Gaze Training to Improve Mobility Problems Caused By Glaucoma-related Visual Deficits

by

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Abstract

People with glaucoma collide with objects and fall more frequently than normally sighted individuals. Glaucoma-related visual field loss disrupts appropriate gaze behaviour, which is necessary for foot placement and route selection through cluttered environments. Thus, we developed a gaze training intervention to modify gaze behaviour. We taught (2, 1-hr sessions) older adults with glaucoma (n = 10) appropriate scanning and task-specific gaze strategies. To assess its effectiveness, participants performed a precision walking and obstacle avoidance task before and one-week after training. After training, participants shifted their gaze away from targets later relative to stepping on them and decreased foot-placement error and error variability. In the obstacle avoidance task, participants made more fixations before walking, shifted their gaze away from obstacles earlier with respect to crossing them, and had fewer obstacle collisions. Our results suggest that gaze is modifiable in older adults with glaucoma, and that gaze training may improve mobility.

Keywords: glaucoma; visual impairment; mobility; dual tasking; gaze training

I would like to dedicate this thesis to the participants who voluntarily gave up their time to contribute to the further understanding of how their visual deficit contributes to mobility. I hope that clinicians and patients will benefit from this work and that this will lead to improved quality of life for those with glaucoma.

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List of Acronyms

AOI	Area of Interest
DTC	Dual Task Cost
DVAT	Dynamic Visual Assessment and Training
ETDRS	Early Treatment of Diabetic Retinopathy Study
HC	Heel-contact
logMAR	Logarithm of the Minimum Angle of Resolution
MET	Melbourne Edge Test
MMSE	Mini-Mental State Exam
O&M	Orientation & Mobility
OCT	Optical Coherence Tomography
S1-S8	Segment 1-8
TO	Toe-off

Chapter 1.

Introduction

Glaucoma is an eye disease characterized by a loss of peripheral vision, and is the second leading cause of blindness worldwide.[1] It is a progressive disease that is usually only diagnosed once it has become clinically significant. Although efforts are made to prevent progression of the disease with varying levels of success, at this time, there is no way to reverse the damage. Most research focuses on preserving vision but comparably little work addresses the visual field related mobility impairments. Reading, driving, shopping, and walking feel unsafe for those with glaucoma, preventing them leaving their homes and actively participating in their communities. Population-level surveys regarding the loss of mobility and increased risk of injury are well documented.[2–8] Gait changes associated with vision loss are also known, which might contribute to increased risk of falling.[9] Recently, our lab demonstrated that changes in gaze behaviour in glaucoma contribute to mobility deficits, and thus may increase the risk of falling. These results suggest that a gaze training program may be warranted to help improve mobility. This thesis provides a proof-of-concept study to establish the feasibility of a gaze training program to alter gaze behaviour in older adults with glaucoma.

Chapter one comprises of a literature review, starting with an introduction to the pathophysiology and current treatments for glaucoma, followed by an explanation of the crucial role vision plays in walking, and gaze behaviours that allow us to navigate our environment. A description of gaze behaviour and mobility changes with age and peripheral vision loss disease will follow. Current gaze training protocols and orientation and mobility practices and limitations provide rationale for a gaze training protocol for glaucoma. Chapter two outlines the intervention and results of gaze training for a precision walking task and obstacle avoidance task. Lastly, Chapter three includes an additional discussion of the findings of this thesis, and their implications for improving future training and quality of life for those living with glaucoma.

1.1. Glaucoma

Glaucoma affects over 70 million people worldwide, with 10% of those affected being bilaterally blind.[10] Unfortunately, glaucoma goes undetected until it has caused extensive damage. In fact, only 10-50% of people with glaucoma even know they have it, and patients may progress from a mild to moderate stage of visual field damage without noticing it in their daily routine.[5] It remains asymptomatic because it is difficult for patients to notice impairments in the peripheral visual field, the disease progresses slowly, and because the better eye often compensates.[11] Thus, treatment is often sought too late; however, even if the disease is caught early, there are only treatments available to slow it rather than reverse or stop it.

1.1.1. Pathophysiology

Glaucoma is a group of optic neuropathies characterized by slow and progressive degeneration of retinal ganglion cells.[12] Retinal ganglion cells are neurons with their cell bodies in the retina and their axons in the optic nerve, making them a part of the central nervous system. The pathogenesis of glaucoma is unclear; however, increased intraocular pressure seems to contribute to retinal ganglion cell death. Intraocular pressure is controlled by the balance of the production of aqueous humor from the ciliary body and outflow through the trabecular meshwork. When the production of aqueous humor is greater than the outflow, intraocular pressure rises and may lead to glaucoma.

The two main categories of glaucoma include open-angle glaucoma and angle-closure glaucoma. Most cases of glaucoma are open-angle but angle-closure glaucoma accounts for the most severe vision loss.[13,14] Patients with open-angle glaucoma experience increased resistance to outflow of the aqueous humour through the trabecular meshwork. This promotes increased intraocular pressure and causes mechanical stress and strain on posterior structures of the eye, including the lamina cribosa. The lamina cribosa is perforated for the central artery, vein, and retinal ganglion cells to exit the eye.[15] Thus, it is the weakest point and is most vulnerable to compression, deformation, and remodeling. As a result, there is mechanical axon damage and disruption of axonal transport of trophic factors to retinal ganglion cells from the lateral geniculate nucleus.[16,17] Mitochondrial damage in retinal ganglion cells and astrocytes prevents high levels of energy from being met, leading to cell death.[18] Blood enters the eye centrally, making nerves far from the fovea most vulnerable to damage, leading to peripheral vision loss.[19]

1.1.2. Clinical presentation and diagnosis

There is no single reference standard to diagnose glaucoma. High intraocular pressure is a common risk factor for the presence and development of glaucoma. Pressures greater than the normal range of 12-22 mmHg are often flagged and some physicians will treat this as glaucoma. However, many people with elevated intraocular pressure never develop glaucoma and are described as ocular hypertension.[20] Furthermore, 25-50% of individuals with glaucoma have intraocular pressures less than 22mmHg and are diagnosed with low tension glaucoma.[16,20] Visual field defects can confirm a diagnosis, but 30-50% of retinal ganglion cells must be lost to be detected by standard visual field testing.[15,21] Thus, other visual exams are necessary to confirm a diagnosis of glaucoma.

The most significant features of glaucoma diagnosis are distinct changes in the appearance of the optic nerve head (optic disc) and retinal nerve fiber layer.[20] Clinicians look for a characteristic “cupping” appearance of the optic nerve head. As the optic nerve dies, the size of the center of the disc becomes larger relative to the size of the entire disc. A cup-to-disc ratio of greater than seven-tenths is indicative of glaucoma.[22] Recently, laser scanning imaging techniques, including confocal scanning laser ophthalmoscopy, scanning laser polarimetry, and optical coherence tomography (OCT), have improved the early identification of glaucoma and tracking of optic nerve fiber loss over time. OCT creates cross-sectional images of retinal and optic nerve tissues using depth-resolved reflection of near-infrared light to micrometer resolution.[23] This early diagnosis of glaucoma helps to slow progression of disease and maintain quality of life.[24]

1.1.3. Treatment and limitations

The main goals of treatment are to arrest disease progression and preserve visual function and quality of life.[20] To-date, the only reliable method to treat glaucoma is lowering intraocular pressure.[25] Glaucoma patients who receive treatment for ocular hypertension show less disease progression than untreated patients.[26] Medications to decrease intraocular pressure to a targeted range of 20-50% of glaucomatous levels are delivered as eye drops, and is necessary, oral tablets. They work by either reducing aqueous humor production, increasing aqueous humor outflow, or a combination of both.[19] When medications are unsuccessful or not tolerated due to side effects, laser and incisional surgeries are an option. Laser trabeculoplasty lowers intraocular pressure by causing physical changes to the trabecular network that are conducive to drainage. It is safe, quick, and effective, but not a permanent fix, as effects decrease 10% each year.[19] An incisional surgery, trabeculectomy, lowers intraocular pressure by removing a piece of the trabecular meshwork or nearby corneoscleral tissue to create a drainage pathway for the aqueous humor. Devices to drain aqueous fluids into an external reservoir are available but risk scarring and infection. Surgeries with lower risk and success rate are available but are temporary and cannot be repeated indefinitely. Thus, it is often necessary to seek out alternative means to help improve the quality of life for those with glaucoma.

1.1.4. Symptoms of glaucoma

The peripheral vision loss that occurs with glaucoma has a significant impact on multiple aspects of patients' lives. They report difficulty with mobility, driving, reading, and other everyday tasks.[27,28] Mobility issues include trouble while shopping and crossing the road, bumping into objects, and increased risk of falling.[29] This is likely a result of difficulties with lighting including glare and adapting to different levels of light,[30] increased disability for night vision,[3] difficulty judging distance and noticing objects to the side,[6] and changes in gaze behavior.[31] Overall, this reduces travel away from home and self-reported quality of life.[32] Furthermore, side effects and administration of treatment can result in decreased satisfaction of treatment.[33] This promotes a physiological burden. Patients with glaucoma are more likely to have depression and anxiety than age-matched controls.[34] Thus, patients must seek ways to improve quality of life outside of medical treatment.

1.2. The role of vision in walking

During adaptive locomotion, where we must modify our movement patterns in response to environmental constraints,[35] we direct our gaze towards the desired future path or objects of interest.[36,37] This allows us to plan paths,[38] modify locomotor patterns,[39–41] and make appropriate stepping corrections.[42–44] As a result, we can avoid disruptions of balance by different ground terrain, ensure obstacles are avoided,[45,46] and navigate towards a goal.[46] To accomplish this, we must acquire the appropriate visual information at the correct time. Optic flow, which is the change in the appearance of light on the retina resulting from relative motion between the eye and the environment,[47] helps set our trajectory and detect impeding objects. Fixations stabilize optic flow patterns and help individuals align themselves with the visual goal.[48–50] Both central and peripheral vision are important for the detection of self-motion.[51] However, some research suggests that optic flow is utilized by central vision primarily to guide heading direction, and by peripheral vision primarily to update our representation of our surroundings for navigation.[52] To acquire this appropriate visual information, distinct patterns of visual sampling are seen depending on the environment and goal.

1.2.1. Vision for precision walking

The ability to safely place our feet is crucial when walking on ground terrain that is varied, uneven, or cluttered. Fixations are rarely directed to the floor when there is no object of interest present; rather, they are made further out into space along the travel path.[53–55] As the terrain becomes more complex and considerably more precision is required, we look closer to our feet and use peripheral vision to monitor foot placement.[45] There are consistent and important spatiotemporal patterns between when we look to a ground location and when we step there. When stepping on targets[40,56–61] or going down stairs,[62] people fixate about one to three steps ahead depending on task constraints. Although vision helps plan paths and maintain orientation, these ground fixations emphasize the importance of vision in controlling foot placement when precision in important.

The nervous system pre-plans swing trajectory to future targets before the toe leaves the ground[63–65] and monitors foot placement throughout the step using peripheral vision. For instance, when precision is required, a saccade is typically made to a target prior to initiating the lift phase of the foot to swing to that target and fixation is maintained until heel contact.[57,58] If this timing if interrupted by allowing visual input only during certain intervals, walking becomes awkward and lacks coordination, although some people show a resilience to these interruptions.[58,63,66] In cerebellar patients with oculomotor deficits, a delay in target fixation is associated with delays in generating accurate steps, and inaccurate eye movements are associated with missed steps.[67] This is also seen with intoxicated healthy individuals, where inaccurate eye movements result in stepping deficits.[68] Visual denial after toe-off towards the stepping target does not influence the swing limb trajectory, but if visual denial occurs prior to toe-off, foot-placement error increases.[63,64] Although this preplanning is quite robust, during the movement (i.e., online), visual feedback about foot position relative to the target is used to make rapid modifications to the ongoing action to ensure success.[69]

Peripheral visual feedback is important to monitor foot placement and to allow for online modifications when precision is paramount for safe travel.[70–72] When the lower peripheral field is blocked, participants tilt their heads down, slow their walking speed, and decrease their step length to compensate while walking over varied terrain.[72] If the lower peripheral field is blocked while walking towards an item to reach on a table, people place their feet further from the table to increase the safety margin to avoid a collision.[71] The "two step" hypothesis suggests that foot placement is most accurate when the next two targets are visible simultaneously. This way, we gather information about two consecutive footfall areas to best plan the steps. Because we can only fixate one target at a time, peripheral vision is necessary to monitor this.[65] Thus, while preplanning is crucial for success during precision walking, monitoring ongoing actions with peripheral vision is also necessary to modulate performance.

The coordination between gaze shifts and stepping seems important not only to acquire the correct visual information at the right time, but also simply to coordinate the eye and limbs. Even when targets are invisible[57] or when we walk in the dark,[73] this eye-stepping synergy is still observed.[63] In these cases, the brain uses corollary discharge to the eye as a feed-forward signal, guiding the body in the necessary direction.[63] Therefore, the fixation location during locomotion must align with the desired path. Thus, this tightly linked pattern of gaze shifts and action are important both for acquiring the appropriate visual information and to coordinate movement.

1.2.2. Vision for obstacle avoidance

Every day, we must navigate through areas cluttered with multiple obstacles (e.g., objects and people). This requires constant information updates regarding the environment. Depending on the nature of the obstacle, we might choose to step over it or to walk around it. To help make this decision, we can judge the obstacle size and position from a distance and update our body position within the environment as we walk.[74] Thus, vision is critical for safe, collision free locomotion in these situations.

Vision provides important information about the position and height of an obstacle ahead of time to plan the proper movement towards it. This is an example of how visual input acts as a feedforward signal. The distance to an obstacle is monitored during the approach and intermittent fixations on the obstacle likely contribute to updating obstacle distance.[74] The information inherent in optic flow is superior to static visual inputs in obstacle avoidance tasks.[75] People normally do not scan the environment ahead of time to plan a route, rather they start walking right away.[46,76] When people visually sample the environment three steps after walking is initiated, they experience fewer obstacle collisions than when they only viewed the obstacle prior to walking. Similarly, when vision is blocked during the approach, this initial dynamic visual sample over the 1-2 strides is enough to extract the necessary visual information to successfully cross the obstacle.[38] The advantage of dynamic visual information, especially when avoiding a single obstacle,[75,77] is that the optic flow provides information to help guide whole body movements.[78] Thus, even initial dynamic visual sampling is adequate to control the variability of foot placement.

Locomotor adjustments are initiated a few steps prior to reaching the obstacle, emphasizing the role of vision in planning actions at a distance. For example, when there is an icy spot on the ground, alternative foot placement needs to be chosen in advance. This requires lengthening the stride[79,80] a few steps before reaching the obstacle.[80]. Indeed, when vision is blocked during the approach to an obstacle, participants can still step over the obstacle, but with less precision.[38] Timely visual input is also required to step over an obstacle.[81] When stepping over obstacles, people fixate on the ground beyond the obstacle where they will step rather than on the obstacle.[74] Gaze is directed at a distance of two to three steps ahead and towards the ground just past the obstacle, that is, the landing area. Similarly, we alter our trajectory prior to circumventing an obstacle. Gerin-Lajoie et al.[82] investigated how participants circumvented a mannequin that crossed their path from the right to interrupt a straight walking path. Participants initially modified their trajectory to pass behind the mannequin about six steps before crossing the mannequin and made a large change 1.5 m before. This highlights that feedforward visual information is important for altering our trajectory, but that we also need to continuously update this information in dynamic environments.

When we need to go around an obstacle or pass through an opening, we must make locomotor adjustments, such as a shoulder rotation,[83] while maintaining the same trajectory. This requires altering our center of mass, which can be done via two different strategies: foot-placement modifications and trunk roll about the anterior-posterior axis.[79,84] This must be done in a way that conserves energy. Donelan et al.[85] proposed that a major component of the metabolic cost of walking is determined by the work required to redirect the center of mass and maintain stabilization. Thus, people choose routes that allow them to avoid clusters of obstacles[46] to minimize the amounts of turns needed, although sometimes this cannot be avoided.

When passing through openings, we must rotate our the bodies by a sufficient amount to ensure a margin of 6-8 cm on either side.[56] The critical aperture to shoulder width ratio[86] defines the relative width of an opening that requires an individual to rotate their shoulders to pass through. This is normally 1.1-1.3 times shoulder width.[86–88] This rotation tends to occur just two steps prior to crossing an opening.[35] Perception of a passable gap depends on many factors, including the width of the gap, judgement of body size, and the direction of gaze.[89] Higuchi et al.[90] had people walk through openings of various widths while holding bars of various lengths. Larger bars required smaller amplitude of rotation but yielded the same spatial margin as bars of other sizes. Thus, we can flexibly change the magnitude of rotation to ensure a minimal spatial margin between our body and obstacles.

Where we orient our gaze directly affects where we step and the trajectory we take.[91,92] Changes in head orientation precede rotation of all other body segments,[79,84,92] suggesting that repositioning the head towards the intended travel direction provides a stable frame of reference for both the visual and vestibular system.[93] When people are prompted to alter their walking trajectory, they make saccadic eye movements and head rotations to align their gaze with the new goal location prior to altering their travel path.[48] This is clear when people look in between obstacles towards their goals and at the border of the path they choose. While passing thorough an aperture, most fixations are directed to the aperture, with a smaller proportion being directed to the edges.[94] As people approach apertures they generally look at the edges to monitor the characteristics of the gap. As they get closer, however, they start to look less at the edges and more towards the center to guide their trajectory.[54] This supports the notion that we tend to look where we want to go, and in this case, it is through the opening.

In dynamic, unpredictable environments, we are able to utilize the probabilistic structure of the environment to proactively allocate gaze towards more unpredictable parts. When walking in an environment where pedestrians have different probabilities of colliding with you, people prioritize fixations towards the pedestrians most likely to be involved in a collision.[95] Participants look both sooner and longer towards these dangerous pedestrians. Similarly, Cinelli et al.[54] investigated how people navigate through a door opening that moved to the side as soon as they began walking. Regardless of the direction the door initially moved, subjects initially aim for the middle of the static doorframe, not the middle of the opening. Alignment with the center of the doorframe allows them to move in either direction. Thus, the authors suggest that participants simplify the task by aiming for a space that will most likely avoid collisions. Once they reach the middle of the pathway, they aim for the middle of the door while maintain gaze on the aperture. By fixating parts of the environment that are uncertain or provide the most information, people can monitor the environmental dynamics better to avoid potentially dangerous collisions.

Not all obstacles are fixated directly, suggesting that peripheral vision must supply the necessary information to avoid potentially harmful collisions.[46,96] For example, in a treadmill walking paradigm, subjects were able to avoid tripping over a suddenly appearing obstacle when they were looking two steps ahead and not directly at the obstacle.[45] To determine which parts of the visual field are important for stepping over obstacles, Graci et al.[97] manipulated the amount of visual field occlusion while negotiating an obstacle. Regardless of condition, subjects successfully crossed the obstacle, suggesting that visual information acquired in a feedforward manner was sufficient for obstacle negotiation. However, when the lower peripheral field was blocked, there was increased variability of toe-clearance. This suggests that the lower peripheral field is important to make final adjustments to gait.[6] In addition, children and adults can successfully navigate cluttered environments with only intermittent fixations on obstacles in their path.[46,72,96] Indeed, peripheral vision is notably important for gathering and updating the spatial structure of an environment that an individual is about to pass through,[98] and allows them to prioritize fixations on objects to avoid or pursue. This spatial map is also critical when the end goal cannot be seen, as individuals can use landmarks to navigate through an environment.[52,99] Given the importance of peripheral vision in maintaining heading direction, monitoring foot placement, and forming a spatial maps, it is understandable that those with reduced peripheral vision due to age and disease have difficulties navigating in various everyday environments.

1.3. Gaze-related mobility changes with age

With age, a decrease in contrast sensitivity, depth perception, and visual acuity makes circumventing around obstacles more difficult, reducing the ability of older adults to safely navigate through cluttered environments.[100] Corrective lenses are used to compensate for some of these problems but can decrease contrast sensitivity from the reflective blur, thus reducing stepping accuracy.[101] Reduced stepping accuracy can lead to increased fall risk; most falls occur during locomotion on uneven surfaces[102] or stairs[103] as a result of poor control of foot placement.

In addition to diminished visual function, older adults use peripheral and central vision to visually sample the environment differently than younger adults.[104] Older adults seem to rely more on central vision, whereas younger adults use both central and peripheral vision, allowing them to better fine-tune their actions.[104] When older and younger adults have their peripheral vision blocked, only younger adults show a change in walking cadence. The opposite is true when central vision is blocked where only older adults show a change in walking cadence.[104] This may contribute to a reduced capacity to use online visual feedback or stored visual information rapidly, or stored visual information to guide their movements, and the resulting changes in gaze behaviour.[105–107] These differences may contribute to mobility deficits and fall risk.

1.3.1. Precision walking

Age-related declines in the visuomotor control of foot placement during precision walking tasks can distinguish fall risk.[108] In a multitarget stepping task, where individuals must step onto assigned squares while avoiding distractor squares, older adults with a high risk of falling have a poor ability to control foot placement towards the assigned squares. Additionally, they step on distracters more often than those at a low risk of falling. The authors suggest this is due to poor path selection and not the inability to identify targets from distractors. Although this clearly demonstrates that difficulty in controlling foot placement is linked to increased fall risk, it also suggests that poorly planned paths lead to inappropriate foot placement and could contribute to fall risk.

There are also differences in age-related gaze patterns and ability to control foot placement between young and older adults, as well as between older adults at a high and low risk of falling.[60,109] Compared to younger adults, older adults look away from targets earlier relative to heel contact (early gaze transfer). Older adults who are at a high risk of falling show a similar, more extreme pattern of early gaze transfer that is accompanied by increased foot-placement error compared to those who are at a low risk of falling.[56,60,61] In Chapman et al.,[60] young adults fixated a target until after their heel contacted it. Older adults looked away from the target before heel contact, with those at a high risk of falling looking away much earlier. Those at a high risk of falling fixated a second target longer, and looked away from the first target earlier with respect to heel contact.[60] This is also seen when the second target requires a change in walking direction.[110] This early gaze transfer away from the target was accompanied by foot placement accuracy differences, where low-risk older adults were the most accurate, while high-risk older adults had the highest error variability amongst groups.[60] Thus, looking away from a target too early with respect to heel contact contributes to poor foot-placement accuracy and is related to fall risk.

Another interval that changes with age, but does not necessarily distinguish fall risk, is the interval between looking towards a target and toe-off to step there. Regardless of age, participants transfer their gaze to the stepping targets before toe-off to step to them.[60,109] Although both young and older adults produce anticipatory downwards saccades before initiating a step onto a raised platform, older adults perform this saccade earlier with respect to toe-off than younger participants.[111] Similarly, older adults, both low and high risk groups, look to targets earlier with respect to toe-off than young adults.[60] Both the high and low risk older adults fixate the first target longer than the second, and fixate all targets longer than younger adults. An earlier saccade with a longer fixation may be reflective of older adults needing more time to acquire and process visual information about the targets and obstacles, or to program the appropriate motor response. This could be attributed to an age-related decline in general visual function,[112] slowed cognitive processing,[113,114] or a decline in visuomotor processing.[115] However, a similar strategy is seen in older adults who are anxious about future steps,[61] so looking too far ahead could also be anxiety provoked. Regardless, this strategy is generally accompanied by poor control of foot placement and increased risk of falls.

These gaze changes are exaggerated with increased task complexity. When only one target is present, both older and younger adults fixate the target until heel contact.[116] However, with increased task difficulty, such as with multiple targets, the latency between the saccade and toe-off increases, but with similar stepping accuracy.[117] When the task is complicated by the addition of an obstacle, older adults at a high risk of falling transfer their gaze away from targets earlier and have higher task failure compared to older adults at a lower risk of falling and younger adults.

Together, these results suggest that older adults, especially those at a high risk of falling, are looking further ahead of their current step than younger adults; this is exaggerated as task complexity increases. This behaviour is related to an inability to control foot-placement accurately and is associated with fall risk. The relationship between gaze behaviour and stepping accuracy suggests that increased foot-placement error variability is partly attributable to the early termination of target fixation during swing phase. This suggests that in a cluttered environment, high risk older adults may prioritize the planning of future actions over ongoing stepping movements. Although they might be doing this because of increased visual processing times, this strategy may actually lead to more falls and trips, as it decreases stepping accuracy.

1.3.2. Stair negotiation

Similarly to when stepping to targets, when walking on stairs, older adults fixate the next step earlier relative to the onset of toe-off compared to younger adults, independent of stepping speed.[111] They also fixate longer on the stairs,[62,118] and generally direct their gaze downward to the travel path compared to younger adults.[62] Whereas younger adults have widely distributed gaze, older adults seldom look more than 4 steps ahead,[62] and have more vertical than horizontal eye movements.[118] This is accompanied by a longer stance phase, and lower cadence.

1.3.3. Obstacle avoidance

Older adults experience increased numbers of collisions when stepping over obstacles.[119] This may be due to a failure to detect an upcoming obstacle, poor path choice, and/or an incorrect modification of gait. Similar gaze patterns are seen in older adults during obstacle avoidance as when precision walking and when walking on the stairs.[120] Older adults make saccades towards obstacles earlier with respect to toe-off and maintain gaze for longer.[111] Those with lower cognitive function have more collisions with the obstacles, make fewer downward saccades before stepping, and look at the target before an obstacle earlier with respect to stepping to it.[121] Chandra et al.[122] looked at the changes in gaze behaviour while stepping over obstacles and onto targets under restricted vision and time pressure with aging. They found that compared to young adults, older adults shifted gaze towards or on the obstacle earlier, and maintained gaze for a longer period of time. When high precision was required, older adults turned their gaze more downward than the younger adults, suggesting that they might be compensating for reduced peripheral vision, and needed more visual information to act successfully.[60,75] Consistently, Di Fabio et al.[120] found that older adults looked down longer than young adults before stepping over an obstacle. High and low risk older adults did not differ in speed despite their difference in gaze behaviour, so these differences in gaze behaviour cannot be attributed to a slower walking velocity.

While walking around obstacles, older adults show a different pattern of gaze[104,123] and body reorientation sequences.[98] Young adults initiate the reorientation sequence with head and trunk yaw, followed by rapid shifts of gaze, then medial-lateral foot displacements. On the other hand, older adults initiate whole body rotations in time with the beginning of a saccade to the direction of the turn. This is then followed by head, trunk, and feet re-orientations.[123] They do not use any head yaw movements. Keeping their head still may help stabilize the frame of reference[93] to help them maintain dynamic stability while negotiating the obstacles. Older adults also rotate their shoulders less than younger adults,[124] indicating that they try to prevent a change in trajectory, thus simplifying the task.

Older adults adopt a more cautious walking and gaze strategy before and during obstacle circumvention. When given a late visual cue in an obstacle circumvention task, older adults look towards the ground two steps before crossing the obstacle, whereas younger adults look mostly at the obstacles and the wall beyond them.[123] In addition, older adults use a shorter step length, slower velocity, longer turning times, and great side-to-side eye movements both while walking on a straight path, and while turning.[123,125] This might help ensure that older adults have adequate time to gather and process visual information and make appropriate adjustments. Younger adults may use their peripheral vision more efiiciently[104] and require less visual information of the ground beyond the obstacle ahead of time. Thus, this suggests that older adults compensate for their aging visual system by taking more time to scan the environment.

1.4. Mobility and peripheral vision loss

Peripheral visual field loss results in difficulties with orientation and mobility,[126,127] and visual dysfunction is an independent risk factor for increased fall risk.[100,128,9,129] Up to half of those with glaucoma fall over the course of a year, and up to one third experience falls resulting in injury.[130–132] They are three times more likely to have a fall than a normally sighted individual, even after adjusted for age, gender, body mass index, medications, and better eye visual field.[29] Falls are a leading cause of death[133] and injury[134–136] in elderly over 65 and injuries due to falls increase the risk of admission to nursing homes.[126,127,137] Mobility problems such as altered balance while standing,[138,139] slower walking speed, [127,8] increased obstacle collisions,[8,140–143] and more mobility incidents (bumps, stumbles, and orientation problems)[140] restrict the amount of independent travel of individuals with glaucoma.[140] When individuals with glaucoma are asked to name aspects of everyday life that they feel are impacted by their visual field loss, they list mobility, driving, and fear of falling.[144,145] Anecdotally, this tends to occur in crowded school corridors and supermarket aisles, but the greatest concern is in open space environments such as shopping malls, buses, trains, airport terminals, and city plazas and parks. These mobility impairments lead to reduced physical activity levels[146] and increased fear of falling.[147]

1.4.1. The effects of peripheral visual loss on mobility

Many visual factors including total visual field, contrast sensitivity, visual acuity, and motion sensitivity are important for mobility. However, most studies find that some measure of visual field is most highly correlated with the time taken to complete a mobility course, errors made,[126,127,140,143,148–152] collisions with obstacles,[126,140,153] and tripping.[153] In particular, individuals with loss in the left and inferior mid-peripheral areas have the most significant mobility limitations[143] and highest fall risk.[130] The central and lower peripheral field are most important to walking speed, although loss of the central 20 degrees leads to most collisions[154] and self-reported walking difficulties.[155]

Peripheral vision loss results in difficulty maintaining an accurate representation of space.[156,157] This leads to orientation errors during locomotion[3] and in poor route selection and wayfinding.[143,158–160] During a task where individuals had to navigate through rooms with various reference cues or those with only a central cue, individuals with glaucoma were slower at performing the task in the first room but not the latter,[160] and this was significantly related to the visual field. The authors suggest that the allocentric frame of reference, which is a frame of reference centered on external objects, may be impaired in glaucoma. This may be due to the lack of coherence between successive fixations preventing an accurate representation of the location objects in space.

Visual field limitation causes deficits when stepping on targets,[31] and avoiding obstacles,[161] which can contribute to increased fall risk.[52] Jansen et al.[161] had participants wear visual field restricting glasses while either stepping over an obstacle, or steering through a multi-obstacle environment. When the visual field was restricted to an intermediate size, they maintained gait speed and planned paths that gave them a larger safety margin. When the visual field was reduced further, they also slowed down. A decreased visual field also resulted in poor path selection. Individuals with glaucoma had increased foot-placement error and foot-placement error variability when stepping to targets.[31] This worsened when a dual task such as counting was added. Poor performance correlated with visual field loss.

Individuals with glaucoma demonstrate changes in several gait parameters. For instance, stride-to-stride variability and slower gait speed are seen in those with glaucoma, and are associated with falling in older populations.[162–164] Mihailovic et al.[9] used the GAITREite Electronic Walkway to investigate measures of gait that may identify glaucoma patients at risk of falling under single and dual task situations (carry a cup or tray). Worse integrated visual field sensitivity associated with greater variation in step length, stride length, and stride velocity during both single and dual task conditions. Gait speed only decreased when carrying a tray, similar to other studies that show decreases in gait speed when walking in challenging conditions such as an obstacle course.[8,154] During dual tasking, visual field loss was associated with more left-right drift, suggesting that those with more severe visual field loss have difficulty maintaining a straight line while walking. Many gait alterations were only associated with integrated visual field sensitivity during dual tasking conditions, suggesting that individuals with visual field loss expend a great deal of cognitive effort towards gait.

1.4.2. Changes in gaze behaviour associated with peripheral vision loss

The loss of peripheral vision associated with glaucoma has profound effects on the execution of saccades and how the environment is sampled. Gaze shifts cannot be made to areas of the environment that are not seen. Because salient visual stimuli are important for the triggering of saccades, reduced peripheral vision may impact the ability to make appropriate saccades. Accordingly, people with glaucoma exhibit changes in the frequency, latency, and size of saccades.[165,166] In many cases, visual field loss results in restricted eye movements, resulting in patients making fewer saccades and looking to different locations of the environment than controls with healthy vision when the scene is static, such as an image.[165,166] In others, more eye movements are made. In a shopping task, individuals with glaucoma took longer to complete the task and made more saccades towards the visual defect. When making a sandwich and completing an unfamiliar model, those with glaucoma made more eye and head movements, scanned longer, had longer fixations, and looked more at irrelevant objects.[167] These results suggest that they need more time to recognize and discriminate relevant from irrelevant objects in areas of the visual field with less sensitivity. If not compensated, this change in gaze behaviour can affect performance during visually guided tasks.

Experiments that examine changes in gaze behaviour with driving receive a great deal of attention[29,168–172] since glaucoma is an important risk factor for self-reported crashes.[29,131,173–178] Drivers with glaucoma have difficulty detecting hazards, maintaining lane positions, changing lanes, and planning ahead.[179] Some studies have found links between visual field loss and driving safety[175,180] whereas others have not.[170–172] Compared to those who drive unsafely, those who drive safe show increased exploratory activity.[170,171,181] Unsafe drivers make shorter eye movements with less amplitude, longer but fewer fixations, and maintain a more straight ahead eye position.[170] These same gaze patterns are associated with an inability to acquire visual information in a quick, effective manner using video-based hazard perception tests, where individuals must identify hazards in a driving scene.[182] Because new information is acquired using fixations, fewer saccades may hinder processing of the visual scene. Driving studies provide evidence that compensation through effective head and eye movement strategies is possible, and thus, glaucomatous vision loss does not always lead to poor performance. How glaucoma affects gaze behaviour in other common motor tasks is less clear.

1.4.3. Changes in gaze behaviour during walking tasks

During walking, many studies suggest people do not compensate for their peripheral vision loss.[183–185] Patients with peripheral vision loss have a narrower horizontal distribution of saccades than normally sighted individuals, but a similar vertical distribution.[182] This may be a result of fewer salient objects eliciting saccades towards the sides and the need to scan up and down for obstacles on the ground. This can impair mobility and judgement of time-to-contact. For example, when street-crossing, those with peripheral visual field loss have a smaller fixation area and make fewer fixations to task-relevant areas. This associated with trouble judging when it was safe to cross a 4-lane street.[186]

However, other studies find that people with visual field loss make more saccades towards the areas of visual field loss, but that these fixations are not necessarily appropriate. Those with tunnel vision make frequent saccades out of their visual field during both visual search and walking experiments.[187] One third of their saccades are made outside of the visual field while walking, and two thirds while searching. However, these saccades are often made towards inappropriate areas of the environment; they mostly fixate downwards at objects or the walls instead of the path.[53] Patients scan downward when they walk in environments containing tripping hazards but not when walking in less cluttered environments,[185,187] suggesting that they do make voluntary saccades to gain information of their surroundings. Authie et al.[188] explored gaze changes during a goal-oriented locomotor task in individuals with retinitis pigmentosa. Patients walked through an obliquely oriented doorway with or without an obstacle in the path. Whereas controls only looked proximally and towards the aperture, patients looked at the floor and towards the proximal and distal edge of the doorframe. The authors suggested that this increased exploration and proactive target selection, and downward fixations allowed for adequate visual sampling and successful path planning and execution.

Systematic scanning is important for visual exploration, navigation, and obstacle avoidance.[181,182,189,190] Thus, the ability to perform a visual search task can be used as a predictor of mobility in those with visual impairment.[189] Individuals with severe visual impairment and controls performed a visual search task where they were instructed to find a target in a sea of distractors. Walking through an obstacle course as fast as possible without making contact with obstacles or boundaries assessed mobility performance. Those with visual impairment were slower at performing the search task—which associated with more obstacle contacts—and took longer to complete the mobility course. Those with worse visual field and poor scanning ability were not even able to finish the mobility course.[152] Compared to normally sighted controls, those with peripheral vision loss made more eye movements to scan vertically, likely as a safety strategy to avoid obstructions at head level or on the floor.[185] Accordingly, those with glaucoma who made more saccades beyond their visual field showed better search performance.[190]

Recently, our lab investigated the differences in gaze behaviour between older adults with and without glaucoma during a precision walking task. When walking and stepping on targets, those with glaucoma looked to targets earlier with respect to toe-off, and away from targets earlier with respect to heel contact. Both of these intervals correlated with increased foot-placement error. This suggests that individuals with glaucoma need more time to plan steps. However, in looking away from the target too early, they rely on their degraded peripheral vision to control foot placement. Indeed, blocking the inferior visual field while walking increases toe-clearance variability while stepping over an obstacle,[75,191] and causes people to tilt their heads to compensate on complex terrain.[72] Thus, the combination of improved systematic scanning and changing the spatial-temporal relationships between looking and stepping could help improve mobility for individuals with glaucoma.

1.5. Orientation and mobility training

Orientation refers to the ability to recognize and establish a position with respect to an environment, and mobility is the physical ability to safely, efficiently, and orderly move through that environment.[192] 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.[192] These individuals learn to enhance their mobility performance by utilizing mobility aids, their remaining vision, and other senses (such as hearing and touch). This allows for personalized adaptive strategies and problem solving for their own unique struggles. According to anecdotal evidence reported by O&M instructors, O&M training successfully improves mobility skills.

1.5.1. Current methods and issues with orientation and mobility training

O&M training can compensate for decreased visual information, especially visual field extent or contrast sensitivity. For example, a systematic scanning strategy, such as dynamic visual assessment and training (DVAT) or the dynamic scanning method can improve people's awareness of the environment.[193] Individuals are taught visual scanning patterns to preview their travel environment. This allows individuals to identify potential hazards in the distance, including obstacles and drop offs. These strategies are useful to improve mobility in those with peripheral vision loss.[126] The addition of paint or tape or the use of head-mounted displays may help identify stairs, curbs, and other changes in depth by increasing contrast.[194] The use of any one of these methods or a combination of them can help with environmental awareness and mobility.

Although O&M training is used worldwide for older adults with low vision, the content is rarely discussed, and detailed descriptions of training protocols are scarce, poorly described, and lack control.[195,196] The few that have investigated it have mixed results, where some find it is beneficial,[193,197–199] whereas others suggest minimal effect.[192] There is no fixed protocol for O&M training, and the feasibility and effectiveness of practice based-training is unknown.[200] Geruschat and Del'Aune[201] investigated the reliability and validity of O&M training based on the instructors' observations of mobility improvements before and after training. They found that mobility scores significantly improved; however, changes could have been due to increased familiarity with the routes. Furthermore, preand post-test training was done using real-world routes where illumination and pedestrian density may have changed. Straw & Harley[202] saw a significant improvement in mobility performance immediately after training. Unfortunately, many subjects had poor health, which caused delays in the training, and 50% of them were blind, which is not representative of adults with low vision. Soong et al.[192] examined the effects of O&M training on walking efficiency and mobility incidents in a group of visually impaired older adults and a control group that received no training. They did not find that there was any significant improvement in mobility performance between visits. The improvements seen appeared to be a result of familiarity with the course. Because of the lack of control groups and consistency in O&M studies, the use of O&M procedures requires further investigation.

The strategies taught in O&M are often designed for people with extremely limited vision and might not be as applicable to those with less severe visual loss such as mild-to-moderate glaucoma. O&M training focuses on general strategies such as identifying objects in the distance and systematically scanning the environment to locate hazards[193] rather than on task-specific situations. While this is beneficial in locating hazards and with route selection, it does not teach people how to use their vision when timing between vison and action is crucial. Miller et al.[31] show how disruption of the spatial-temporal relationship between stepping and walking impairs the ability to control foot placement. This is important when stepping on curbs or transitions between surfaces. Although more general gaze strategies are extremely useful, this spatial-temporal relationship should be taken into consideration, as training it improved mobility in older adults.[203] Since both inappropriate spatiotemporal gaze behaviour and scanning methods are strongly associated with reduced mobility, they are ideal targets for training.

1.6. Gaze training

Gaze training involves coaching individuals on where and when to move their eyes to best perform a task. Because gaze and action are so tightly linked, appropriate gaze behaviour can maximize performance on various tasks. For example, medical students improve performance after watching videos of an expert's gaze during the completion of a ball pick up and drop task.[204,205] In this study, they were instructed to make long, stable fixations on both the ball and the cup and to make smooth gaze transfers from one to the next and shown videos of their own performance as a source of feedback.[204] In addition, teaching older adults and cerebellar patients where to look while walking improved stepping performance.[203,206] This suggests that training gaze is a feasible option that can help improve performance during a variety of tasks, and importantly, during walking.

1.6.1. Gaze training to improve mobility

Computer-based gaze-training programs used to improve search speed and to encourage exploratory saccades outside the visual field have been used for individuals with visual impairment due to hemianopia, tunnel vision, and central vision loss. Systematic scanning training is commonly utilized in the rehabilitation of bilateral hemianopia, a visual disease which can occur after stroke in which the visual field is missing in the same part of both eyes.[207,208] Training saccadic eye movements is done using a standardized computer screen or on devices that use a larger visual area to encourage head movements. This results in a larger dynamic visual field and more successful search. However, this does not necessarily transfer to everyday life, and the influence it has on mobility is unknown. The Neurovision Technology Program[209] is a standardized therapy that is under development and involves both static scanning training and dynamic mobility training. However, this is still undergoing clinical trials.

Ivanov et al.[210] and Kyuk[211] have developed eye movement training paradigms to encourage beneficial gaze strategies in those with tunnel vision and central vision loss based on the principle that goal-directed eye movements are necessary when vision is lost. They used computer-based exploratory saccade training programs, which involved a saccadic search task that aimed to improve visual search outside of the seeing visual field. To test the effectiveness of their intervention, they had participants walk through a mobility course in a hallway[210] or complete an obstacle avoidance walking task.[211] Walking speed through the mobility course increased after training.[210] Although there was no change in the number of saccades made, they were shorter in duration. Importantly, perceived quality of life did not change and the number of errors made did not improve.[210] In contrast, Kyuk[210] found no difference in speed to complete an obstacle avoidance walking task, but found minor improvements in obstacle contacts during low lighting conditions.[211] Although exploratory saccade training improve visual search performance, the training was likely not specific enough to walking, limiting the effectiveness for what it was intended for.

Task-specific gaze training interventions for older adults at a high risk of falling[203] and cerebellar patients[206] show success in improving mobility. Young and Hollands[203] taught older adults at a high risk of falling to maintain gaze on a target until making heel contact with that target through video instruction. Participants successfully decreased the interval between looking away from and stepping to a target, which accompanied improved foot-placement error. Importantly, the time between initiating a saccade away from the target and heel contact on that target had a negative correlation with medial-lateral foot-placement error. Similarly, Crowdy et al.[206] trained the gaze of two patients with cerebellar degeneration in a similar precision walking task. Patients were instructed that during visually guided walking, their eye movements were generally not large enough, and they usually made corrective saccades after that led to detriments in their performance.[206] They were then asked to focus on making accurate eye movements rather than just accurate steps and rehearsed the saccadic eye movements to the first six targets while standing stationary at the beginning of the walkway. After this training, both patients decreased the occurrence of saccadic sequences and made a higher proportion of accurate steps. Thus, when made task-specific, people can change their gaze behaviour, and this is accompanied by improved performance.

Interestingly, gaze patterns can sometimes change even when they are not explicitly being instructed. A randomized control trial done by Yamada et al.[212] utilized a multitarget stepping pattern to reduce fall risk in older adults. They had participants walk through a 10m long path with both targets and distracters in each row that got progressively more challenging over 3 weeks. The control group did standardized exercises and walking. The group undergoing the multitarget training reduced their fear of falling, performed better in the multitarget stepping task, and even showed different gaze behaviour. They both initiated and terminated gaze earlier with respect to stepping. This is surprising given that these are the gaze patterns that Chapman and Hollands attributed to high risk of falling.[60] This nevertheless suggests that even by just training mobility, gaze may be altered through practice.

Based on the changes in gaze behaviour we observed during walking in individuals with glaucoma, gaze training may present a feasible option to improve their mobility. By focusing on modifying gaze behaviours that are correlated with poor performance, these task-specific strategies, in conjunction with general scanning strategies, may help older adults with glaucoma to optimize the use of their remaining visual field to ensure safe mobility.

1.7. Multitasking while walking

While we are walking, often we are carrying out a conversation or looking for landmarks in addition to modulating our steps. These all require attention, which can be limited.[213] The capacity sharing theory suggests that performance of one or more tasks should decrease when attention capacity is exceeded.[214,215] Attention capacity decreases with age as a result of cognitive decline,[216,217] impairing the ability to multitask. Indeed, cognitive impairment is associated with an increased risk of falling in older adults.[218] Walking while carrying out a secondary task impacts gait performance in both young[219,220] and older adults.[221–223] "Stopping walking while talking," or the inability to maintain a conversation while walking, is a reliable predictor of older adult fall-risk.[224–226] Gaze behaviour may also be affected by multitasking. Ellmers et al.[227] looked at changes to gaze behaviour during dual tasking and walking in young and older adults. Participants had their eyes tracked while walking along a path where white squares indicated a place to step, and black squares indicated non-pathway areas. While performing a secondary task, participants made more "outside" or task-irrelevant fixations towards the black squares, and fewer "inside" task-relevant fixations towards the white squares. Slower walking and poor stepping accuracy accompanied this behaviour. Our lab recently demonstrated that among older adults with glaucoma, dual tasking greatly exaggerated inappropriate gaze behaviour, which contributed to increased foot-placement error.[31] Together, this suggests the ability to allocate attention appropriately between walking and a secondary task is impaired in older adults, especially those with glaucoma. Thus, in order for gaze to improve mobility, the learned strategies must be maintained while multitasking.

1.8. Specific aim:

To establish the ability of a gaze training intervention to change the gaze behaviour of older adults with glaucoma, thereby improving their mobility

Gaze metrics are impaired in glaucoma. Unfortunately, these individuals often do not develop beneficial compensatory strategies, thus mobility is also affected. During precision walking tasks, older adults with glaucoma look too far ahead, leading to a poor ability to accurately control foot placement. During obstacle avoidance tasks, they look close to their feet, and avoid looking towards their end goal, resulting in increased obstacle collisions. Appropriate scanning, maintaining gaze on a stepping target until heel contact, and making fixations in the direction of travel may allow individuals with glaucoma to adequately visually sample their environment, step more precisely, and avoid collisions with obstacles. By teaching these gaze strategies under single and dual tasking conditions, improvements may be maintained in a variety of walking situations, including when searching for a landmark or having a conversation with a friend. In this study, we taught participants to systematically scan their environment before walking, to maintain gaze on targets until heel contact on that target, and to look in between obstacles with frequent fixations towards the end goal. We used videos, pamphlets, and task-specific instructions, as well as different mobility courses as part of the training. To test the efficacy of the gaze training program, we used two mobility tasks: a precision walking task where participants had to step to the center of four sequential targets as they walked, and an obstacle avoidance task, where participants had to navigate around four foam poles without bumping into them. Participants performed these tasks with and without a secondary task. The secondary tasks included counting backwards and performing a visual search task.

Hypothesis: We will test the hypothesis that a gaze training intervention results in older adults with glaucoma using more appropriate gaze strategies while walking, and that this change in gaze will result in improved mobility. Specifically, looking at targets until heel contact will result in improved foot-placement accuracy on targets, and looking in-between obstacles and towards the goal will result in fewer collisions with obstacles, both in single and dual-task situations.

Chapter 2.

Modifications in gaze behaviour and mobility after a gaze training intervention in a precision walking and obstacle avoidance task

2.1. Introduction

Glaucoma is a leading cause of irreversible blindness in the world, affecting more than 70 million people worldwide.[228] It is a chronic progressive neuropathy of the optic nerve and leads to peripheral vision loss. The inability to properly see has a negative impact on the quality of life in individuals who live with glaucoma. Given the loss of peripheral vision in glaucoma and tremendous importance of vision in walking, it is not surprising that those with glaucoma have problems with mobility, putting them at greater risk for falls.[131] In fact, mobility concerns are one of the most frequently reported issues amongst this population.[229,230] On average, those with glaucoma walk more slowly, experience twice as many bumps and stumbles, and are 3-4 times more likely to fall in a year than those with normal-vision, making mobility difficult especially when in a crowded or unfamiliar area.[231] These events are exacerbated when multi-tasking, such as when counting.[31]

Recently, our lab established a link between visual field loss, mobility, and gaze behaviour in older adults with glaucoma. In a precision walking task, those with glaucoma look away from targets significantly earlier relative to heel contact compared to controls. This is correlated with increased foot placement error and visual field loss,[31] and is similar to older adults who are at a high risk of falling.[109,116,117,232] This gaze behaviour also suggests that they prioritize the planning of future steps over the execution of the current step.[116] In an obstacle avoidance task, those with glaucoma fixate closer to their current position and make a greater number of fixations towards the obstacles (Lajoie et al., unpublished results). They also made fewer route planning fixations (such as those towards the ground and between obstacles). This was accompanied by a greater number of obstacle contacts, which was correlated with visual field loss, where greater visual field loss resulted in more obstacle contacts. Together, these results suggest that inappropriate gaze behaviour impairs mobility in individuals with glaucoma.

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.[192] O&M training focuses on general strategies, such as identifying objects in the distance and systematically scanning the environment to locate hazards[193] rather than on task-specific situations. However, the spatiotemporal relationship between gaze and movement is not practiced. Since both inappropriate spatiotemporal gaze behaviour and scanning methods are strongly associated with reduced mobility, they are ideal targets for training.

Gaze training is effective at improving motor skills related to sports and certain medical surgeries.[204,205,233] In laparoscopic surgeries, showing a video demonstrating "expert" gaze strategies led to faster completion times during a single and dual task procedure.[204] Instructing older adults where and when to look can improve their performance in a precision walking task.[203] Thus, teaching individuals with glaucoma systematic scanning and task-specific spatiotemporal strategies may change their gaze behaviour and improve mobility.

This study determined whether gaze is modifiable, and if this improves mobility in older adults with glaucoma. To accomplish this, we taught older adults with glaucoma task-specific and general gaze strategies over two, 1-hour sessions. To determine the efficacy of the training, we had participants perform a precision walking and obstacle avoidance task before and after training. We hypothesized that participants would appropriately follow the gaze training instructions, and that this would lead to improved mobility in the two tasks.

2.2. Methods

2.2.1. Participants

We recruited ten individuals with glaucoma through two collaborating ophthalmologists. The Office of Research Ethics at Simon Fraser University approved the study, and all participants provided informed written consent prior to performing the experiments.

Two ophthalmologists 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. To be eligible, participants met the following inclusion criteria: a Humphrey visual field mean deviation worse that -2 dB on the 30-2 test and -1.5 dB on the 24-4 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 (cataracts, macular degeneration), aged 60 years or older, able to understand instructions in English, free of history of cardiac, neurological (Parkinson's disease, stroke), or musculoskeletal disorders (i.e. arthritis) that could affect balance or gait, ability to walk without assistance (or mobility aid) for >5 minutes, and a >26 score on the Mini-Mental State Exam (MMSE).[234] In addition to the above screening, we quantified how often the participant had fallen in the past 12 months. We defined a fall as an unexpected event in which the person landed or came to a rest on the ground, floor, or lower level.[235]

2.2.2. Visual assessment

We obtained visual field scores for participants from the ophthalmologist's office. Each ophthalmologist had a different Humphrey systems visual field analyzer (model HFA-II 750-11949-4.2/4.2; Carl Zeiss Meditec, Inc., Dublin, CA; model HFA-II 750-8983-5.0/5.0; Carl Zeiss Meditec, Inc., Dublin, CA), and use either the SITA-Fast central 30-2 or 24-2 threshold test procedure (size III Goldmann white target and background luminance of 10.03 cd/m^2). This method is effective at monitoring vision loss with glaucoma.[236] Since one ophthalmologist used the SITA-Fast central 30-2, whereas the other used the SITA-Fast central 24-4, all 30-2 scores were converted to 24-4 scores by eliminating the 6 additional peripheral points used in the 30-2. The remaining 24 points values were averaged. This allowed us to remain consistent in the visual field measurements of our participants. We determined the visual field: binocular best location by determining the best eye value for each total deviation location, and averaging these values to obtain a mean deviation score.[237] This quantified the amount of visual field loss, where a more negative number indicates greater visual loss than an age-adjusted norm.

We determined best-corrected binocular visual acuity using the Early Treatment of Diabetic Retinopathy Study (ETDRS) chart at a distance of 4 m.[238] We terminated the test when a minimum of three letters on a line could not be read. We subtracted 0.02 logMAR units for every letter correctly identified on that row from the last row they identified more than 3 letters correctly.

We assessed binocular contrast using the Melbourne Edge Test (MET) at a distance of 40 cm.[239] Participants identified the orientation of an edge in a series of test circles with progressively declining contrast. We terminated the test when the participant reported two orientations wrong in a row. The dB value of the lowest contrast patch the participant could correctly identify was recorded as the participants contrast sensitivity. Contrast was recorded in dB between 1 and 24 dB.

2.2.3. Gaze training

Gaze training occurred immediately after the pre-training assessment and at home between pre-training and post-training assessments, which were separated by one week. In each case, training lasted approximately 1 hour. Participants were encouraged to use the strategies taught in the gaze training at the beginning of the post-training assessment. Training consisted of four components: general gaze strategies, task-specific training, home-based training, and cognitive (or dual-task) training. We increased training complexity slowly and progressively at the same rate for all participants.

General gaze strategies

We created an obstacle course inside the lab, which contained various terrain, obstacles, shapes, landmarks, and targets (Figure 2-1 A; B). This trained participants how to manage the environment, how to prioritize fixations, and on scanning technique. We instructed participants to conduct a gridline scan of the area, similar to the dynamic scanning method.[193] This involved a systematic scan back and forth and up and down to learn the layout of the environment as illustrated in Figure 2-2. We had them identify and locate hazards, areas of interest, and a safe, clear path. For the first few practice trials, we assisted using a pointing stick to outline the gridline pattern they should use. We blocked the participant's vision of the obstacle course before starting. On some trials we gave them an object to search for. When the board was withdrawn, they began their scan, which a researcher timed. Specifically, we timed how long it took the participant to correctly identify the location(s) of the object(s) by stopping the timer as soon as they found it, or when they said “done.” We notified participants of the time it took, and instructed them to become faster with each trial, eventually reducing the time to 4 seconds. We chose 4 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 at least 12 times without an additional task.

A B

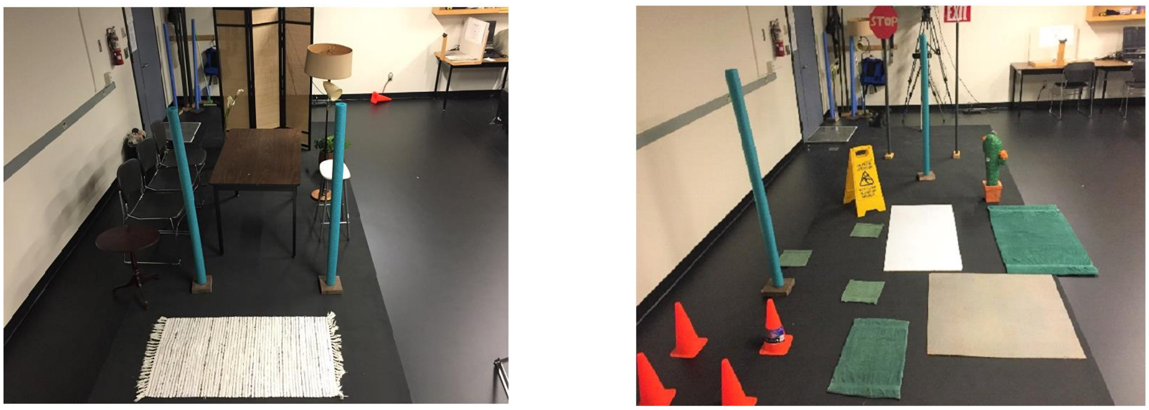

Figure 2-1: Mobility courses.
A. Photo of the “indoor” mobility course. B. Photo of the “outdoor” mobility course. We used these mobility courses to train the gridline scan and practice all training in a realistic environment at the end of the pre-training assessment.

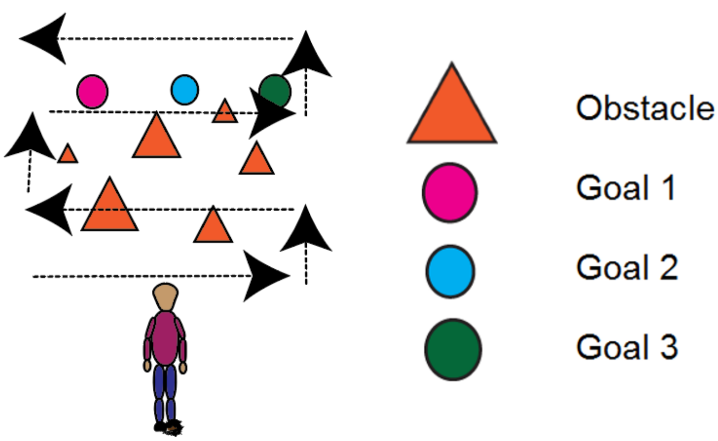

Figure 2-2: Schematic of the gridline scan.
After participants identify their end goal, they scan back and forth and up and down all the way from their current position up to their end goal.

After the task-specific training, participants walked through these same mobility courses (Figure 2-1). This gave them the opportunity to practice all of the strategies taught in a more realistic environment. We blocked their vision and changed the position of objects in the course at the beginning of each trial. We told them what objects we wanted them to walk to, and if we wanted them to search for any other objects before unblocking their vision. Once they could see the course, they performed a gridline scan, and pointed towards any objects we told them to identify before walking towards where we told them to walk. We emphasized that they should use both the precision walking and obstacle specific gaze strategies we taught as necessary.

Task-specific training

For the task-specific training, we used a precision walking and obstacle avoidance paradigm. Our lab has previously defined changes in gaze behaviour with glaucoma on these tasks.[31]

Precision walking

We showed videos that demonstrated two different gaze strategies: one of an "expert" late gaze transfer, where gaze is transferred once heel contact has been made with the target; and one of a typical glaucoma patient that shows an early gaze transfer, where gaze is transferred to the next target before the step on the current target. We first showed the late gaze transfer video, followed by the early gaze transfer video, then played the late gaze transfer video once more. Prior to showing the video, we verbally explained what the videos showed. We provided a rationale for why these strategies are beneficial or not. We then gave participants the opportunity to ask any questions.

Participants practiced the late gaze transfer strategy while stepping to the center of a target (width, 15 x length, 30 cm). First, we instructed the participant to systematically scan the environment. This included a saccade to each target (i.e., from target one to target 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 possible. We told them to follow gaze behaviour 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. Participants practiced this 12 times. For the first three trials, the seventh trial, and the 11th

trial, we used a laser pointer for the participant to fixate on. This reminded participants of the strategy while encouraging them to practice it on their own. They practiced this with one target before progressing to two targets.

Obstacle avoidance

We used narrated homemade videos to help train gaze. This included various videos of an "expert" navigating through multiple obstacles. We emphasized that we wanted them to have a good idea of where the obstacles were, but that looking at the safe gap between them is critical for safe passing. The video explained how it is important to look at the space between the obstacles about two steps before crossing, since we tend to walk in the direction we are looking.[48]

Participants practiced the obstacle avoidance task using only two obstacles (height, 165 cm, diameter, 3.5 cm). We instructed participants to begin with a gridline scan of the area to identify any obstacles, areas of concern, or end gates. To train safe gap detection, we changed the size of the obstacle gaps in the medial-lateral direction 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 need to rotate their bodies. We instructed participants to fixate on the pole closer to them until they are approaching a distance in which they would like to cross it. At this time, they made a saccade to the second pole, and immediately another saccade to the gap between the poles before they passed between them. We instructed them to frequently look towards the end goal as they passed between the obstacles. This was to help encourage a longer gaze distance. Participants practiced this 12 times.

Cognitive (or dual-task) training

Task performance decreases when an additional task is added. Thus, participants also practiced the task-specific strategies with a dual task. The additional task required them to list words that start with a given letter. This task is cognitively challenging, and importantly, it is different than the dual task used during pre- and post- testing. This was done to prevent changes in dual task performance due to practice.

Pamphlets

We provided participants with pamphlets before they left with written instructions about the general gaze strategies, precision walking strategies, and obstacle avoidance strategies. The precision walking pamphlet showed graphically how gaze is transferred in relation to heel contact on a ground location (or target). It explained the temporal relationships between gaze and limb movement, and that when accuracy is key, gaze should be maintained on the location they are stepping to until they have planted their foot. The obstacle avoidance pamphlet showed graphically how gaze should be directed ahead and towards the end goal, and how it should be directed in the middle of two obstacles prior to passing through gaps. It emphasized how it is important to direct gaze in the direction of intended travel.

Home-based training

A researcher visited the participant in their own home between pre-training and post-training assessment. During this one-time visit, we used objects in the participant's home (e.g., doorframes, chairs, kitchen items, etc.) to create an obstacle course that challenged both precision walking and obstacle avoidance. We asked the participants to utilize the gaze strategies taught in the lab to scan the environment and navigate through the course. On each trial, we asked participants to identify an obstacle or object within the course before they started walking. On some trials, the end goal was denoted by an agreed upon object, whereas on others, the goal was to make it to the other side of the room. To add variation to the courses, the objects and obstacles were moved, and various end goals were set.

Survey

We provided a survey for the participants to fill out after the post-training testing to address issues such as the ease of instructions to follow, the helpfulness of the pamphlets, the feasibility of the home training, and how the gaze training changed their mobility and situational awareness. Questions included:

1.) Were the instructions easy to understand?
2.) Were the instructions easy to follow?
3.) Did you find the pamphlets helpful?
4.) Did you find the home-based training helpful?

5.) Do you feel more aware of the environment after the training program?
6.) Do you feel that the training program has helped your mobility?
7.) What would you like to see added to the training program? Changed?
8.) Do you think that you will continue to review the pamphlets and practice what you have learned now that your participation in the research study is complete?

2.2.4. Pre- and post-gaze training assessment

Immediately before and one-week after training, participants performed a precision walking task and obstacle avoidance task. These tasks were used to assess the efficacy of the gaze training on changing gaze behaviour and mobility. Due to technical constraints, participants first performed the precision walking task followed by the obstacle avoidance task.

The precision walking task involved walking across a 6-m path and stepping to the center of four sequential targets (width, 15 x length, 30 cm) without stopping (Figure 2-3A). 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 varied the positions of targets two and three by five cm in either the anterior-posterior or medial-lateral direction each 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.

In the obstacle avoidance task, participants walked across a 4.5 m long and 1.25 m wide path, trying to avoid 4 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) (Figure 2-3B). Obstacles were spaced 60 cm apart from each other in the anterior-posterior direction but varied in the medial-lateral direction. We randomly varied the positions of the obstacle and end gates trial-to-trial in one of four pre-determined arrangements. This ensured that the task was visually-guided and not based on memory. We designed each configuration such that there was always a clear path to get from the beginning to the end gates. We instructed participants to walk at a self-selected pace, to navigate through the course by taking the simplest route possible, to not contact the obstacles, and to not have any part of their body go outside of the lateral walkway boarders. An experimenter demonstrated the task to ensure participants understood the instructions.

We blocked participant's vision with a wooden board prior to a "go" command, at which point vision was restored and the participant could begin to walk. This prevented participants from relying entirely on memory of target positions. All participants wore their habitual vision corrective lenses for the duration on the experiment.

Participants performed each task under three conditions in a randomized order: single task, dual task counting, and dual task visual search. Participants completed 12 trials of each condition, resulting in a total of 36 trials (72 trials total). For all conditions, except the counting condition, we told participants that when the board blocking their vision is withdrawn, they are free to begin. In the counting condition, they began walking and counting when they heard the starting number and the board was withdrawn.

In the *single task* condition, participants preformed the precision walking or obstacle avoidance task without any additional task. This served as a baseline condition to which we could compare performance during dual tasking against.

In the *counting dual task* condition, we provided participants with a random two-digit number between 50 and 100 to count backwards from in serial fives. This is a modification of a common secondary task that increases cognitive load and simulates having a conversation with someone. We instructed participants to walk accurately to each target while saying as many correct numbers as they could until toe-off from the fourth target or to avoid contact with the obstacles as best as possible until they passed the blue end gates. 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 4 black shapes (13 cm, all dimensions) printed on white tiles (20 cm x 15 cm) laid out on the floor. At the end of 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., which shape is located at a particular position) 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, a task that people with eye disease identify as challenging.[240] We instructed participants to stop walking after stepping off the fourth target or past the blue end gates so we could ask them for the position of one of the four shapes. We recorded the number of correct responses for each trial as the dual tasking visual search performance.

Prior to testing, we had participants count and perform visual search trials without walking to establish baseline performance. For the visual search, participants observed the shapes while standing still for five seconds (the typical duration participants could see the shapes during walking based on previous pilot testing) before having their vision blocked. When their vision was blocked, we asked them to identify the location of one randomly selected shape. They performed this 12 times. We calculated the proportion of correct responses for both the baseline and dual-task trials and normalized these to trial duration. To assess counting performance, we had participants count down backward by fives for a total of 10 seconds for six trials. We calculated the number of correct responses in this task and during the baseline and dual task situations, then divided these values by their respective trial duration (the time of toe-off from the fourth target or chest crossing the last obstacle minus the time the eye enters the scene). We calculated a dual task cost (DTC) using the following formula (dual task – single task)/single task.[216] A negative value indicates worse performance.

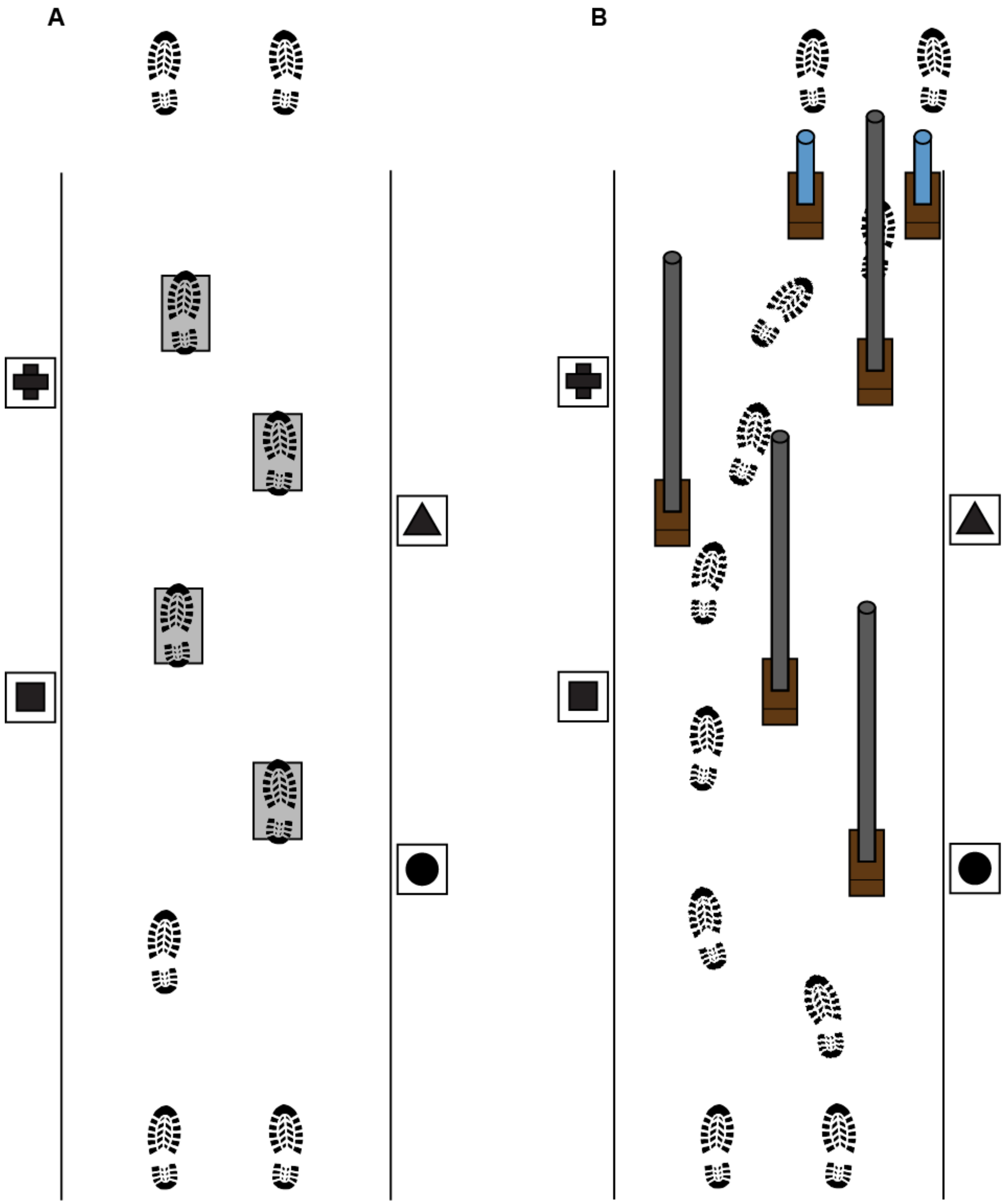

Figure 2-3: **Precision walking and obstacle avoidance task set-ups. A. Experimental set-up for the precision walking task. Anterior-posterior target distance was scaled to 70% of participant's leg length. B. Experimental set-up for the obstacle navigation task. Visual search task shapes were only present during the visual search condition during both tasks.**

2.2.5. Kinematic measures

We recorded, at 120 Hz, the position of motion-capture markers located on the head, chest, and bilaterally at the forefoot, midfoot, and heel with two Optotrak Certus cameras (Northern Digital, Ins., Waterloo, Canada) that were synchronized with an eye tracker. We filtered kinematic data with a Butterworth low-pass filter at 6 Hz in a custom MATLAB program, and then analyzed it using custom-written LabVIEW (National Instruments, Austin, TX) programs.

In the precision walking task, we assessed mobility performance by quantifying foot-placement vector error for all targets. This was defined 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 trial. Heel-contact and toe-off events were defined as the local maximum vertical velocity of the mid-foot marker,[241] and local minimum anterior-posterior acceleration of the toe marker,[242] respectively, for each target. Finally, we recorded gait speed by measuring the time it took the chest marker to move from target one to target four, divided by the anterior-posterior distance between them.

In the obstacle avoidance task, we assessed mobility performance by quantifying gait speed, number of obstacle collisions, and path choice. We quantified gait speed as the time it took the chest marker to pass from the first to last obstacle, divided by anterior-posterior distance. We determined obstacle crossing events by calculating the time at which the chest marker crossed the anterior-posterior position of each obstacle. We determined the number of obstacle collisions by recording any occurrences where any part of the participant's body contacted an obstacle or end-gate, and was verified by a second researcher. We then divided the number of collisions per condition by the number of trials in that condition.

2.2.6. Gaze measures

We recorded gaze data using an Applied Science Laboratories (Bellerica, MA, USA) high-speed head-mounted eye tracking system, which tracks rotation of the left eye at 120 Hz, and records video data on a head-mounted or stationary camera at 30 Hz. We calibrated the eye tracker using the system's standard 9-point calibration method. Participants wore their habitual spectacles, if applicable. This software produces a 120 Hz signal of gaze position and overlays 2 dimensional gaze coordinates on a 30 Hz video, with gaze position represented by an intersection of vertical and horizontal cross hairs.

In the precision walking task, we used the eye-head integration feature. Here, we subtracted head rotation from gaze rotation (both in room coordinates) to extract a 3D vector of eye rotation. In the obstacle avoidance task, we calculated the vector gaze position at each time point. To do this, we first converted the vertical and horizontal eye units to degrees. Then we calculated the vector gaze position in degrees at each time point. This allowed us to determine the angular gaze velocity. We also used this method for two participants in the precision walking task due to technological issues with eye-head integration.

We first filtered gaze data with a Butterworth low-pass filter at 15 Hz. We then identified saccade onset and offset times. We defined saccade onset and offset as eye rotation velocities (precision walking task) or angular gaze velocities (obstacle avoidance task) that exceed 100 degrees/s for a minimum of 16 ms and return below this value, respectively.[60] We identified saccade and fixation durations using the 120 Hz data, and performed area of interest (AOI) classification using a 30 Hz video. We identified gaze times as stable gaze on a location for >66 ms[53] and defined as the onset of a saccade away from a target minus the offset of the saccade onto a target or shape. Saccades made within the same AOI before gaze was shifted away from it were included in the AOI gaze time in the precision walking task. In the obstacle avoidance task, we used all individual fixations, as they were made towards different parts of the large ground segments. Depending on the task, AOI included targets, route planning locations (ground segments, non-task relevant locations), obstacle (or end gates), or a shape in the case of the visual search condition. Participants rarely, if ever, fixated outside of these locations.

Precision walking task

In the precision walking task, we calculated two intervals based on the kinematic and gaze data: Heel-contact (HC)-interval and toe-off (TO)-interval. We defined the heel contact interval as the time a saccade is made away from a target minus the time heel contact is made on that same target. A negative value indicates a saccade made away from the target before heel contact. We defined the toe-off interval as the time a saccade is made towards a target minus the time the toe is lifted to step towards that target. A negative value indicates that a saccade was made towards the target before the toe is lifted to step towards that target. Since some participants made multiple fixations towards the same target, we used the last made fixation to the target in these calculations.

Obstacle avoidance task

We used spatial gaze distance and spatial-temporal gaze distance measures to determine how far and for how long participants looked while walking through the obstacles. To do this, we first divided the path into eight segments (S1-S8) using the obstacle and end-gate positions as shown in Figure 2-4. Each segment was 60 cm (the distance between the obstacles) except for S1 and S8. This was a result of the participants starting position (S1) and the rest of the ground beyond the obstacles (S8). The chest marker identified when they passed the boundary of each ground segment. For both measures, we assigned a value to each fixation based on how many segments ahead participants were fixating while they were in segments S1-S5. Segments S6-S8 were excluded because the participant had already passed the fourth obstacle. We assigned a fixation to the next segment a value of one, etc. Occasionally, participants fixated the ground segment they were currently in; we assigned these fixations a value of 0.5.

For the spatial gaze distance measure, we averaged all values given to fixations within a given segment. A larger value indicates that within that segment, the participant fixates a greater distance ahead. For the spatial-temporal gaze distance measure, we first divided the duration of each fixation by the total time a participant is in that given segment and multiplied this by the value assigned to that fixation. This allowed us to scale the spatial gaze distance by the relative duration of each fixation. We then averaged the spatial-temporal gaze distance score for each segment. Larger values indicate that the participant allocates gaze, on average, further ahead for longer.

To determine if participants performed a gridline scan before walking through the obstacle course, we counted the number of fixations made before the participant left segment 1 (S1). We also calculated the standard deviation of the spatial gaze distance score of these fixations to determine how much of the environment they sampled.

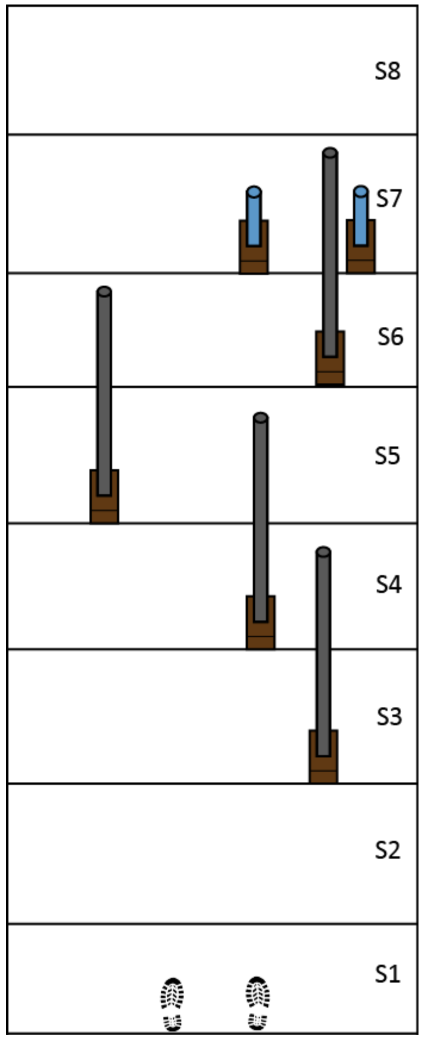

Figure 2-4: Illustration of how gaze distance scores were assigned. The participants start in segment 1 (S1). Gaze is limited to S1-S8. Each fixations is assigned a score based on how far ahead the fixation is directed with respect to the participant's current location. Scores are averaged for each segment the participants walks through before passing the fourth obstacle (S1-S5). For the spatial-temporal gaze distance measure, we scaled the scores to fixation duration and the length of time participants are in the segment.

Next, we quantified the proportion of the number of fixations and the proportion of gaze time to route planning locations (i.e. ground segments and fixations beyond the obstacle course), obstacles (obstacles and end-gates), and shapes (when applicable). We also quantified the time interval between a gaze shift away from an obstacle and anterior-posterior chest crossing time (i.e. the saccade – obstacle crossing interval). If a participant fixated an obstacle more than once, we used the last gaze shift away from the obstacle before crossing in this calculation. A negative interval indicates gaze transfer away before crossing the obstacle.

2.2.7. Statistical analysis

We used JMP 12 (Cary, USA) software with an α-level of 0.05 for all statistical analyses. To determine differences in gait speed between times (pre-training and post-training) and across conditions (target only, dual count, and dual search), we used separate two-way (Time x Condition) ANOVAs on gait speed for each task. To determine differences in foot-placement error between times, across conditions, and across targets (targets 1-4), we used a three-way (Time x Condition x Target) ANOVA. We used a two-way (Time x Condition) ANOVA to compare differences in step-to-step foot-placement error variability. To determine differences in the TO- and HC-intervals between pre- and post-training, across conditions, and across targets (targets 1-4), we used separate three-way (Time x Condition x Target) ANOVAs. To determine the differences in the spatial and spatial-temporal gaze distance between times, and across conditions and segments (S1-S8) we used separate three-way (Time x Condition x Segment) ANOVA's. 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 segment 1 between pre- and post-training and conditions using separate two-way (Time x Condition) ANOVAs. To determine differences in the proportion of fixations and gaze time directed to obstacle and route planning locations between pre- and post-training and tasks, we used separate two-way (Time X Condition) ANOVAs. The same analysis was used for the gaze obstacle-crossing intervals and obstacle collisions. For the proportion of fixations and gaze time directed towards shapes between pre- and post-training, we used a one-way ANOVA. We used Tukey's post hoc tests to identify differences between levels when the ANOVAs indicate a main effect or interaction is present. We also compared dual task cost differences between pre- and post-training using separate two way (Time x Condition) ANOVA's for each task. We included subject as a random factor in all analysis.

2.3. Results

We trained 10 older adults with glaucoma (5 female, 5 male) on where and when to look during precision walking and obstacle avoidance tasks. The characteristics of these participants are shown in Table 2-1. Participant characteristics.

Table 2-1. Participant characteristics.

Age (y)	75.1 (5.7)
Sex (male/female) (n)	5/5
Self-reported faller (n)	4
Visual field: binocular best location	-5.25 (4.22)
Visual field: better eye (MD) (dB)	-6.20 (5.21)
Visual field: worse eye (MD) (dB)	-11.19 (8.24)
Binocular visual acuity (logMAR)	0.048 (0.3)
Binocular contrast sensitivity (dB)	17.2 (3.08)
MMSE (/30)	29.8 (0.42)

Data are mean (SD) for age, visual field, visual acuity, and contrast sensitivity; counts for sex and self-reported fallers. MD indicate mean deviation; RNFL, retinal nerve fiber layer thickness; logMAR, logarithm of the minimum angle of resolution; MMSE, mini-mental state exam

2.3.1. Precision walking task

Pre-training, participants walked and stepped onto four consecutive targets under three different conditions using their natural gaze behaviour. Post-training, we asked them to follow the gaze training instructions by fixating the current target until their heel contacted it. As shown in Figure 2-5B, participants successfully followed the instructions by maintaining their gaze on the targets later relative to heel contact on it in all conditions. Because gait speed changes between pre- and post-training and conditions, we included it as a covariate for the TO- and HC-intervals. On average, participants looked away from targets 0.36 s before heel contact on that target post-training compared to 0.8 s pre-training (Time main effect: $F_{1,205} = 82.6$, $p < 0.0001$, non-significant Time x Condition interaction: $F_{2,200} = 1.01$, $p = 0.36$). Both pre- and post-training, participants transferred their gaze away from targets earlier with respect to heel contact in the two dual task conditions compared to during the target only condition (Condition main effect: $F_{2,205} = 11.0$, $p < 0.0001$). In addition, they transferred their gaze away from target 1 and 2 earlier with respect to heel contact than from target 3 and 4 (Target main effect: $F_{3,200} = 8.22$, $p < 0.0001$).

Although we did not train them when to look towards targets before initiating a step towards them, participants fixated targets later with respect to lifting the foot to step there in all conditions post-training compared to pre-training (Time main effect: $F_{1,205} = 44.1$, $p < 0.0001$). Participants reduced the time between making a gaze shift towards a target and lifting their foot to step there from 0.85 s to 0.54s. However, this interval did not change for target 1 between pre-training and post-training (Target x Time interaction: $F_{3,200} = 5.7$, $p = 0.001$). Both pre- and post-training, participants looked at targets earlier with respect to toe-off in the count dual task condition compared to the target only and search dual task conditions (Condition main effect: $F_{2,205} = 5.0$, $p = 0.008$). We also found a main effect of target, where participants looked towards target 1 relative to toe-off earlier compared to targets 3 and 4 (Target main effect: $F_{3,200} = 8.44$, $p < 0.0001$). This is shown in Figure 2-5A.

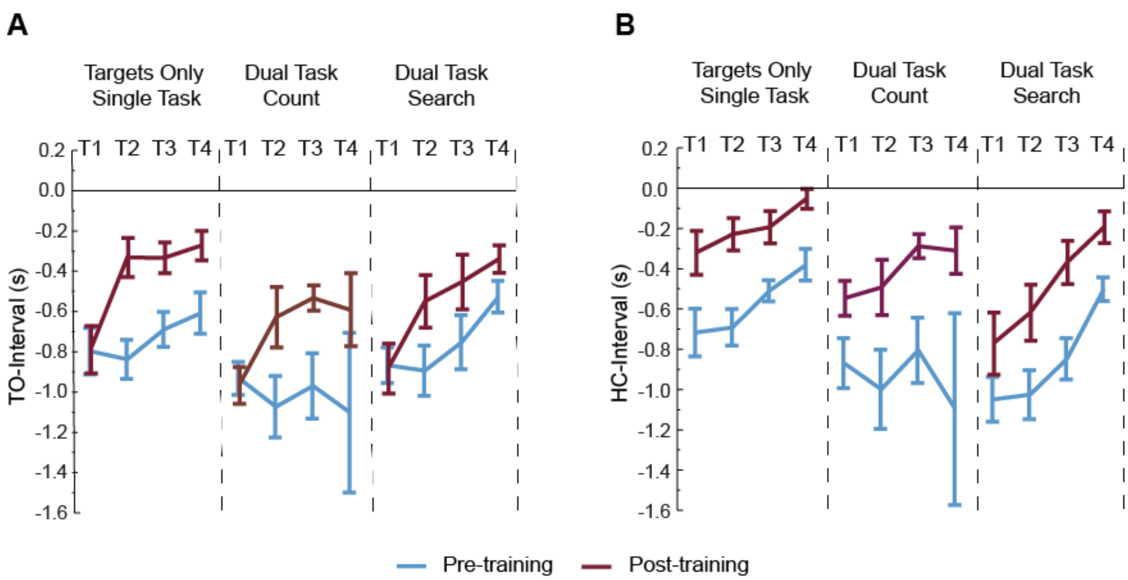

Figure 2-5: Gaze-foot spatiotemporal coupling during the precision walking task.
A. Mean TO-interval for pre-training and post-training across all 3 conditions and 4 targets. A negative TO-interval represents gaze shifts towards targets prior to lifting the foot to step to that target. B. Mean HC-interval for pre-training and post-training across all 3 conditions and 4 targets. A negative HC-interval represents gaze shifts away from targets before heel contact on it. Error bars represent standard error.

Changes in gait speed, foot-placement error, and foot-placement error variability accompanied the changes in gaze measures. In all conditions, participants walked slower post-training compared to pre-training (Time main effect: $F_{1,45} = 6.85$, $p = 0.012$). On average, gait speed reduced from 0.86m/s to 0.81 m/s. Participants walked fastest in the target only condition and slowest in the count dual search condition both pre- and post-training (Condition main effect: $F_{2,200} = 16.8$, $p < 0.0001$). Since gait speed differed between pre- and post-training and conditions, we added it as a covariate for foot-placement error and error variability. As shown in Figure 2-6A, foot-placement error decreased from pre-training to post-training (Time main effect: $F_{1,212} = 20.78$, $p < 0.0001$). However, the reduction in error depended on the condition. Decreases in foot-placement error only occurred in the dual task conditions, not the target only condition (Time x Condition interaction: $F_{2,207} = 5.03$, $p = 0.007$). Both pre- and post-training, participants had lowest foot-placement error in the target only condition and highest in the count condition (Condition main effect: $F_{2,212} = 4.05$, $p = 0.018$). In addition, foot-placement error variability reduced post-training compared to pre-training in all conditions (Time main effect: $F_{1,47} = 7.19$, $p = 0.01$; see Figure 2-6B). Foot-placement error variability decreased from 24.2 mm to 19.8 mm from pre-training to post-training

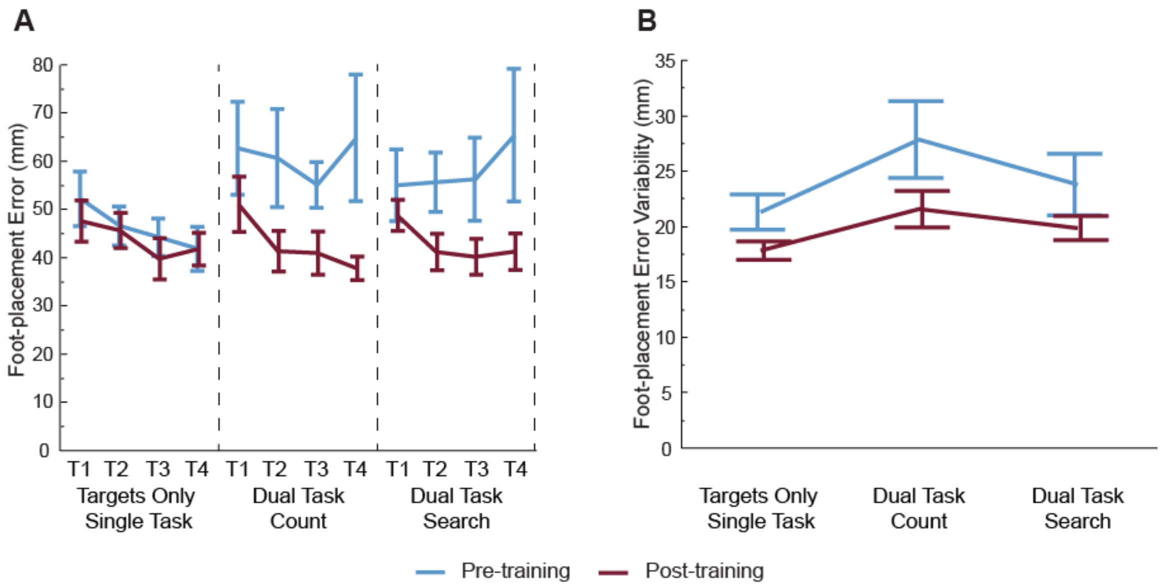

Figure 2-6: Foot-placement error and error variability in the precision walking task.
A. Mean foot-placement error for pre-training and post-training across all 3 conditions and 4 targets. B. Mean foot-placement error variability for pre-training and post-training across all 3 conditions. The mean foot placement error represents step-to-step foot placement error variability as it is calculated across all 4 targets. Error bars represent standard error.

2.3.2. Obstacle avoidance task:

In this task, participants navigated through four tall foam poles. Pre-training, they used their natural gaze behaviour, and post-training they followed the gaze training instructions to the best of their ability. The gaze data from one participant is not included in the obstacle avoidance task due to technical problems with the eye tracker.

We instructed participants to perform a gridline scan of the environment prior to walking through it to encourage longer gaze distance. We used a spatial gaze distance score to determine, on average, how far ahead participants fixated (Figure 2-7A). Spatial gaze distance did not differ pre-training compared to to post-training (No time main effect: $F_{1,232} = 1.18$, $p = 0.278$). However, we found a strong effect of segment both pre- and post-training (Segment main effect: $F_{4,117} = 116.5$, $p < 0.0001$), such that participants looked furthest from where they were currently standing in the first segment, and this distance progressively decreased with each segment. They looked 3.61 segments ahead in the first segment compared to only 1.9 segments ahead in the last segment. Participants looked furthest ahead of where there were currently located in the count and obstacle conditions, and slightly less far ahead in the search condition ($F_{2,232} = 8.86$, $p = 0.0002$).

We also looked at the time participants spent looking at these distances using a spatial-temporal gaze distance measure (Figure 2-7B). We found no change in spatial temporal gaze distance from pre- to post-training (No time main effect: $F_{1,232} = 0.003$, $p = 0.955$). We found a Time x Segment interaction (Time x Segment Interaction: $F_{4,232} = 3.46$ $p = 0.009$), however, post hoc tests did not reveal any differences between pre- and post-training on various segments. Similarly to the spatial gaze distance, we found a strong segment effect (Segment main effect: $F_{4,232} = 19.2$, $p < 0.0001$). In this case, participants had a trend to look further in front on where they were located for longer in segment 2 than segment 1, 4, and 5. They also looked further for longer in segments 2, 3, and 4 than segments 1 and 5. Participants looked further ahead for longer in the count and obstacle condition than in the search condition (Condition main effect: $F_{2,232} = 13.4$, $p < 0.0001$).

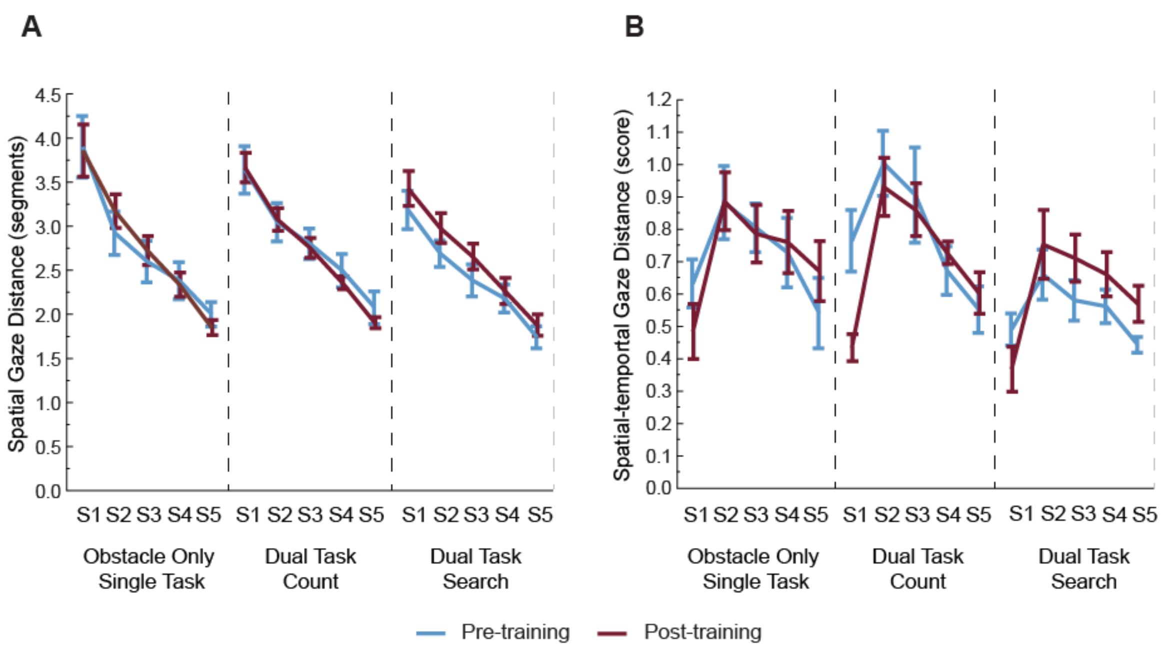

Figure 2-7: Gaze distance measures in the obstacle avoidance task. A. Mean spatial gaze distance for pre-training and post-training across all 3 conditions and 5 segments. B. Mean spatial-temporal gaze distance for pre-training and post-training across all 3 conditions and 5 segments. Error bars represent standard error.

We classified the number of fixations participants made before entering the segment that contained the first obstacle to determine the extent of their initial scan (Figure 2-8B). Participants made more fixations post-training compared to pre-training before entering this segment in all conditions (Time main effect: $F_{1,40} = 53.3$, $p < 0.0001$). They made more fixations in the search condition when the shapes were present than in the count condition both pre- and post-training (Condition main effect: $F_{2,40} = 3.72$, $p = 0.033$). The variability of these fixations was greater post-training than pre-training (Time main effect $F_{1,40} = 10.8$, $p = 0.002$; Figure 2-8A).

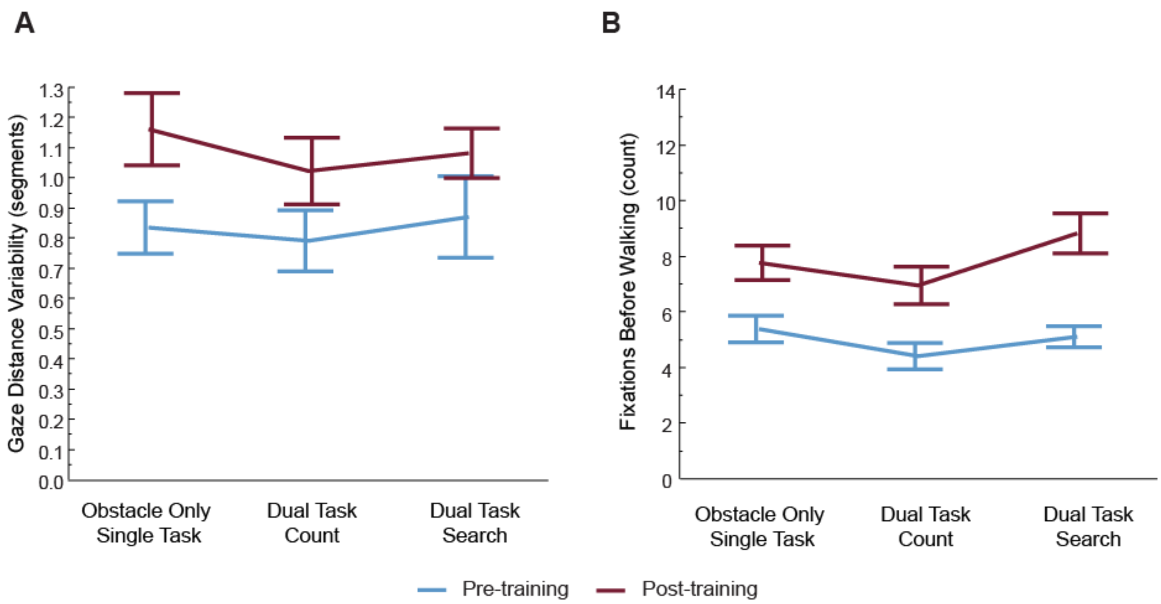

Figure 2-8: Gridline scan fixations before walking through obstacles in the obstacle avoidance task.
A. Variability of spatial gaze distance of fixations made before entering the segment that obstacle 1 is in for pre-training and post-training across all 3 conditions. B. Average number of fixations made before entering the segment that obstacle 1 is in for pre-training and post-training across all 3 conditions. Error bars represent standard error.

We found a decrease in gait speed from pre-training to post-training (Time main effect: $F_{1,42} = 5.02$, $p = 0.03$). Participants decreased their gait speed from 0.73 m/s to 0.67 m/s from pre-training to post-training. In addition, gait speed differed between conditions (Condition main effect: $F_{2,42} = 4.96$, $p = 0.012$) with obstacle only being the fastest and dual task count being the slowest both pre- and post-training.

We determined the percentage of fixations and percentage of time fixating route planning (ground and non-task relevant) and obstacles (obstacles and end gates) features. Given that these measures are calculated as proportions, we did not take differences in gait speed into account.

Approximately 60-80% of fixations were directed towards route planning locations across conditions both pre- and post-training (Figure 2-9A). Participants made proportionally fewer fixations towards route planning locations during the dual search task compared to the count dual search and obstacle conditions both pre- and post-training (Condition main effect: $F_{2,40} = 75.8$, $p < 0.0001$). They also spent a lower percentage of time fixating route planning locations in the search dual task than the count dual task and obstacle only conditions (Condition main effect: $F_{2,40} = 43.5$, $p < 0.0001$) as seen in Figure 2-9B. This is because the shapes were present during the search dual task, providing an extra area of interest to fixate on. Interestingly, participants made a greater proportion of fixations towards the non-task relevant features pre-training compared to post-training (Time main effect: $F_{1,40} = 6.23$, $p = 0.017$) and spent a greater percentage of time fixating these areas (Time main effect: $F_{1,40} = 5$, $p = 0.030$). Only 15-20% of fixations were directed towards obstacles both pre- and post-training (Figure 2-9C). Participants made a greater proportion of obstacle fixations in the obstacle only task than in the dual tasking conditions (Condition main effect: $F_{2,40} = 3.45$, $p = 0.042$). However, we found no difference in the proportion of time spent fixating obstacles between conditions (No condition main effect: $F_{2,40} = 2.08$, $p = 0.138$; Figure 2-9D). They also spent ~2% more time fixating on the gate alone post-training than pre-training (Time main effect: $F_{1,40} = 4.2$, $p = 0.047$). We found no differences in the proportion of fixations made towards (No time main effect: $F_{1,8} = 0.005$, $p = 0.943$), or spent fixating on (No time main effect: $F_{1,8} = 0.002$, $p = 0.964$), shapes between pre- and post-training. During the search condition, ~25% of fixations were made towards shapes, and shape fixations made up 23% of fixation time.

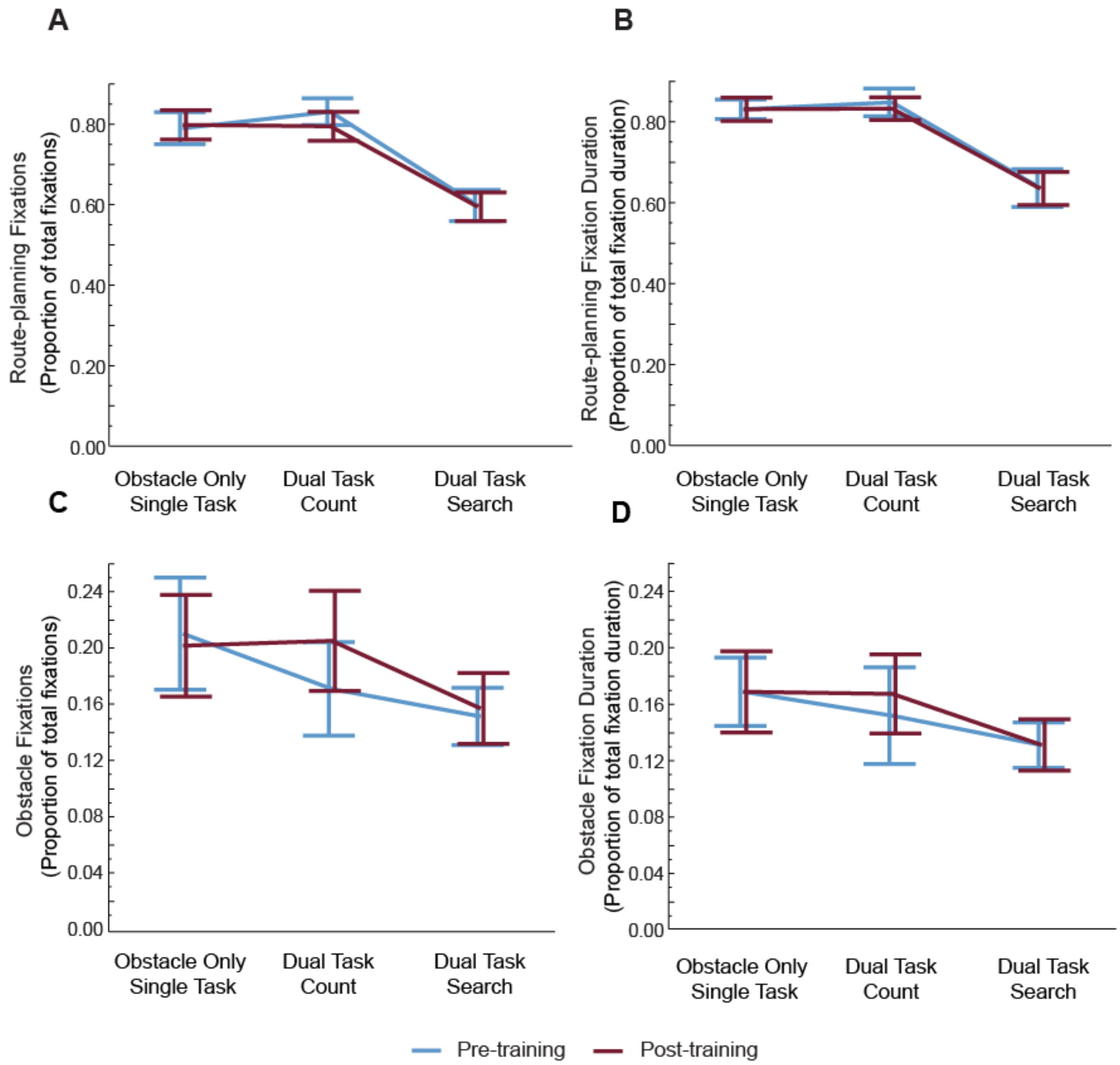

Figure 2-9: **Proportion of route planning and obstacle fixations and fixation duration in the obstacle avoidance task.**
A. Proportion of fixations made towards route planning locations pre-training and post-training across all 3 conditions. B. Proportion of total fixation time spent fixating route planning locations pre-training and post-training across all 3 conditions. Route planning locations include the ground and areas in between obstacles (non-task relevant). Error bars represent standard error. C. Proportion of fixations made towards route planning locations pre-training and post-training across all 3 conditions. D. Proportion of total fixation time spent fixating obstacles pre-training and post-training across all 3 conditions. Obstacles include both obstacles and end gates. Error bars represent standard error.

Interestingly, we found a change in the saccade – obstacle crossing interval measure pre- to post-training (Time main effect: $F_{1,42} = 13.2$ $p = 0.0008$) as illustrated in Figure 2-10. Specifically, participants looked away from obstacles ~ 1 s earlier with respect to crossing them post-training compared to pre-training. Since gait speed differed between pre- and post-training and conditions, we included it as a covariate in this analysis.

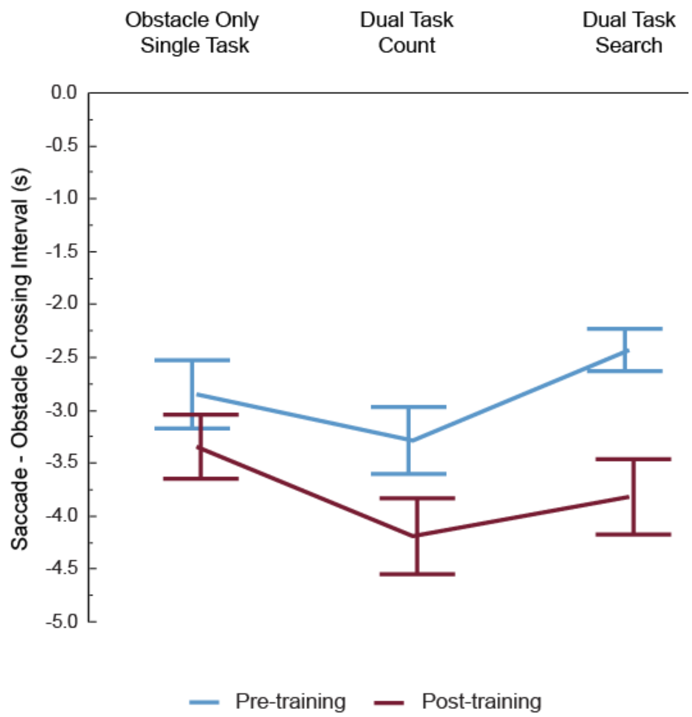

Figure 2-10: Saccade – obstacle crossing interval for the obstacle avoidance task.
Mean obstacle crossing interval for pre-training and post-training across all 3 conditions. A negative interval represents gaze shifts made away from an obstacle prior to the chest crossing that obstacle. Error bars represent standard error.

A change in the number of obstacle collisions accompanied the change in gaze behaviour. Importantly, we found a dramatic reduction in the number of obstacle contacts per trial post-training compared to pre-training in all conditions (Time main effect: $F_{1,45} = 53.0$, $p < 0.0001$; see Figure 2-11). All participants had at least one collision pre-training whereas only 7 had collisions post-training. In total, there were 101 obstacle collisions pre-training compared to only 13 obstacle collisions post-training.

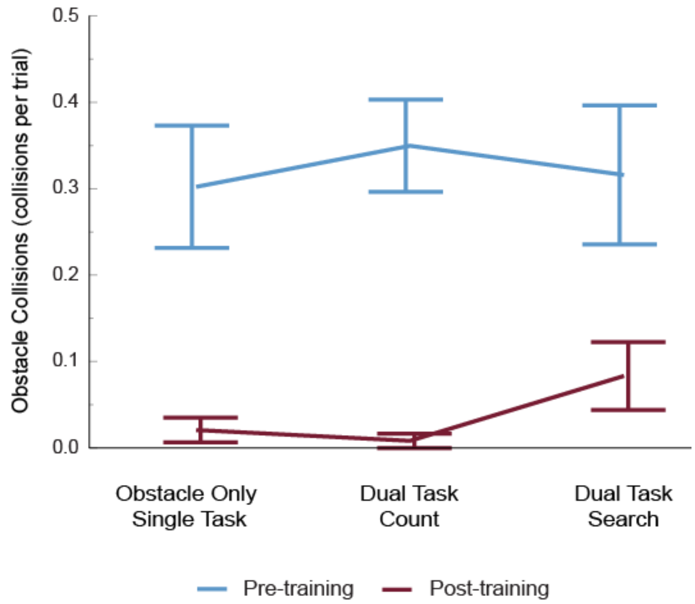

Figure 2-11: Obstacle collisions during the obstacle avoidance task.
Mean obstacle collisions per trial for pre-training and post-training across all 3 conditions. The number of collisions is normalized to the number of trials for that condition. Error bars represent standard error.

2.3.3. Dual task performance

We evaluated the dual task costs pre- and post-training to determine if participants could continue to perform an additional task while following the gaze training instructions. We found no significant differences in dual task costs between pre- and post-training for the precision walking task (No time main effect: $F_{1,27}$ = 1.0, p = 0.325; see Figure 2-12A). However, dual task costs increased during the obstacle avoidance task post-training (Time main effect: $F_{1,25}$ = 5.35, p = 0.029; see Figure 2-12B). This only occurred for the search dual task (Time x Condition main effect: $F_{1,25}$ = 5.26 p = 0.03; see Figure 2-12B)

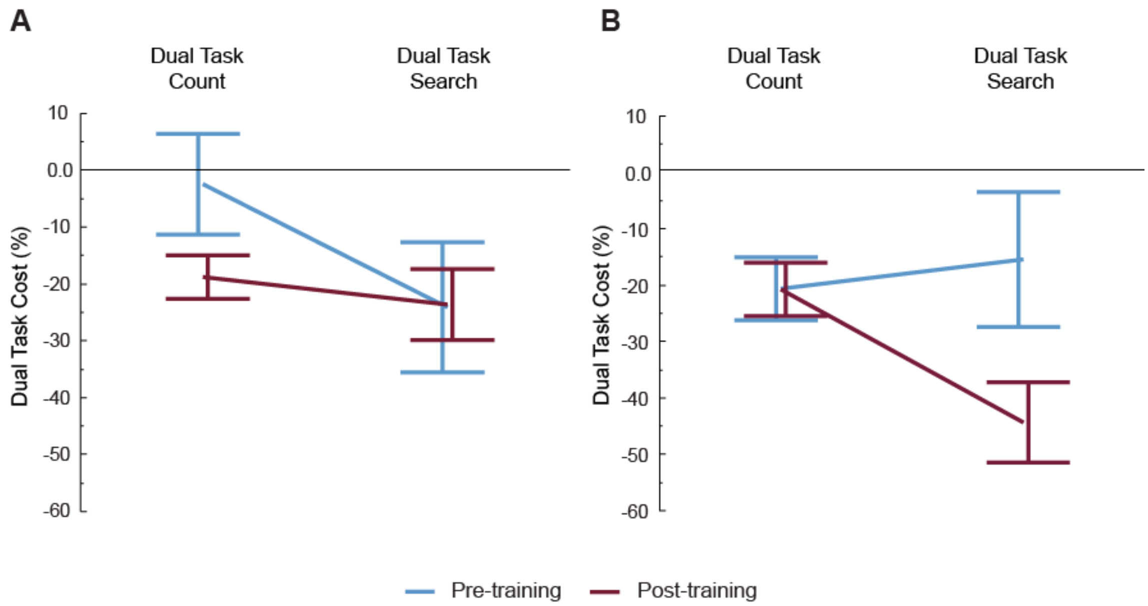

Figure 2-12: Dual task costs for the precision walking and obstacle avoidance task.
A. Dual task costs for pre-training and post-training across dual task conditions for the precision walking task. B. Dual task costs for pre-training and post-training across dual task conditions for the obstacle avoidance task. Negative values indicate poorer performance while walking than during baseline. Error bars represent standard error.

2.3.4. Survey results

Finally, we provided participants with a questionnaire about the gaze training to help us determine the positive and negative aspects of it, and if participants found it useful. The survey results are reported in Table 2-2.

Table 2-2. Gaze training questionnaire results.

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The gaze training instructions were easy to understand and follow	0.6	0.4	0	0	0
The gaze training pamphlets were helpful	0.3	0.7	0	0	0
The home-based training session was helpful	0.3	0.7	0	0	0
I am more confident while walking after the gaze training program	0.7	0.3	0	0	0
I am more aware of my environment after the gaze training program	0.9	0.1	0	0	0
I have started to use the gaze strategies in my daily life	0.4	0.5	0	0.1	0
The gaze training program has helped my mobility	0.3	0.6	0.1	0	0
I will continue to review the pamphlets and practice what I learned now that my participation in the research study is complete?	0.5	0.4	0.1	0	0

Responses represent the proportion of participants that gave that response for each question.

2.4. Discussion

Glaucoma-related changes in gaze behaviour prevent the acquisition of appropriate environmental information and result in impaired mobility.[31] Current interventions, including O&M training, are beneficial for individuals with vision loss.[193,197–199] However, they lack scientific validation[195,243] and do not incorporate changing the gaze behaviour our lab has identified as being different and detrimental.[31] Current gaze training interventions for peripheral vision loss are computer based and do not transfer to real-life situations.[210,211] Thus, we created a multi-dimensional gaze training intervention for older adults with glaucoma. In situations where precision is key, we trained participants to look at a ground location until their heel contacted it. Indeed, in the precision walking task, participants transferred their gaze away from targets later with respect to heel contact on that target post-training compared to pre-training. We also saw improved foot-placement error and foot-placement error variability post-training. When obstacle avoidance is key, we trained participants to look at obstacles and then between them before passing through. As such, participants looked away from obstacles earlier with respect to their chest crossing them. A reduction in obstacles collisions accompanied these gaze changes. Together, our results suggest that gaze is modifiable in older adults with glaucoma and may improve mobility performance.

2.4.1. Changes in gaze behaviour during precision walking

Acquiring the appropriate visual information in a timely manner is important to ensure that the foot is placed appropriately. Individuals with glaucoma demonstrate inappropriate gaze behaviour while preforming precision walking tasks, such that they look too far ahead relative to where they are stepping.[31] We trained individuals with glaucoma to maintain fixation on the ground location they would like to step until heel contact on it in situations where precision is key. We evaluated this aspect of training using the precision walking task. Indeed, participants transferred their gaze away from targets later with respect to heel contact post-training compared to pre-training. Interestingly, they also looked towards targets later with respect to lifting their toe off to step towards that target post-training compared to pre-training. Maintaining gaze on a target until heel contact allows less time to fixate the next stepping target before lifting the toe off to step there, which may explain this result.

We incorporated dual task training into the gaze training program, where we had participants locate landmarks or perform a cognitive task (naming words that start with a given letter) while walking. Accordingly, post-training, participants transferred their gaze away from the current stepping target later with respect to heel contact on it in all conditions. This suggests that participants were able to follow our gaze training instructions even when preforming a secondary task during walking. Similarly, Wollesen et al.[244] found that training older adults under dual task conditions improved gait performance while dual tasking. However, both pre- and post-training, participants transferred their gaze away from the targets earlier with respect to heel contact in the dual task conditions. For the dual count task, this likely indicated that counting was most challenging. This was self-reported from patients in this study and our previous work.[31] Similar behaviour is seen when older adults at a high risk of falling step over an obstacle while counting.[232] We made the counting task easier than in our previous studies (counting down backwards from 5's instead of 3's) to prevent participants from looking up or away from the walkway, although it still proved to be a difficult task. For the dual search task, the early gaze transfer was likely because participants had difficulty prioritizing fixations between shapes and targets, and they wanted to perform well in both tasks.

There are a few reasons why we saw a change in gaze behaviour from pre-training to post-training, although we believe that the gaze training plays a major role. Gait speed decreased from pre-training to post-training, which could contribute to the changes in these intervals result. However, they are relatively independent of gait speed,[120] and adding gait speed as a covariate did not change the results. Thus, we believe the gaze training lead to changes in the HC- and TO-interval.

Although we argue the changes in gaze behaviour observed were due to the training, reduced anxiety could have played a role. Anxiety and fear of falling can result in early gaze transfer with respect to heel contact.[61,245,246] It is possible that participants were less nervous about the task post-training due to increased confidence from the gaze training, or due to familiarity with the tasks. However, only two of our participants reported a fear of falling, and half of our participants had already participated in a study with the same protocol. In addition, our flat targets are less likely to provoke anxiety than the ones with raised edges used in Young et al.[61] Although reduced anxiety likely played a minor role in the results, further work should explore how anxiety levels change with gaze training, as anxiety reduction could be an additional focus.

2.4.2. Changes in mobility during the precision walking task

Interestingly, foot-placement error only improved in the dual task conditions. Foot-placement error was lowest in the target only condition and highest in the counting dual task condition both pre- and post-training. Thus, there was likely less room for improvement in the target only condition compared to the dual task conditions. These findings are important, as the ability to count backwards while walking is associated with fall risk in older adults.[232,247] Foot-placement error itself is also related to fall risk,[60,108,109] highlighting the importance of these results to improving mobility and quality of life for those with glaucoma.

Changes in the HC-interval may, in part, explain why we saw improved control of foot placement. Older adults at a high risk for falling and older adults with glaucoma show a tendency to prioritize planning future stepping locations at the expense of the current step.[31,116] Although this may provide additional time for older adults with glaucoma to extract the necessary visual information and use it to plan an appropriate step to the target, it might actually prevent the acquisition of visual information necessary for the current step. The HC-interval correlates with foot-placement error and foot-placement error variability such that a premature transfer of gaze with respect to heel contact decreases performance.[31,109,116,203] Maintaining a fixation on a target until heel contact ensures that the correct visual information is acquired and reduces the reliance of peripheral vision to supply this information; something that is potentially reduced in individuals with glaucoma. Indeed, directly fixating a stepping target allows for better accuracy than when the target is fixated eccentrically in both young and older adults.[248,249] Improved foot-placement error may suggest that participants are better able to make online, visually guided alterations to foot placement. Reynolds & Day[69] suggest that young adults can make online changes to their foot trajectory up to 300 ms after their foot leaves the ground to swing to that target. However, older adults are less able to use this information during swing phase,[59] making this unlikely. It may also be a product of better planning. Some contribution from all of these factors likely contributing to decrease foot-placement error and error variability

2.4.3. Dual task performance in the precision walking task

We did not see a decrease in either of the dual tasks costs from pre-training to post-training, which was somewhat unexpected. Typically, older adults prioritize the dual task over the motor task as the dual task becomes increasingly complicated.[250–252] Thus, we expected dual task performance to decrease when participants were instructed to focus on using appropriate gaze strategies. For the count, many participants used a strategy where they would say a number with each step to simplify the task. Since the number of steps did not change, they still said at least 4-5 numbers. In the search dual task, if participants chose to prioritize the precision walking task more than the search task, we likely would have seen a greater change in HC-interval and a reduction in search dual task performance. This suggests that participants still prioritized both tasks but were able to prioritize gaze behaviour more appropriately.

2.4.4. Changes in gaze behaviour in the obstacle avoidance task

Individuals with glaucoma visually sample the environment differently than normally-sighted controls such that they direct their gaze closer to their current position (Lajoie et al., unpublished results). This is opposite to the strategy seen while stepping on targets.[31] Thus, we trained gaze differently for when obstacle avoidance is key. Looking too close to the feet may hinder appropriate path selection, and the path chosen may require more turns or turns of larger amplitude, increasing the risk of obstacle collisions. Thus, we instructed participants to conduct a gridline scan of the environment prior to walking to help plan a path, a technique commonly taught by O&M specialists to those with low vision.[193]

Participants made many more fixations post-training than pre-training before passing through the obstacles, suggesting that they did make an effort to systematically scan the environment. They made the most fixations in the search dual task condition, likely as a result of searching for the shapes as well as planning a route. Since this scan involved looking both far and near, this was not reflected in a great spatial or spatial-temporal gaze distance. This is likely because post-training, participants made more fixations around a distributed area as a part of the gridline scan. Indeed, the variability of spatial gaze distance was larger post-training than pre-training, suggesting the participants are making these fixations to a larger distribution of the environment. Scanning the environment may have helped participants form a better spatial map of the environment,[156,157] allowing them to select an appropriate path and reduce obstacle collisions. Individuals with retinitis pigmentosa who make more exploratory saccades than normally-sighted controls do not show decreased performance.[188] Indeed, conducting an initial scan over 1-2 strides is enough to extract visual information to successfully cross an obstacle.[38]

Individuals with glaucoma make a greater proportion of fixations in terms of number and time to obstacles (Lajoie et al, unpublished results), which may contribute to increased number of collisions. Thus, we instructed participants to look at obstacles prior to passing through them, as maintaining a fixation may actually steer them into the obstacle.[48,253] We found that participants transferred their gaze away from obstacles earlier with respect to the chest crossing that obstacle post-training compared to pre-training. In other words, the participants looked at the gap between the obstacles, which is where they want to steer themselves. This may have contributed to the reduced number of obstacle collisions seen post-training compared to pre-training. It is possible that the gridline scan at the beginning enabled them to assess the obstacles appropriately from the start and prevented the need to re-locate the obstacle as they were walking. However, the proportion of obstacle fixations (number and duration) did not differ pre- to post-training. This suggests that participants are making similar amounts of obstacle fixations, but that these fixations are made earlier with respect to crossing.

Previous data from our lab suggests that individuals with glaucoma spend less proportion of time fixating route-planning locations than normally-sighted controls (Lajoie et al., unpublished results). During obstacle navigation tasks, to help plan an optimal path, fixations are often directed towards future goals and foot fall areas,[46,96] especially at the beginning of the path. Interestingly, we did not find a difference in the proportion of fixation number or duration made towards route planning locations post-training compared to pre-training. Thus, our participants did not reweight the proportion of fixations towards route planning locations vs obstacles. Interestingly, if we separate the end gates from the tall foam pole obstacles, we find that participants spent a greater proportion of time fixating the end gates post-training than pre-training. This suggests that they are spending more time re-orienting themselves with the location of the goal.

2.4.5. Dual task performance in the obstacle avoidance task

Participants were able to maintain this new gaze behaviour even when preforming an additional task. However, we did find an increase in dual task cost for the dual search task post-training compared to pre-training, but not for the dual count task. In contrast to the precision walking task dual costs, this is in line with evidence suggesting that older adults prioritize the dual task over a motor task.[250–252] This is interesting because there was no difference in the proportion of fixations, in terms of duration and number, towards the shapes. It is possible that since participants walked slower in the obstacle avoidance task than the precision walking task, the longer trial duration made it more difficult to store the location of shapes in their head.[254]

2.4.6. Conclusions

Overall, these results suggest that gaze is modifiable, and that these modifications can be maintained even when a secondary task is present. These changes in gaze behaviour were accompanied by improvements in mobility performance in both tasks. While our sample size is too small to run reliable correlations, given the importance of vision for mobility, we presume that the changes in gaze behavior, in part, contribute to these improvements. Our results from the precision walking task closely resemble those from Young & Hollands,[203] where they taught older adults to maintain gaze on targets until heel contact, highlighting the importance of receiving the correct visual information in a timely manner. Our results from the obstacle avoidance task show more positive improvements in mobility than computer-based interventions targeted at improving search performance. This is likely, in part, a result of making the training task-specific and based on real-life environments. The results highlight the importance of looking where you want to go,[48,253] and planning a path before walking through a complex environment. It is interesting that we saw improvements in mobility performance despite slower gait speed post-training, as gait speed is often used as a gross indicator of mobility function.[8,255] However, this slowing down may be an indicator of the additional focus it takes to consciously apply these gaze behaviours. With practice, we hope that older adults with glaucoma could increase gait speed while maintaining these gaze behaviours. Thus, this study provides proof-of-concept evidence that practicing these gaze strategies in realistic environments can modify gaze, and that these changes in gaze can be accompanied by improvements in mobility. Further research should tease out which strategy was most beneficial and incorporate a control group to eliminate improvements in performance based on familiarity. Regardless, we suggest that gaze training may be an effective way to improve mobility and should be further explored to allow O&M specialists to incorporate it into their current training protocols.

Chapter 3. General discussion

This study aimed to provide proof-of-concept evidence that gaze is modifiable in individuals with glaucoma, and that this could contribute to improved mobility. Older adults with glaucoma were able to follow the gaze training instructions, showing changes in gaze behaviour post-training compared to pre-training. They transferred their gaze away targets later with respect to heel contact and away from obstacles earlier with respect to their chest crossing it in all three conditions. They made more fixations to a variety of places before walking though the obstacles. Along with these changes in gaze behaviour, we saw an improvement in performance on these tasks. Participants improved foot-placement accuracy and reduced foot-placement error variability. They also dramatically reduced obstacle collisions in all conditions. The findings of this study may be used to create improved gaze training programs to improve mobility in those with peripheral vision loss, and specifically glaucoma.

3.1. Feasibility

While conducting this study, we encountered difficulty recruiting participants. This was likely due to the location of the University. Many potential participants commented on the distance they would have to travel and the inconvenience of location. In addition, the duration of the study, albeit only 3 days, was enough to deter those who did not believe themselves to have any mobility limitations. On the other hand, those with more severe mobility limitations were too nervous to participate. We may have had better luck with recruitment if we were attached to a hospital where patients regularly went to visit their doctor so we could integrate this program into their routine appointments.

One concern prior to starting this project was if people would understand the gaze training directions. As the survey given to participants at the end of the training suggests, there was no issue in understanding the instructions. Participants quickly understood and were able to follow the instructions provided. The training itself lasted ~30-45 minutes in the lab and ~45-60 minutes at home. This included videos, pamphlets, and task-specific, mobility course, and home-based practice.

The survey results also highlighted that most of our participants enjoyed the gaze training and found it beneficial. Most of them indicated that they felt more confident after the training and intended to use these strategies in their everyday life. Comments such as "more aware of my surroundings," and "it was great" were given. Many participants commented on how much they enjoyed the home visit, as it emphasized when and where certain gaze strategies would be useful. Fewer found the pamphlets of use, likely because they re-iterated what we had already taught them. However, most still found the pamphlets useful to refer back to. Although some participants commented on the length of testing in total, no one thought that the gaze training intervention itself was too long.

Whether all of these forms of practice is necessary is questionable. Future work is needed to determine which means of practice is most efficient and effective. We only spent a total of 2 hours training our participants. While the results we got are very positive, more sessions over a larger amount of time would help make this behavior more natural and effortless.

3.2. Limitations

There are a number of limitations present in the design of the experiment due to technical constraints and feasibility. First and foremost is the small sample size. Unfortunately, patient recruitment is challenging. Of all the patients at the clinic, not all have glaucoma. Of those with glaucoma, many do not have visual fields poor enough to be eligible, or only have glaucoma in one eye. Of those who have glaucoma, not all of them have strong enough mobility to participate, or have another visual disease. Of those that were eligible, only a few were willing to make the commitment to come up to SFU. However, the main objective of this research was to provide proof-of-concept. This data can be used to determine the necessary sample size for a larger randomized clinical trial.

Another limitation is that the shapes were not present during all the tasks, only the search condition. This of course meant that during the search condition, the percentage of fixations to obstacles/ground would be less since there were also shapes to fixate on. While we believe people would not look at the shapes during the other conditions since people tend to make task relevant fixations, this makes it harder to compare the percentage of fixations on certain AOI's.

Finally, our testing occurred in a lab-based setting and it is hard to know how this would carry over into the real world. Although we made our tasks as realistic as possible, they are also very controlled. Precision walking tasks and obstacle courses are commonly used to assess mobility performance in older adults.[109,8] The use of home-based training, however, would likely help the gaze strategies transfer to real-life conditions.

3.3. Implications and future directions

This research suggests that since gaze is modifiable, it may be an effective means to improve gaze-related mobility issues in people with peripheral vision loss. These findings are important to develop interventions that can help improve the quality of life for individuals with glaucoma. Current gaze training methods are limited to computer-based programs aimed at improved search speed and accuracy.[210,211] While these methods help screen-based search tasks, they have limited transfer to mobility. Thus, interventions focusing on training gaze behaviour in real-life walking tasks are necessary. Currently, O&M training is available to those with low vision. However, the strategies taught are often most useful for those with very poor vision. Other techniques such as minification through lenses or augmented-vision head-mounted displays are beneficial for some tasks such as reading,[256,257] but can reduce resolution and be annoying during walking. If made more effective and ergonomic, these devices have potential for the future.[258] However, the most cost-effective and most accessible way is to take advantage of people's remaining vision, and teach them how to optimally use it. Thus, these skills can be incorporated into what is already taught in O&M training prior to seeking out more sophisticated and expensive technology.

We used many different strategies to train our participants, including videos, task-specific training, mobility courses, home-based training, and pamphlets. We also had participants practice the gaze strategies while preforming a secondary task. Changes in gaze behaviour and mobility were still present when preforming a dual task. While we cannot say with certainty that this is due to training concurrently with a dual task, it likely did play a role. Further research should delve into determining which of these methods is most effective and determine whether preforming a dual task during gaze training practice is necessary to see these results. This will help improve the efficacy and efficiency of training, making people more likely to adhere to their programs.

Our previous work showed that there are greater detriments to mobility and gaze behaviour with more peripheral vision loss.[31] Thus, we need to explore the relationship between improvements in gaze behaviour and mobility and peripheral vision loss. This will help determine at what stage of glaucoma does training become helpful, and if we should focus on different gaze strategies for different levels of peripheral vision loss. Ideally, training could be tailored to the specific individual's needs.

We recommend that O&M specialists implement these gaze training strategies into their protocols once the ideal gaze training program is established. These strategies ensure that the appropriate visual information is gathered at the appropriate time. They should also continue to educate patients on the impacts of dual tasking on mobility. Older adults with glaucoma should put more of their efforts into walking rather than focusing on the other task at hand. When possible, older adults with glaucoma should stop walking while performing additional tasks. This is not always possible, such as when walking with a friend, or looking for your destination. Thus, it is important that this training is done while concurrently performing a secondary task. This will encourage participants to utilize these strategies even when performing an additional task, and help them learn to prioritize fixations towards the travel path.

Given the results of our proof-of-concept study, we recommend that a larger randomized clinical trial be conducted. Ideally, different groups of participants can experience different aspect of training as part of this larger study so that the contribution of the various training strategies can be assessed.

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