since it related directly to one of the strategies taught to participants.

We used spatial gaze distance and spatial-temporal gaze distance measures to determine how far (and for how long at that distance) participants looked while walking around the obstacles. These measures differentiated persons with glaucoma from controls and have been described in detail previously.[22] Briefly, the walkway was divided into a series of segments based on the positions of the obstacles and end gates. A score was given to each fixation based on how many segments it was from the participant. For the spatial gaze distance measure, we averaged all values given to fixations while the participant was walking within a given segment. A larger value indicated that within that segment, the participant fixated a greater distance ahead. For the spatial-temporal gaze distance measure, we first divided the duration of each fixation by the total time the participant spent walking through a given segment while fixating and multiplied this by the spatial gaze distance value assigned to that fixation. This allowed us to scale spatial gaze distance by the relative duration of each fixation. We then averaged the spatial-temporal gaze distance scores for each segment. Larger values indicated that the participant allocated gaze, on average, further ahead for longer. We only analyzed data for the first five segments, since stability of the eye tracker data dramatically decreased when participants were near the end of the walkway.[22]

To determine if participants performed a gridline scan before walking through the obstacle course, we counted the number of fixations made from the start of the trial until the participant walked out of segment 1 (S1); this was determined based on when the position marker placed on the chest crossed into the next segment. Participants could take up to one complete step forward during this interval. Obstacles were present starting at segment 3. We also calculated the standard deviation of the spatial gaze distance score of these fixations to determine how much of the environment they sampled. Together we refer to these as gridline-scan metrics.

For both mobility tasks, we calculated gait speed from the chest marker between the first and last targets (precision walking task) or between the first and last obstacles (obstacle negotiation task). For the precision walking task, we assessed mobility performance by quantifying foot-placement vector error. We defined this as the average vector distance between the mid-foot marker and target center when the mid-foot marker's anterior–posterior velocity and acceleration profiles stabilized to zero. We averaged this error separately for each target and condition. We also calculated foot-placement error variability, defined as the standard deviation of foot-placement error across targets in each walking trial. For the obstacle negotiation task, we assessed mobility performance by quantifying the number of obstacle collisions and deviation from the safest path choice. We determined the number of obstacle collisions by recording any occurrences where a portion of the participant's body contacted an obstacle or end-gate, which was verified by a second researcher. For path choice, we first calculated the aperture of all gaps between an obstacle and the walkway borders and between two obstacles for each obstacle configuration. The "safest" path choice represented the walking path that had the largest average gap size in each configuration. We verified the participant's walking path for each trial by using the videos from the eye tracker and calculated the average gap size for the path chosen. We subtracted these values from the safest path to quantify the deviation from the safest path, where smaller values indicate that the participant chose the path where they were least likely to collide with an obstacle based on the gap size between obstructions.

Questionnaire

We provided a questionnaire for the participants to complete at the end of the posttraining testing session. Questions addressed issues, such as the ease of instructions to follow, helpfulness of the pamphlets, feasibility of the home training, and how the gaze training changed their perception of mobility and situational awareness.

Statistical Analysis

We used JMP 13 software (Cary, NC) with an α level of 0.05 and included participant as a random effect for all statistical analyses. Tukey's post hoc tests identified differences when the analysis of variance (ANOVA) indicated the presence of a main effect or interaction.

To determine whether gaze training altered gaze behavior in the precision walking task, we compared the HC- and TO-intervals across time (before and after training), across conditions (single task, count dual task, visual search dual task), and across targets (targets 1–4) using separate 3-way ANOVAs. To determine whether changes in mobility performance occurred, we compared foot-placement error across time, conditions, and targets using a 3-way ANOVA. We used a 2-way (time × condition) ANOVA to compare differences in step-to-step foot-placement error variability.

To determine whether gaze training altered gaze behavior in the obstacle negotiation task, we first compared gaze-obstacle-crossing intervals across time and conditions with a 2-way ANOVA. To validate that participants performed a gridline scan, we compared the number of fixations and standard deviation of the spatial gaze distance of these fixations before leaving S1 across time and conditions using separate 2-way (time × condition) ANOVAs. Next, we determined differences in the spatial and spatial-temporal gaze distance measures using separate 3-way (time × condition × segment) ANOVAs. We then compared the proportion of fixations and fixation durations directed to obstacle and route planning locations across time (before and after training) and conditions (single task, count dual task, visual search

Table 2. Participant Characteristics

	Glaucoma, $N = 13$
Age, years	75.3 (6.5)
Sex, # female/male	5/8
Weight, kg	74.5 (13.5)
Height, cm	167.3 (9.0)
Shoulder width, cm	48.4 (5.1)
Race/ethnicity: Asian/White	3/10
Self-reported faller (falls in past 12 months), #	5
RNFL thickness: better eye, µm	68.1 (11.2)
RNFL thickness: worse eye, µm	60.8 (10.5)
Integrated visual field: binocular best location, MD in dB	–4.8 (3.8)
Visual field: better eye, MD in dB	–5.5 (4.7)
Visual field: worse eye, MD in dB	–10.4 (7.7)
Visual acuity: habitual binocular, logMAR	0.06 (0.27)
Contrast sensitivity: habitual binocular, dB	16.8 (3.7)

Data are mean (SD) for age, weight, height, shoulder width, visual field, visual acuity, contrast sensitivity; and counts for sex, race/ethnicity, and self-reported fallers. RNFL, retinal nerve fiber layer; MD, mean deviation.

dual task) using separate 2-way ANOVAs. To compare the proportion of fixations and fixation durations directed towards shapes between testing sessions, we used a 1-way ANOVA. Finally, to determine whether mobility performance changed, we compared the number of obstacle collisions per trial and deviation from safest path choice between testing sessions and across conditions using separate 2-way ANOVAs.

For both tasks, we used separate 2-way (time × condition) ANOVAs to determine differences in gait speed. Since we found differences in gait speed, we used this variable as a covariate for all measures associated with the precision walking task. However, we did not include this as a covariate for the measures of the obstacle negotiation task because they are independent of gait speed (e.g., the measures are quantified as proportions). We also compared dual task cost differences between pretraining and posttraining using paired *t*-tests.

Results

Characteristics of the glaucoma participants are shown in Table 2. The type of glaucoma ranged from primary open-angle ($N = 8$) to normal- (or low-) tension ($N = 4$) to pseudoexfoliative ($N = 1$). In the worse eye, visual loss was present in double, inferior, and superior hemifields of 10, one, and two participants, respectively. In the better eye, visual loss was present in double, inferior, and superior hemifields of 5, two, and four participants, respectively (two eyes did not meet our criteria for hemifield classification). Note that one participant did not perform the obstacle negotiation task in one session due to technical problems with equipment (and, thus, was excluded from that task's analysis).

Precision Walking Task

In the precision walking task, participants walked and stepped onto four sequential targets as accurately as possible. In two of three conditions, they also performed a secondary task. Since the gaze training program emphasized maintaining fixation on a target until after stepping on it, we first examined the HC-interval, a measure that is directly related to this strategy. If gaze is modifiable, we expect this interval to become less negative (or even positive) after training. As illustrated in Figure 1A, the HC-interval was, indeed, less negative after training (time main effect, $F_{1,274} = 128.2$, $P < 0.0001$). Pooled across time and conditions, this difference equated to approximately 370 ms, suggesting that participants shifted gaze away from the target later relative to stepping on it after training. We also found a less negative HC-interval in the single task condition compared to both dual task conditions (condition main effect, $F_{2,274} = 33.4$, $P < 0.0001$). Similar to our previous work (Miller et al.[23]), we also found a main effect of target ($F_{3,267} = 24.7$, $P < 0.0001$), where post hoc tests revealed a less negative HC-interval for target 4 compared to target 3, and less negative HC-interval for targets 3 and 4 compared to targets 1 and 2.

Although not specifically trained, we found that participants delayed shifting gaze towards a future target before lifting the foot off the ground to step on it (i.e., a less negative TO-interval) after compared to before training (Fig. 1B; time, $F_{1,275} = 50.7$, $P < 0.0001$). This strategy also occurred in the single task and search dual task conditions compared to the count dual task condition (condition, $F_{2,275} = 13.6$, $P < 0.0001$). We also observed a main effect of target ($F_{3,267} = 25.1$, $P < 0.0001$). Specifically, participants looked later to the upcoming fourth target compared to targets 1 and 2, and also looked later to the upcoming third target compared to targets 1 and 2. A significant time × target interaction ($F_{3,267} = 8.2$, $P <$

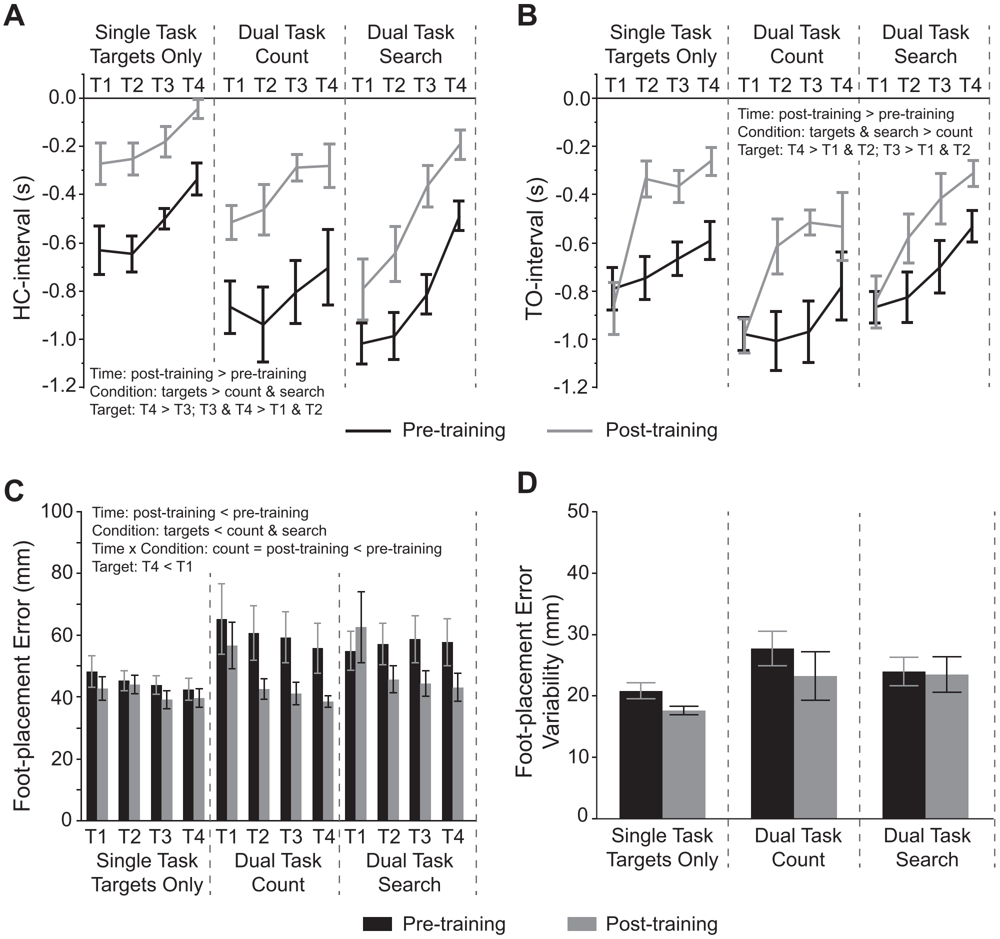

Figure 1. Gaze and mobility measures for the precision walking task. (A) HC-interval between pretraining and posttraining and across conditions and targets. Negative values indicate that gaze shifts away from the target before heel contact on it. (B) TO-interval between pretraining and posttraining and across conditions and targets. Negative values indicate gaze shifts to the target before toe-off of the foot about to step on it. (C) Foot-placement error between pretraining and posttraining and across conditions and targets. (D) Foot-placement error variability between pretraining and posttraining and across conditions and targets. Data are represented as mean ± SE.

0.0001) revealed a less negative TO-interval to targets 3 and 4 after compared to before training.

We next asked whether any changes in mobility performance occurred after training. Foot-placement error depended on time and condition (time × condition interaction, $F_{2,277} = 3.2$, $P = 0.042$). Specifically, we found reduced foot-placement error after training for only the count dual task condition (Fig. 1C). In addition to the interaction, we observed main effects of time ($F_{1,283} = 13.4$, $P = 0.0003$) and condition ($F_{2,283} = 8.9$, $P = 0.0002$). We also found reduced error when stepping on target 4 compared to target 1 regardless of time or condition (target, $F_{3,275} = 3.3$, $P = 0.020$). In contrast, we found no effects of time, condition, or target on foot-placement error variability (Fig. 1D; $P > 0.05$). In terms of gait speed, participants walked slower (0.88 ± 0.16 vs. 0.82 ± 0.13 m/s) at posttraining (time, $F_{1,60} = 9.0$, $P = 0.004$). In addition, they walked slowest during the count dual task condition (0.78 ± 0.17 m/s), fastest in the single task condition (0.92 ± 0.14 m/s), and in between for the search dual task condition (0.84 ± 0.10 m/s; condition main effect, $F_{2,60} = 17.4$, $P < 0.0001$).

Although performing the secondary tasks influenced gaze and mobility performance, and the gaze training program included dual-task practice, we found no difference between pretraining and posttraining count DTC (pretraining, –0.018 ± 0.279 versus posttraining: –0.137 ± 0.164; $t_{12} = -1.4$, $P = 0.192$). Similarly, we found no difference in search DTC (pretraining versus posttraining, –0.248 ± 0.351 vs. –0.247 ± 0.180; $t_{12} = 0.01$, $P = 0.991$).

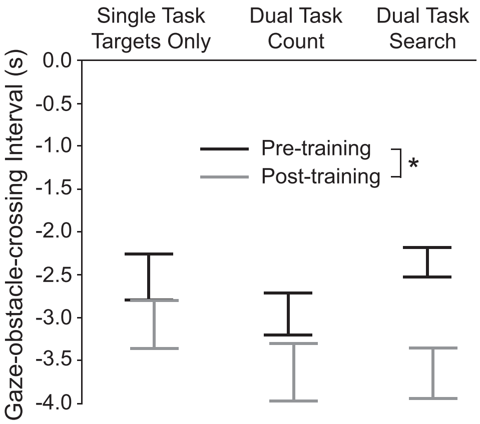

Figure 2. Gaze-obstacle-crossing interval for the obstacle negotiation task. Negative intervals indicate gaze transfer away from an obstacle before walking past it. Data are represented as mean ± SE. *Significant main effect of time ($P < 0.05$).

Obstacle Negotiation Task

In the obstacle negotiation task, participants walked through an array of obstacles in single and two dual-task conditions. Because the gaze training program emphasized the timing of saccades onto obstacles and fixating the gap between them, we first examined the gaze-obstacle-crossing interval. Participants shifted gaze away from the obstacles before walking past them sooner after training (Fig. 2), presumably to look ahead or through the gap as trained ($F_{1,55} = 23.7$, $P < 0.0001$). However, we found no effect of condition ($F_{2,55} = 2.8$, $P = 0.072$) or a time × condition interaction ($F_{2,55} = 1.7$, $P = 0.186$).

An important part of the gaze training program was to teach participants how to use a gridline scan. If participants used this strategy, we would expect a greater number of fixations made at the very beginning of the walking trial, and the location of these fixations should be scattered throughout the environment (which would be reflected by greater variability). Figure 3A shows how the walkway was divided into different segments and how a spatial gaze distance score is calculated (see Methods for more details). As illustrated in Figure 3B, participants made a greater number of fixations while in S1 after compared to before training ($F_{1,55} = 65.0$, $P <$ 0.0001). More fixations also were made in the search dual-task condition compared to the count dual-task condition ($F_{2,55} = 5.6$, $P = 0.006$). We found a nonsignificant time × condition interaction ($F_{2,55} =$ 1.6, $P = 0.208$) for this measure. In addition, we found greater variability in spatial gaze distance while in S1 after versus before training (Fig. 3C; $F_{1,55} = 14.4$, $P =$ 0.0004). However, condition had no effect on this measure (condition, $F_{2,55} = 0.8$, $P = 0.464$; time × condition interaction: $F_{2,55} = 0.2$, $P = 0.804$).

To determine whether gaze training resulted in participants allocating gaze further ahead while walking, we calculated a spatial gaze distance score and a spatial-temporal gaze distance score (Fig. 3A). On average, participants looked further ahead during the obstacle and count conditions compared to the search condition (Fig. 3D; $F_{2,319} = 15.3$, $P < 0.0001$). In addition, participants looked closer to their current position as they progressed from one segment of the path to the next ($F_{4,319} = 191.3$, $P < 0.0001$; all segments different from one another). Although we found a significant time × condition interaction ($F_{2,319}$ $= 4.7$, $P = 0.009$), post hoc tests showed no effect of time. When accounting for the duration of each fixation (i.e., using the spatial-temporal gaze distance measure; Fig. 3E), participants looked further ahead for longer before training while in S1 (time × segment, $F_{4,319} = 2.7$, $P = 0.032$) and during the obstacle and count conditions compared to the search condition (condition, $F_{2,319} = 22.0$, $P < 0.0001$). In addition, participants looked further ahead for longer while walking in S2 – S4 compared to S1 and S5, and in S2 compared to S4 (segment, $F_{4,319} = 30.9$, $P < 0.0001$).

Figure 4 illustrates the fixation characteristics (proportion of fixations and proportion of fixation durations) to route-planning regions, obstacles, and shapes (when applicable). The majority of fixations were made to route-planning features, which included ground regions, the gap between obstacles, and the end goal region. The proportion of fixations to route-planning features was greater in the obstacle and count conditions compared to the search condition (Fig. 4A; $F_{2,55} = 99.6$, $P < 0.0001$). However, we found no significant effect of time on this measure (time, $F_{1,55} = 0.0001$, $P = 0.993$; time × condition, $F_{2,55}$ $= 0.3$, $P = 0.717$). Similarly, we found no significant effect of time for fixation durations to route-planning features (Fig. 4B; time, $F_{1,55} = 0.3$, $P = 0.601$; time × condition, $F_{2,55} = 0.3$, $P = 0.757$). In addition, fixation durations to route-planning features decreased in the search dual-task condition compared to the obstacle only condition ($F_{2,55} = 67.0$, $P < 0.0001$).

Participants made a greater proportion of fixations to obstacles in the obstacle only condition versus the search dual-task condition (Fig. 4A; $F_{2,55} = 5.0$, $P =$ 0.010), presumably since the presence of shapes in the latter drew attention away. The identical result occurred for fixation durations to obstacles (Fig. 4B; $F_{2,55} = 5.1$, $P = 0.009$). However, we found no

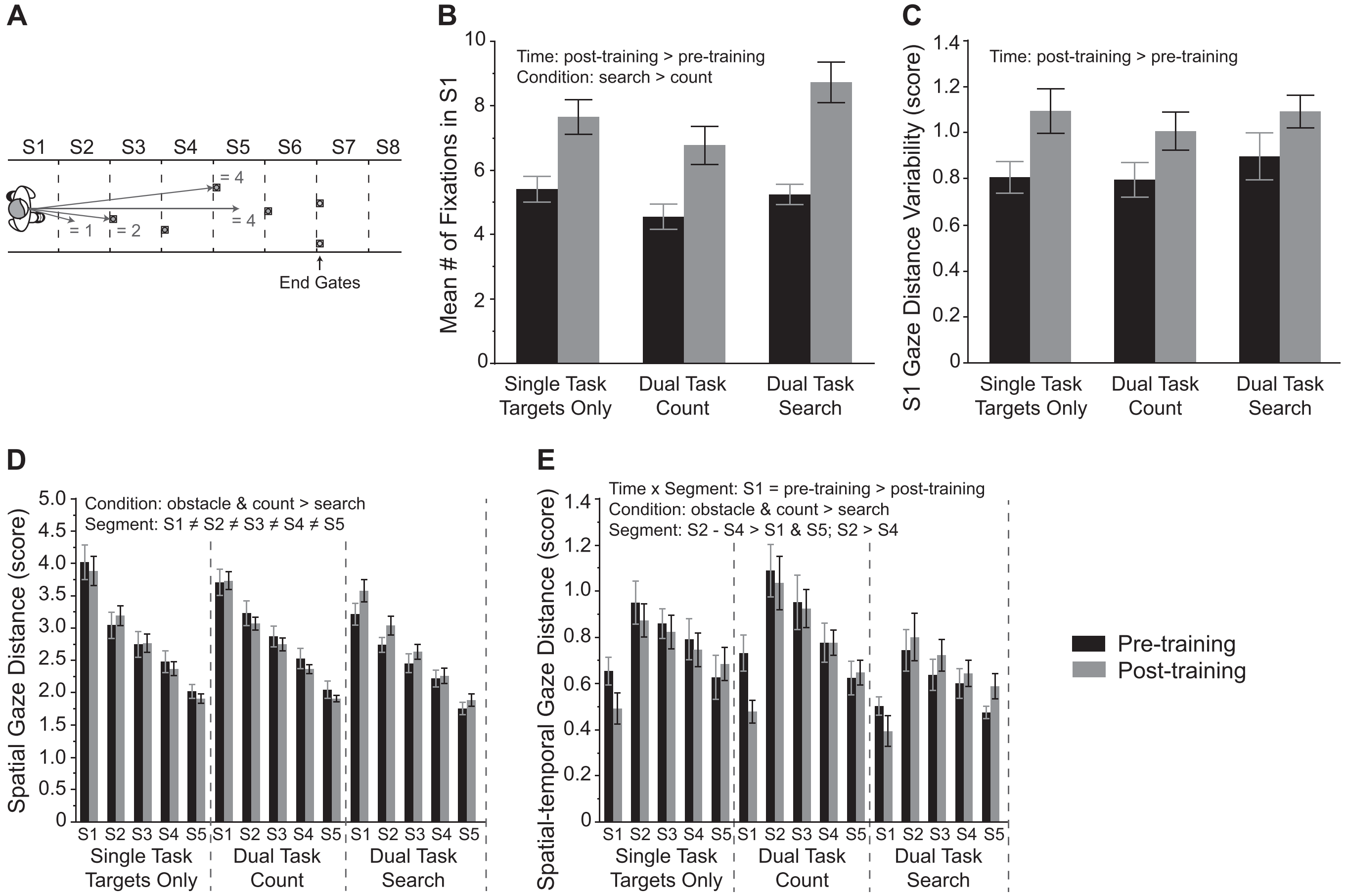

Figure 3. Gridline scan metrics and gaze distance measures for the obstacle negotiation task. (A) An illustration of how the gaze distance scores were assigned. In this example, the participant is walking in segment 1 (S1). See text for details. (B) Number of fixations made while in S1. The greater number of individual fixations suggests the use of a gridline scan after training. (C) Variability in spatial gaze distances while in S1. Greater variability suggests the use of a gridline scan after training. (D) Spatial gaze distance scores between pretraining and posttraining for each condition and across the first five walkway segments (S1–S5). (E) Spatial-temporal gaze distance scores between pretraining and posttraining for each condition and across segments. Data are represented as mean ± SE.

significant effect of time on the proportion of fixations to obstacles (time, $F_{1,55} = 0.2$, $P = 0.678$; time × condition, $F_{2,55} = 0.2$, $P = 0.780$) or with obstacle fixation durations (time, $F_{1,55} = 0.0007$, $P = 0.979$; time × condition, $F_{2,55} = 0.02$, $P = 0.982$). We also found no significant effect of time on shape fixations ($F_{1,11} = 0.4$, $P = 0.522$) or shape fixation durations ($F_{1,11} = 0.7$, $P = 0.410$).

Did mobility performance differ after training? We used the number of obstacle collisions per trial as our primary mobility measure and found a drastic reduction after compared to before training (Fig. 5A; time main effect, $F_{1,55} = 66.0$, $P < 0.0001$). Specifically, participants experienced an 88% reduction in the number of obstacle collisions per trial during the posttraining testing compared to the pretraining session. However, walking condition had no effect on obstacle collisions (condition, $F_{2,55} = 0.4$, $P = 0.642$; time × condition, $F_{2,55} = 0.5$, $P = 0.609$). As illustrated in Figure 5B, we also found a reduction in the deviation from the safest path after compared to before training (time, $F_{1,55} = 22.4$, $P < 0.0001$). In fact, path deviation was closer to zero during the posttraining session. This indicates that after gaze training, participants chose the path with the largest average gap size between obstructions. Again, walking condition had no effect on this measure (condition, $F_{2,55} = 0.9$, $P = 0.412$; time × condition interaction, $F_{2,55} = 0.8$, $P = 0.454$).

Gait speed depended on time ($F_{1,55} = 7.5$, $P = 0.008$) and condition ($F_{2,55} = 7.2$, $P = 0.002$) during the obstacle negotiation task. Specifically, participants walked slower after (0.64 ± 0.12 m/s) compared to before (0.70 ± 0.19 m/s) training. Furthermore,

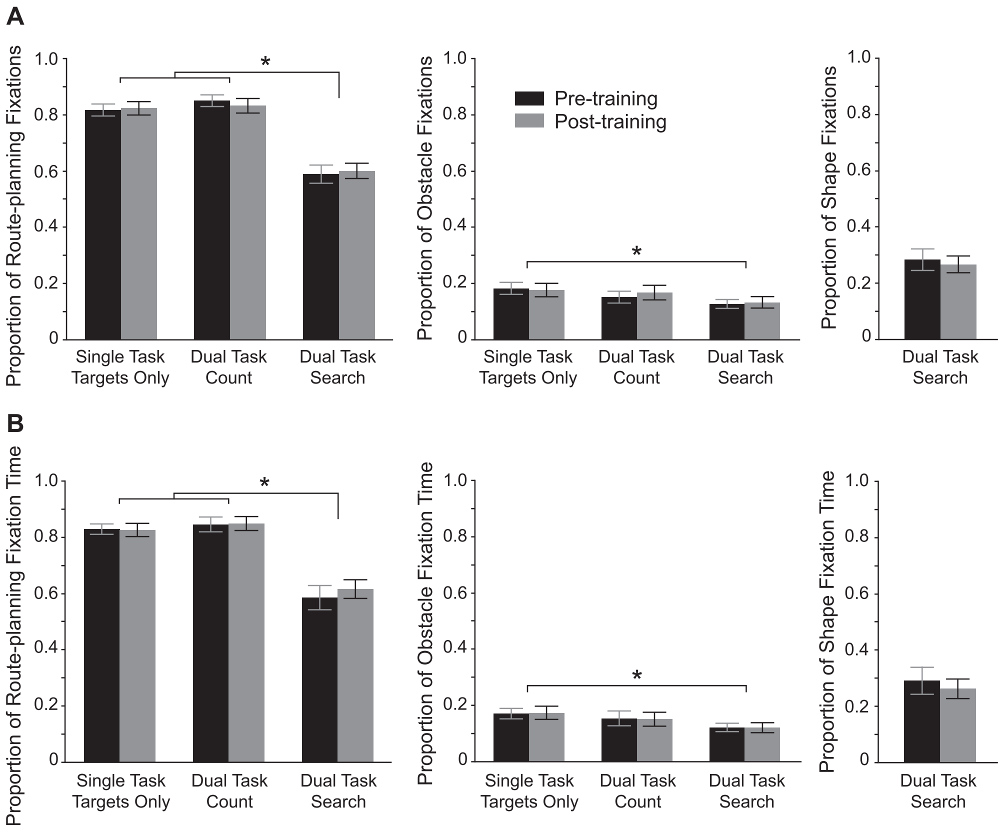

Figure 4. Gaze fixation locations and times in the obstacle negotiation task. (A) Proportion of route-planning, obstacle, and shape fixations between pretraining and posttraining and across the different walking conditions. (B) Proportion of route-planning, obstacle, and shape fixation times between pretraining and posttraining and across the different walking conditions. Data are represented as mean ± SE. *Significant main effect of condition ($P < 0.05$).

participants walked slower in the count dual (0.63 ± 0.17 m/s) and search dual (0.66 ± 0.15 m/s) task conditions than in the single task (0.72 ± 0.16 m/s) condition.

Similar to the precision walking task, we found no difference between pretraining and posttraining count DTC (–0.183 ± 0.238 vs. –0.188 ± 0.192, respectively; $t_{11} = -0.1$, $P = 0.908$) in this task. In addition, we found no difference in search DTC (–0.159 ± 0.321 vs. –0.356 ± 0.389, respectively; $t_{11} = -1.7$, $P = 0.123$).

Perceptions About the Gaze Training Program

Taken together, our results indicated that it is possible to teach people with glaucoma to change their gaze behavior during different mobility tasks. To determine how participants perceived the gaze training program, we asked them a series of questions after completing the posttraining testing session. Table 3 shows the results of this questionnaire. Participants generally were positive. In fact, 77% and 23% of those reporting Strongly Agree and Agree, respectively, that they were more aware of their environment after training. In addition, 62% and 31% of those reporting Strongly Agree and Agree, respectively, that they felt more confident while walking after training.

Discussion

Older adults with glaucoma are at a high risk for collisions with objects and falling to the ground when walking.[2,3,8,10–15] In addition to visual field loss,[11,22,39] inappropriate gaze strategies may contribute to these adverse events.[22,23] We designed a gaze training program focusing on general and task-specific gaze strategies to determine whether we could modify mobility-related gaze behavior in older adults with glaucoma. We found significant changes in gaze behavior after training that were directly related to the strategies taught. These changes were accompanied by improvements in mobility performance,

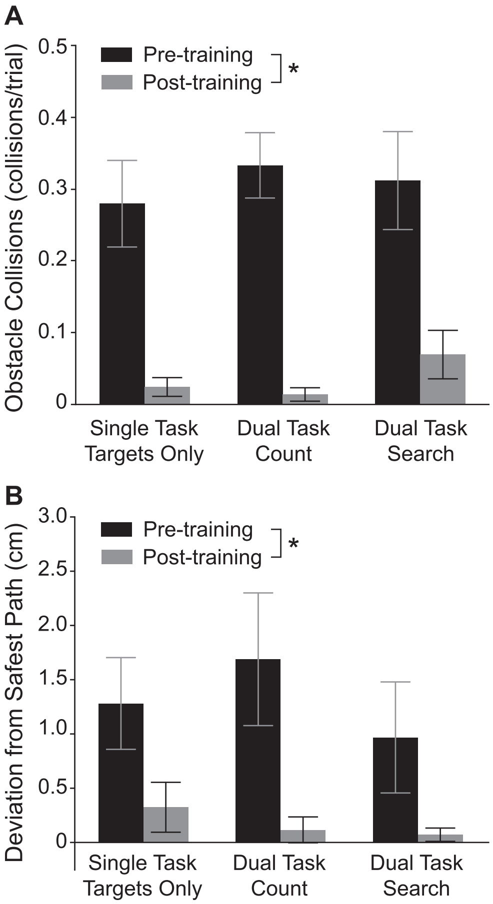

Figure 5. Mobility measures for the obstacle negotiation task. (A) The number of obstacle collisions per trial between testing sessions and across conditions. (B) Deviation from the safest path between testing sessions and across conditions. The safest path is the one with the largest average distance between two obstacles and between obstacles and the walkway borders. Data are represented as mean ± SE. *Significant main effect of time ($P < 0.05$).

including a reduction in foot-placement error and obstacle collisions. These results suggest that gaze training is a viable avenue for intervention and support the notion of conducting a larger, randomized controlled trial in this population.

The gaze training program taught gaze strategies that were geared towards ensuring accurate foot placement and avoiding collisions with obstacles. In the precision walking task, participants shifted gaze away later from the current stepping target after the training. On average, we observed a more than 350 ms difference in this measure between pretraining and posttraining, such that after training, the interval between the gaze shift away from the current stepping target and heel contact on it (i.e., HC-interval) resembled that seen for normally-sighted older adults.[23] Previous research in normally-sighted older adults also demonstrates the feasibility of teaching this gaze strategy.[28] In the obstacle negotiation task, after training, participants shifted gaze away from the obstacles sooner before walking past them. This is in line with what they were taught in the training sessions; that is, to fixate the obstacle(s) and then shift gaze to look between the gap about two steps before crossing through. This strategy is important because we naturally walk in the direction of our gaze.[34–36] Despite this strategy, participants continued to fixate the obstacle after training to the same extent as before training (see Fig. 4). In addition to this highly specific gaze strategy, our gaze training program taught participants to use a gridline scan at the start of a walking trial. After training, we found that the number and variability in location of fixations to different regions of the environment increased at the beginning of the walking path (see Fig. 3B,C). The gridline scan likely helped participants form a better spatial map of the environment, allowing them to select a more appropriate path and to reduce obstacle collisions (Fig. 5). This scanning technique is commonly taught as part of O&M training.[18,33] Interestingly, a recent study in normally sighted young and older adults found that previewing a route with stepping targets and obstacles to step over before starting to walk led to changes in gaze behavior and greater foot-placement accuracy to targets.[40] Though participants were not instructed to use a gridline scan in that study, together these results support its use. Overall, our findings clearly indicate that our gaze training program modified mobility-related gaze behavior.

Although the focus of this proof-of-concept study was on whether we could modify gaze, it is encouraging that we found significant improvements in mobility performance following the gaze training program. Specifically, a reduction in foot-placement error occurred in the precision walking task and a striking reduction in the number of obstacle collisions per trial occurred in the obstacle negotiation task. We think this latter finding is particularly important given that bumping into objects is reported frequently among people with glaucoma.[2,3,8,10]

There is minimal research on the effects of gaze training for people with peripheral visual field loss. Kuyk et al.[30] showed that visual search training in individuals with visual impairments led to a decrease in obstacle contacts on a mobility course under mesopic lighting, but not under photopic lighting. In that study, visual impairment ranged from macular

Table 3. Results of the Questionnaire About Gaze Training

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The gaze training instructions were easy to understand and follow	0.69	0.31	0	0	0
The gaze training pamphlets were helpful	0.31	0.69	0	0	0
The home-based training session was helpful	0.23	0.77	0	0	0
I am more confident while walking after the gaze training program	0.62	0.31	0.08	0	0
I am more aware of my environment after the gaze training program	0.77	0.23	0	0	0
I have started to use the gaze strategies in my daily life	0.31	0.62	0	0.08	0
The gaze training program has helped my mobility	0.31	0.62	0.08	0	0
I will continue to review the pamphlets and practice what I learned now that my participation in the research study is complete	0.46	0.46	0.08	0	0

Values represent the proportion of participants that gave that response.

degeneration (70% of sample) to glaucoma (8% of sample) to retinitis pigmentosa (3% of sample) to optic nerve disease (11% of sample). Consequently, it is unclear how the people with glaucoma fared. More recently, Ivanov et al.[29] tested people with retinitis pigmentosa and found that exploratory saccade training that forced people to make saccades into their blind visual field led to decreased reaction time in that task, and on a mobility course, led to faster walking speed and shorter fixation durations. However, the training had no effect on the number of obstacle contacts. Importantly, neither one of these studies trained gaze during realistic mobility tasks, which may have limited their results. Based on our findings, we argue that if the goal of gaze training is to improve mobility performance, then training should focus (though not exclusively) on appropriate gaze strategies to ensure accurate foot placement to avoid hazardous terrain, like a spilled drink on a sidewalk or hole in the ground, or deal with circumventing objects in the environment, like pedestrians or furniture.

Dual tasking affected gaze behavior in both mobility tasks regardless of the gaze training program. However, our primary gaze measures showed improvements following training. The dual-task conditions also increased foot-placement error in the precision walking task. Interestingly, we found reduced foot-placement error specific to the count dual-task condition, with a trend towards a reduction in the search dual-task condition. In each case, the error dropped to the level seen in the targets only condition. These findings are important, as the ability to count backwards while walking is associated with fall risk in older adults.[41,42] Furthermore, foot-placement error itself is related to fall risk.[4,43] The gaze training program likely did not reduce the error in the targets only condition, since it already matched that seen for normally-sighted young and older adults performing a similar paradigm.[23,38] It is noteworthy that we found no differences in the DTC measures between testing sessions, which suggests that participants can maintain secondary task performance (i.e., counting or searching for shapes) even after altering their gaze strategy and showing improvements in mobility. Collectively, we argue that gaze and mobility training should incorporate multitasking conditions that mimic real-life situations.

Our study has several limitations. First, we did not have a control group. We chose a single-group design because we were interested in determining the feasibility of gaze training and providing proof-of-concept that mobility-related gaze behavior is modifiable. Importantly, this study provides the necessary information to calculate a proper sample size for future glaucoma-related gaze training research (e.g., a randomized controlled trial). Although we lacked a control group, it is interesting to note that the gaze measures that changed were directly related to the gaze strategies specifically taught. This strengthens our claims that gaze training can modify gaze behavior. A second limitation, closely related to the first, is whether familiarity with the mobility tests after the pretraining session (or some effect of learning) helps to explain the posttraining results. We do not believe this is the case for three reasons: (1) obstacle and target configurations were randomized to prevent learning across trials and testing sessions (and post hoc analyses did not indicate systematic changes in any measure across the trials in either session), (2) changes in gaze behavior were in the direction that was trained, rather than showing random patterns, and (3) six of the 13 participants had participated in our previous studies using the same mobility tasks[22,23] and, therefore, were somewhat familiar with the testing procedure already; these participants still showed deficits before training (compared to normally-sighted controls from our previous work) and changes after gaze training. A third limitation is that we did not determine how long the gaze training effects lasted, since we did not perform a retention test. It is highly possible that the two, 1-hour training sessions were not sufficient to ensure long-lasting effects. A fourth limitation is that not all of our outcome measures may generalize to outside of the lab. However, many are clinically meaningful. For instance, obstacle collisions are reported commonly among those with glaucoma[2,3,8,10] and foot-placement accuracy and our HC-interval measures are associated with fall risk.[4,24,25,43] Furthermore, appropriate gaze behavior is important regardless of the environment.[22,23,38] Despite these limitations, our results strongly suggests that a randomized controlled trial with a larger sample size and a retention test is warranted. This future work should track object collisions and falls outside of the laboratory setting during and after the training.

In conclusion, we showed that a specialized gaze training program can modify mobility-related gaze behavior and alter mobility performance. Feedback from participants regarding the program was generally positive, with the majority feeling as though it helped them with their confidence and environmental awareness. Based on our findings, we recommend that gaze training programs incorporate general gaze strategies (like a gridline scan) as well as more mobility-task-related gaze strategies (to ensure accurate foot placement and avoidance of obstacles). Additionally, we recommend that training (and tests of its effectiveness) should involve multitasking situations. Before firm conclusions can be drawn on the merit of such a gaze training program, it is imperative to conduct larger, randomized controlled trials. With the price of mobile eye trackers decreasing and the performance capabilities increasing, the use and testing of gaze training is easier now than ever.

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