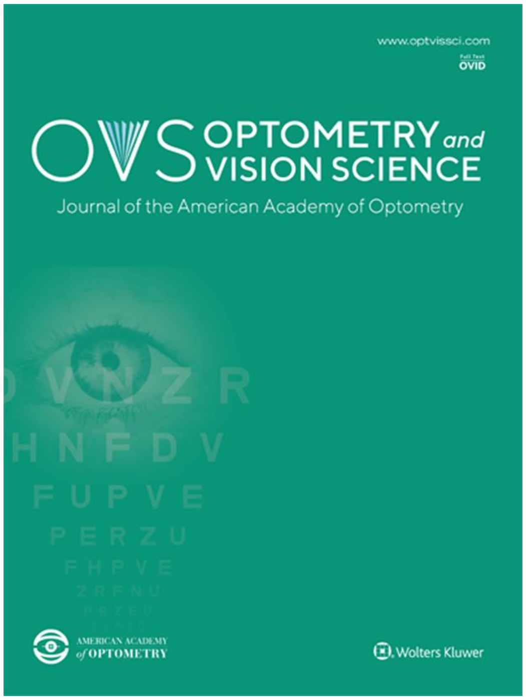

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REVIEW

Topical Review: Impact of Central Vision Loss on Navigation and Obstacle Avoidance while Walking

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ABSTRACT

Significance: Individuals with central vision loss are at higher risk of injury when walking and thus may limit trips outside the home. Understanding the mobility challenges associated with central vision loss (CVL) can lead to more effective interventions.

A systematic literature review focusing on mobility in central vision loss was conducted. Using the PRISMA method, 2424 articles were identified in 4 databases (PsycINFO, APA PsycArticles, PubMed, and Web of Science). To be included within this review, the study methodology needed to be related to the three components of walking: (1) navigation, defined as the ability to reach a target destination; (2) obstacle avoidance, defined as the ability to avoid collisions with obstacles located at various heights and directions; and (3) street crossing, defined as the ability to both navigate a path and avoid collisions in a traffic environment. The methodology also needed to be empirical. Case studies, unstructured observational studies, studies based on self-report, research proposals and existing systematic reviews were excluded. Titles, abstracts and full text of identified articles were screened, yielding 26 articles included in the review. Results showed that, in many tasks, individuals with CVL can accomplish a level of performance comparable to individuals with normal vision. Differences between normal and impaired vision were due either to age or in how the groups completed the task. For example, individuals with CVL could cross a street successfully, but did so less safely (i.e. smaller safety margins) than individuals with normal vision. To identify new interventions for CVL, future research should focus on the differences in the mechanisms underlying mobility between individuals with normal and impaired vision rather than solely on performance differences.

Most individuals who are legally blind have some form of residual vision.[1,2] The Social Security Administration of the United States defines legal blindness as having 20/100 or worse in the better eye or as having a visual field of 20 degrees or less. Therefore, complete vision loss is not necessary for an individual to be considered legally blind.[2] For example, in central vision loss, foveal vision is degraded but peripheral vision is intact.[3] Individuals have difficulties seeing fine details and may have scotomas in the central visual field, resulting in degraded reading, navigation and activities of daily living.[4] Therefore, central vision loss can be defined as loss of central detailed vision with remaining peripheral vision being mostly intact.[5] Causes of central vision loss include macular diseases such as age-related macular degeneration and diabetic retinopathy.[6]

Age-related macular degeneration affects 2.95 million persons in the United States,[3] is the fourth leading cause of blindness (defined as a visual acuity of 20/400) worldwide[7] and is the leading cause of vision loss in older adults in the United States.[6] A common symptom of age-related macular degeneration is central vision loss, resulting in peripheral vision being used as a substitute. Thus, it is important to identify the effectiveness of existing aids designed for navigation and obstacle avoidance by individuals with central vision loss. Indeed, a previous review[4] on quality of life with central vision loss identified key challenges as traveling outside the home, navigating steps and curbs, noticing objects, and greater risks of falls. Therefore, mobility related to walking is impacted in central vision loss and warrants investigation. Further, our preliminary analysis of the literature resulted in few articles focused on aids to facilitate navigation and obstacle avoidance for individuals with central vision loss. On the other hand, research has investigated mobility aids for peripheral vision loss. For example, augmented reality, [8] collision warning devices, [9] and visual field expansion devices,[10] have been investigated as methods to improve mobility for peripheral vision loss. There is a dearth of studies which investigate mobility aids for central vision loss. One goal of this review is to highlight this gap.

Central vision loss is associated with mobility issues, including navigation and obstacle avoidance. Individuals with central vision loss are more likely to fall compared to individuals with normal vision,[11] possibly due to not detecting obstacles or misjudging their distances. Susceptibility to falls can decrease trips outside the home[12] and increase social isolation. Restricted mobility due to central vision loss is associated with mental health disorders such as depression,[13] and anxiety.[14] Central vision loss also is associated with injuries due to events other than falls, with over one-third of non-fall related injuries caused by collisions with other objects.[11]

There are several reasons that individuals who use peripheral vision rather than central vision as their primary source of visual information may have more challenges with mobility than those who rely on central vision. Peripheral vision has lower visual acuity, making it more difficult to discern details about the environment compared to central vision. Peripheral vision also is characterized by poor depth perception, and difficulty noticing stationary objects.[15] Consequently, individuals reliant on peripheral vision, such as those with central vision loss, may not notice static obstacles when walking, especially if the obstacle has features that are similar to the background; or if the object is detected, its distance may be misjudged due to inaccurate depth perception.[16] Although generally peripheral vision results in the rapid detection of object motion,[17] judgments about an approaching object's time to collision are not as accurate as central vision due to greater looming or optical expansion thresholds in peripheral vision. Looming refers to the increase in an approaching object's optical size as its distance to the observer decreases. Observers can use looming to detect approach if looming is above detection threshold.[18] This threshold is larger in peripheral vision than central vision.[19,20] This means that the object must be relatively closer before the observer notices looming (and thus approach).

To mitigate effects of central vision loss on mobility, aids have been created to help individuals with activities of daily living, navigation, and obstacle avoidance. For example, individuals with visual impairment commonly use the white cane, which helps users scan the environment to identify obstacles and hazards.[21] Mobility aids can be classified into three broad categories. First, sensory substitution devices translate visual information into a different modality (e.g., sound) which can be used to avoid collisions.[22] Second, training can be used to help individuals learn to avoid collisions. A widely used type of training is orientation and mobility training which provides individuals with different skills based on their specific visual capabilities and lifestyles.[23] Finally, screen-based devices enhance vision of specific parts of the environment by removing unnecessary visual information so that individuals can better navigate around obstacles.[24]

Individuals with central vision loss can develop an alternate retinal area as a surrogate fovea, known as the preferred retinal locus, which, if located close enough to the fovea, may negate the need for additional mobility aids. However, the preferred retinal locus takes approximately six months to develop into a stable fixation location.[25] Further, evidence suggests that individuals with central vision loss have multiple preferred retinal loci, which are used interchangeably based on the task being performed[26] or the characteristics of the environment, such as lighting.[27] Due to the length of time necessary to develop a stable preferred retinal locus, individuals with recent central vision loss may require greater support during walking and with tasks of daily living while they are adapting. One option is to refer patients to a Low Vision Clinic, which provides exercises tailored to patients' ability levels.[28] However, treatment and training can last many months and take time before patients see improvements in their abilities.[28] Therefore, it is essential to find alternative options to help patients walk and perform daily tasks effectively while they are still developing a stable preferred retinal locus. Additionally, the progression of visual diseases can lead to additional vision loss in already developed preferred retinal loci, requiring patients to re-establish a preferred retinal locus in a new location.[29] This location change also requires new training at a Low Vision Clinic. Therefore, providing visual aids to support mobility could potentially make this adaptation period easier.

In short, peripheral vision degrades the ability to notice still and moving objects, and therefore individuals with central vision loss (who rely more on peripheral vision) might potentially benefit from mobility aids, including those originally designed for peripheral or complete vision loss, such as sensory substitution devices or a white cane to navigate within an environment. Traditionally, sensory substitution devices are used as a complete replacement for vision; that is, the device replaces vision.[30] However, individuals who have only central vision loss do not need devices to completely replace their vision because they can still use peripheral vision for navigation.[3] Instead, sensory substitution devices could complement vision by alerting the user to stationary and moving obstacles, which may be missed in peripheral vision due to deficits described previously. For example, individuals with central vision loss often misjudge the distance of an obstacle[16] and thus may fail to avoid it. Collision avoidance may be improved with a sensory substitution device that alerts the individual that something is in their path and draws the user's attention, even if the device cannot specify the exact location and size of the obstacle.

There are numerous literature reviews on central vision loss and age-related macular degeneration and most of them focus on epidemiology,[31] treatment,[32] quality of life,[4] and rehabilitation including assistive devices.[33] There are several reviews that focus on effects of central vision loss on mobility while driving. For example, Owsley and McGwin[34] focused exclusively on driving and central vision loss due to age-related macular degeneration. The main finding was that, despite no significant association between age-related macular degeneration and crashes, individuals with central vision loss primarily due to age-related macular degeneration typically have worse driving performance than individuals with normal vision. The low rate of accidents likely occurs because drivers avoid driving at night, driving in unfamiliar areas, and driving in traffic. More recent reviews[35,36] focused on effects of different types of visual field loss, including central vision loss, on driving performance, motor vehicle crashes, and hazard detection. These reviews again suggested that driving performance with central vision loss primarily caused by age-related macular degeneration is worse than driving performance with normal vision. For example, in one study less than 25% drivers with central vision loss passed an on-road driving assessment.[35] Further, reaction times were slower for drivers with central vision loss than drivers with normal vision even though drivers with central vision loss travelled at relatively slower speeds. An important gap of the prior reviews is that none focused on effects of central vision loss on navigation and obstacle avoidance while walking. This gap is addressed in the current review.

It is essential to understand the impact of central vision loss on navigation, such as wayfinding in unfamiliar environments, and obstacle avoidance so that interventions can be developed to reduce falls and injuries, and to enhance mobility, independence, and mental health. A systematic review was conducted to synthesize research on the effects of central vision loss on mobility, and to identify knowledge gaps to guide future research and identify opportunities for interventions. The review was guided by three questions: (1) How does central vision loss affect mobility? (2) What behavioral and cognitive changes occur in mobility with central vision loss? (3) What interventions have been developed to counteract adverse effects of central vision loss on mobility?

METHODS

The guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement to find, collect, and sort articles were followed.[37,38] These guidelines provide authors with a systematic way of collecting and sorting articles that is both transparent and replicable, ensuring the quality of the systematic review.

As mobility can be achieved in various ways (e.g., feet, vehicles, bicycles), we narrowed our search by operationalizing mobility as movement achieved by walking. In a preliminary review of the literature on mobility, we identified three components of walking: (1) navigation, defined as the ability to reach a target destination; (2) obstacle avoidance, defined as the ability to avoid collisions with obstacles located at various heights and directions; and (3) street crossing, defined as the ability to both navigate a path and avoid collisions in a traffic environment.

To be eligible for inclusion, articles had to meet the following criteria: The study population was at least 18 years old. The study methodology was related to the three components of walking and factors that could influence these components, such as walking speed and time to complete a walking task. Third, the methodology was empirical. Case studies, unstructured observational studies, studies based on self-report, research proposals and existing systematic reviews were excluded. All peer-reviewed, English-language articles meeting these criteria were eligible.

Article searches were conducted in October and November, 2020. Two separate syntaxes which represented mobility abilities in central vision loss, and mobility interventions, were run in four databases, PsycINFO, APA PsycArticles, PubMed, and Web of Science:

Syntax 1. Mobility Abilities: (Age-Related Macular Degeneration OR Macular Disease OR Central Vision Loss OR Central Visual Field Loss) AND (mobility OR navigation OR "orientation and mobility" OR Street Cross* OR Time to contact OR Time to collision OR obstacle avoidance OR obstacle crossing).

Syntax 2. Mobility Interventions: (Age-Related Macular Degeneration OR Macular Disease OR Central Vision Loss OR Central Visual Field Loss OR Low Vision OR Vision Loss) AND (mobility OR navigation OR obstacle* OR Street Cross*) AND (intervention OR Training OR Rehabilitation).

During preliminary searches that we conducted before articles were chosen systematically, it became clear that virtually none of the studies included empirical measures of interventions that aim to help individuals with central vision loss. Consequently, we included studies of mobility interventions for individuals with vision loss generally rather than solely for central vision loss. We did this by changing the mobility intervention syntax to include all individuals with low vision. This qualification only applied to studies on interventions. The other search component (i.e., abilities) was limited to central vision loss. The goal of including all vision-related mobility aids was to identify existing mobility interventions and technologies that could be considered in developing recommendations for new ways to help patients with central vision loss. Discussion of mobility aids, including sensory substitution devices such as a tongue-based device, must be considered carefully because they were not designed for, nor evaluated with, individuals with central vision loss; thus, their potential as a mobility aid for individuals with central vision loss as discussed herein is theoretical.

Study Selection

Search results yielded 1743 articles (after duplicates were removed) for consideration. There were three rounds of evaluation. In the first two rounds, titles and abstracts were assessed for relevance, that is, for whether the studies measured mobility in individuals who had central vision loss (or general vision loss for mobility interventions). If there was any uncertainty regarding the inclusion of an article, it was included in the next round of evaluation. The first round resulted in 209 articles.

In the third round, the full text of the 209 articles were reviewed. Articles excluded in this round primarily did not measure mobility empirically. In this round, studies were examined for relevance to our questions concerning mobility abilities and central vision loss, or mobility interventions and general vision loss. Studies of mobility abilities were included only if they clearly stated that participants had central vision loss. Studies that included diseases which could lead to central or peripheral vision loss (e.g., glaucoma) were excluded if they did not specify that vision loss was central. Lastly, we only examined full-text articles that were accessible; there was one article where the full-text was not accessible and was excluded. This screening yielded 26 articles to be included within the systematic review.

RESULTS

Results fell under two broad categories: mobility abilities and mobility interventions. Within each of these two categories, three main areas of research were identified: navigation, obstacles, and street crossing abilities. Table 1 presents a summary of each article included in this review.

Navigation

Mobility Abilities in Navigation

Typical measures of navigation (e.g., preferred walking speed) did not differ between individuals with central vision loss and individuals with normal vision.[39,40] For example, when participants walked along an indoor path,[39] task performance and preferred walking speed differed between low and high illumination conditions but did not differ between individuals with central vision loss and age-matched controls.

Similarly, although participants with central vision loss could navigate successfully to a specified location, their gaze patterns were different from those of sighted controls.[40] Specifically, when participants walked along a corridor to find the correct office door (marked with a room number), individuals with central vision loss exhibited more fixations on the floor compared to controls, who gazed mostly on the left-side doors which is where the target door was located.

Mobility aids in navigation. Mobility aids for navigation consisted of training and technologies, and results indicated varied levels of effectiveness. Results of one study suggested that individuals with vision loss may benefit from visual search training to help them avoid obstacles when walking.[41] Participants with low vision (including individuals with peripheral and central vision loss) first went through an obstacle course twice with different lighting conditions on each run. Participants in the training group then received one week of visual feature search training (finding a slightly larger square within an array of smaller squares). Participants who did not receive training simply completed the pre/post tests. Subsequently, both groups repeated the obstacle course. Participants who received visual search training made significantly less contact with obstacles after training than in the initial run but only in the mesopic lighting condition. Participants who did not receive training did not show this difference. Effects of training did not occur in photopic lighting.

Another study examined the effects of Orientation & Mobility training on the ability to walk to reach an obstacle.[23] Participants with vision loss, including central and peripheral loss, completed an obstacle course once as a pre-test measure, and then either received orientation and mobility training (training group) or did not receive such training (control group). Effects of training on walking efficiency were not significant. In contrast, training to navigate a maze in a virtual environment was effective; the benefits transferred to a real environment and resulted in improved navigational skills.[42] Specifically, individuals with complete vision loss and individuals with low vision who were blindfolded completed an obstacle course as a pretest measure using the visual aid EyeCane. Subsequently, participants were trained to complete the maze in one environment (real or virtual) and completed a posttest in the other environment. Participants made fewer mistakes (i.e., collisions, wrong turns) after training in one environment and completing the task in the other environment. The practical implication is that results of training individuals with severe visual impairments in virtual environments can transfer to real environments. Further research on training tailored for central vision loss is warranted.

Bioptic telescopes have been used to aid mobility and enhance details in the environment by projecting visual information from the impaired central visual field to unaffected areas of the visual field. For example, Szlyk and collegues measured the effects of the telescopes on navigation by individuals with central vision loss. [43] One group of participants with central vision loss received training on how to use the bioptic, whereas the second group (also central vision loss) received no training. Participants in both groups wore the bioptic and were tested three times—once when they received the bioptic (before receiving training for the training group), once after having the bioptic for three months, and once after having the bioptic for six months. Although the bioptic did not improve navigation, it improved driving performance. Individuals in the training group had significant driving improvements over and above that of the no-training group.

Mobility aids for navigation also consisted of technological devices. For example, Maidenbaum and collegues developed the EyeCane navigation aid which provides spatial information through auditory frequencies and tactile actuators to help users understand spatial layout and move through the environment.[22] While navigating an obstacle course, individuals collided with obstacles more frequently when using a white cane than when using EyeCane. Individuals with central vision loss could potentially use this device to notice obstacles missed in peripheral vision. Accordingly, individuals with central vision loss could use this device as a warning system to safely navigate the environment. Another navigation tool, developed by Legge and collegues[44] uses barcodes posted around the environment to help users find a specific area. The user can scan a barcode with a mobile device; an app then provides detailed, voiced directions to their desired destination. Blind and blindfolded individuals successfully used this device to reach a specific room within their environment. Individuals with central vision loss who struggle to read office numbers may benefit from this device to navigate to the correct office without having to use office numbers as a guide.

Obstacles

Mobility Abilities in Obstacle Avoidance

The literature reviewed in this section suggests that an obstacle's height, and the lighting surrounding the obstacle, affect the ability of an individual with central vision loss to navigate around the obstacle. For example, individuals with real central vision loss,[45] simulated central vision loss using contact lenses,[46] and normal vision were asked to walk through an indoor obstacle course and step over small hurdles without touching them.[46] Simulated central vision loss was either complete loss, 10 degrees of loss or 20 degrees of loss. Measures included how high participants stepped over the hurdle[45] and walking speed.[46] Performance was compared between groups with central vision loss and normal vision[45], and among simulation groups with complete, 10-degree and 20-degree vision loss.[46] Participants with central vision loss took significantly higher steps than those with normal vision; those with 20-degree loss had the highest steps and had the highest toe clearance when crossing the hurdle. Higher obstacles led to slower walking speed for the 20-degree loss group. The implication is that individuals with central vision loss may acquire less useful visual information from the environment and may compensate for their vision loss to navigate safely by taking higher steps.

Individuals with age-related macular degeneration have difficulty adapting to changes in lighting, which in turn impacts how they navigate within an environment. For example, participants with age-related macular degeneration walked through an obstacle course by stepping onto the center of a flat target[16] or a curb[47] in different lighting conditions. Measures included walking speed, and accuracy of foot placement on the target or relative to the curb. Individuals with age-related macular degeneration were less accurate in their foot movement in low light and in lighting that changed suddenly compared to individuals with normal vision. Foot placement also correlated with visual acuity, contrast sensitivity, and visual field loss where reduced acuity and sensitivity, and greater field loss, was associated with reduced foot movement accuracy.[16,47] Individuals with age-related macular degeneration also adopted a slower walking speed[16] and shuffled towards the curb[47] when lighting was low. In contrast, another navigation study did not indicate any performance differences between age-related macular degeneration and normally sighted controls in reduced illumination conditions.[39] In this study, participants with age-related macular degeneration and normally sighted controls walked through a multistage indoor obstacle course. For one part of the course, the lighting was greatly reduced and only came from one source, which created glare. Walking speed was slower in the reduced lighting part of the course compared to parts with normal lighting, but there were no differences between the age-related macular degeneration group and the control group.

Mobility aids for obstacle avoidance. Mobility aids for obstacle avoidance included sensory substitution devices, which translates visual information into information that can be used by another sensory modality such as audition. For example, to alert the user to impending collisions, the frequency of the sound increases as an obstacle gets closer. Results of one study showed that a sensory substitution device, EyeCane, which translates obstacle distance information to auditory information, can be used for obstacle detection with minimal training.[22] Blindfolded participants walked down a hallway with different obstacles located on the ground (e.g. office chair, coffee dispenser, person) using either a white cane or the EyeCane. All participants who used the EyeCane navigated the hallway successfully and exhibited significantly fewer contacts with obstacles on the last trial compared to the first. In contrast, individuals who used the white cane did not show a large improvement between trials and made significantly more contacts with obstacles on the last trial than users with the EyeCane. The EyeCane also has been shown to help users detect and avoid obstacles located above or at waist level.[48] Individuals with central vision loss could use this device to notice and avoid obstacles; the device can draw their attention to an object that needs to be avoided.

Other sensory substitution devices, transform visual information, such as obstacle distance, into auditory and tactile information. Kim and collegues developed a system which transforms visual information to auditory information and translated distance information into pitch such that closer objects emitted higher-pitched sounds compared to further objects.[49] This allowed participants to recognize their surroundings successfully, reflected in their ability to detect and avoid obstacles. Chebat and colleagues developed a similar system in which visual information captured by a camera worn by the user was translated into electro-tactile pulses presented on a tactile grid worn on the user's tongue.[50] Participants navigated through a maze successfully and avoided significantly more obstacles than chance probability level while using this device. One limitation of this study was that a control group was not included. Tongue-based devices could be used by individuals with central vision loss to better notice objects and obstacles in the environment while walking, to navigate steps and curbs, and to facilitate navigation in dim lighting; all of these activities were identified as critical challenges by patients with central vision loss.[4] Similarly, tongue-based devices could help individuals who use white canes detect and avoid obstacles, which can be missed by individuals with central vision loss especially in dim lighting.[4] This tongue-based device acts similarly to other sensory substitution devices, where visual information about the environment is presented in another modality, in this case as vibrations on the tongue. The implication is that individuals with central vision loss could use this device to be alerted to obstacles they do not notice in peripheral vision. This device does not provide details of the environment, but could potentially act as a warning system of an approaching obstacle, helping an individual avoid them. In short, sensory substitution devices can facilitate walking with central vision loss by drawing attention to information about the environment that is missed.

However, not all sensory substitution device improved obstacle avoidance. When participants with low vision, including central and peripheral loss, used an Android phone that was placed in a head-mounted display and translated distance, height and width information to auditory outputs such as volume and pitch, performance was degraded on measures of collision avoidance or task completion time.[51] Similarly, a sensory substitution device did not exhibit a beneficial effect over and above the benefits of the white cane.[52] In this study, a novel sensory substitution device was attached to a white cane and participants were asked to navigate two mobility courses with obstacles of different heights and sizes. Measures included the number of contacts with obstacles, time taken to complete the mobility courses, and how much ground was covered. There were no significant differences in performance between the white cane alone and the white cane with the sensory substitution device. Therefore, it is unlikely that this device would provide information about an obstacle missed in peripheral vision that an individual with central vision loss would not detect by using a white cane alone.

The devices discussed thus far assumed that users could not use any residual vision and needed to rely entirely on their other senses. However, certain devices utilize users' remaining visual abilities, whether they are central or peripheral. One system simplified visual information through an LED panel placed in glasses worn by the user.[24] Objects were represented as a cluster of LED lights, and brightness was used to represent distance. Participants exhibited fewer contacts with obstacles when they navigated through an obstacle course while wearing the glasses. However, walking speed was greatly reduced even when participants were informed that no obstacles were present in the trial.

Street Crossing Judgments

Street Crossing Judgments with Central Vision Loss

Studies of how individuals with central vision loss cross the street can be split into three categories: crossing the street at roundabouts, crossing the street at unsignalized intersects, and crossing the street at signalized intersections. Generally, individuals with central vision loss may take longer to identify whether a traffic gap is safe to cross, and to decide when to start crossing the street. For example, participants with central vision loss due to age-related macular degeneration and participants with peripheral vision loss due to glaucoma or retinitis pigmentosa,[53] made street-crossing decisions at roundabouts with three[54] or five[53] legs. Participants were instructed to identify when it was safe to cross and then either crossed by walking[54] or depressed a button for the entire time it was safe to cross and released the button when it was no longer safe.[53] Measures included the safety of the crossing decision by determining whether a participant would have safely crossed the street[54] or how much time remained between the participant's crossing (button release) and the vehicle's arrival at their location (safety margin).[53] The two vision loss groups did not differ from each other in the number of identified traffic gaps that were wide enough to allow enough time to cross the street safely. However, participants with central vision loss took longer to identify traffic gaps and had shorter safety margins compared to controls.

Street crossing judgments at unsignalized intersections differed between younger and older individuals but did not differ between individuals with normal and impaired vision. In these studies, participants had age-related macular degeneration[55,56] or simulated central vision loss.[57] Normally sighted-individuals were included as age-matched controls. Participants stood at a curb with 2 lanes, one in each direction, a curb with a single-lane,[56,55] or at a curb of a central island with only one lane.[57] Participants reported (i.e., button press and release) the moment they could cross the street, or they actually crossed the street. If the pedestrian cleared the intersection by the time the vehicle arrived, this was considered an accurate crossing decision. Visually impaired participants had a similar number of accurate street crossing decisions as age-matched controls. When collapsed across visual abilities, older adults were more likely to have unsafe crossing decisions compared to younger adults.[56] However, a small association between visual acuity and street-crossing decisions was found, where a lower visual acuity lead to less safe crossing decisions.[57,56] This finding was not replicated across all studies.[55] Taken together, results imply that age, but not visual impairment affected street-crossing decisions.

Stages of street crossing judgments in central vision loss. Although significant differences in the ability to make safe street crossing judgments were not observed between individuals with central vision loss and age-matched controls, differences were seen in how individuals behave while making such judgments. For example, participants with age-related macular degeneration or glaucoma stood at the curb of a 2-way intersection or 3-leg roundabout and walked toward the curb wearing while wearing an eyetracker or head-tracker to measure their movements during the three stages of crossing the street—walking to the curb, standing at the curb, or crossing the street.[54,58] Differences in eye and head movements between individuals with low vision and individuals with normal vision were measured including the number of fixations, the number of head turns, and the time spent fixating different locations within the environment. Regardless of whether they have age-related macular degeneration or glaucoma, individuals fixated on crossing elements (crosswalk, curb) while approaching the curb and switched to looking at cars while standing at the curb. Compared to individuals with normal vision, individuals with central vision loss exhibited longer fixations on crossing elements (e.g. pedestrian light). Further, individuals with age-related macular degeneration had fewer head movements and did not meet the required number of head turns for safe crossing (i.e., moving the head fully to the right and left) established by the National Highway Traffic Safety Administration.[58] Overall, these studies suggest that although individuals with central vision loss can still make crossing decisions on par with age-matched controls,[56] they may exhibit less safe behavior, such as smaller safety margins possibly due to less efficient eye movement patterns.

Mobility Aids for Street Crossing

Only one study directly examined interventions that aid mobility during street crossing and results indicated that individuals with vision loss can be trained to use environmental auditory cues to cross a signalized intersection.[59] Using a within-subjects pre/post-test design, individuals with significant vision loss viewed a signalized intersection either in a real environment or in a virtual environment and reported when it was safe to cross. Following the pretest, participants were trained, in either a real or virtual reality environment, to distinguish between the sound of a vehicle engine when the vehicle was idle and the sound of the engine when the vehicle was moving. Following training, all participants completed the street-crossing judgment task again. Results showed safer street crossing judgments after participants were trained to use engine sounds as cues, regardless of the training environment environments. Notably, the improvements gained through virtual training generalized to real intersections. The implication is that individuals with central vision loss can be trained to cross the street in virtual reality to improve their street crossing judgments.

DISCUSSION

Our systematic literature review of the effects of central vision loss on mobility resulted in several key findings. First, differences between individuals with central vision loss and individuals with normal vision were not consistent across different types of performance measures. In many tasks, individuals with central vision loss achieved a level of performance comparable to individuals with normal vision. Differences between normal and impaired vision were due either to age,[56] or due to differences in how the groups completed the task.[54] An implication of our results is that future studies of navigational abilities with central vision loss should examine how the underlying processes differ between individuals with central vision loss and individuals with normal vision instead of focusing solely on differences in abilities to complete tasks successfully. For example, individuals with central vision loss performed less accurate movements in low light and lighting that dimmed suddenly.[47,47] It is possible that this was due to degradation of cone receptors and ultimately the central visual field.[61] It is important to understand performance detriments in central vision loss as well as the underlying causes of these detriments.

For example, gaze patterns during street crossing were different in people with central vision loss compared to people with normal vision,[54] although both groups were comparable in their ability to cross successfully.[56] Although this was shown in just one study and this study only measured performance in individuals with central vision loss, other studies reported similar results with low vision individuals (both peripheral and central vision loss). Matsuda and collegues reported that individuals with low vision tend to keep their gaze lower than individuals with normal vision when walking along a roadway and a sidewalk,[62] and were more likely to gaze on environmental objects on the road, such as the lane markings while navigating. Freedman and collegues reported that,[63] while walking along an indoor obstacle course, individuals with low vision spent more time focusing their gaze on the intersections) of an environment, such as where the floor and wall meet, compared individuals with normal vision wearing glasses that blurred vision. Such results further support the notion that key differences between central vision loss and normal vision occur in processes underlying performance rather than performance outcomes.

Surprisingly, we did not find any studies linking walking mobility and the use of a preferred retinal locus. We did find studies that investigated preferred retinal locus training to allow patients to better find and identify objects in the environment and considered whether they could potentially be applied to help observers notice obstacles while walking. Specifically, individuals with age-related macular degeneration were successfully trained to use their preferred retinal locus in a discrimination task in which they were asked to find a target and report whether the target matched a control stimulus.[64] The target position was adjusted to each participant's preferred retinal locus position. The location was chosen to optimize eye movements between targets and the preferred retinal locus. With this discrimination training, participants successfully used their preferred retinal locus to discriminate stimuli and were more accurate in their judgments than when they used other parts of their visual field. The implication is that such training may help individuals with central vision loss use their preferred retinal locus to identify obstacles during navigation and improve their ability to avoid obstacles. One caveat is that preferred retinal locus training has not transferred to other visual search tasks.[64] Therefore, training applications are currently limited to individual tasks on which an individual explicitly received training.[64] Further research is needed to apply preferred retinal locus training to mobility while walking.

Further, visual stimuli presented to individuals with degraded vision (e.g. central vision in age-related macular degeneration or peripheral vision in glaucoma) is more likely to be detected when paired with an auditory stimulus, compared to when the visual stimulus is presented alone.[65,66] When participants were asked to report whether a visual stimulus was present, detection was better when the visual stimulus was paired with an auditory stimulus than when it was presented alone. The implication for mobility is that adding an auditory stimulus to a visual stimulus may improve detection of obstacles and thus the ability to avoid collisions while walking.

Results of this review also highlighted differences in street crossing judgments between central vision loss and normal vision as well as the lack of mobility aids available to assist in making said judgments. Generally, individuals with central vision loss could successfully make it across the street; however, their crossings were less safe (i.e., smaller safety margins) compared to individuals with normal vision.[57,55,56] The implication is that sensory substitution devices could be considered as an aid to street crossing, in particular to help people with visual impairments decide when to start crossing the street to achieve larger, and therefore safer, safety margins.

The results of this review identified three main drawbacks to research on central vision loss and mobility. First, although empirical studies exist, a large percentage (almost 40% of the rejected articles in this search) of the existing literature on central vision loss relied on self-reported mobility data. Self-reports are limited because the data rely on subjective measures rather than objective measures.[67] By excluding self-reports, the number of reviewed articles was limited, which also limits the scope of the findings. Second, studies that examined mobility aids typically included individuals with various forms of vision loss rather than specifically central vision loss. These studies often included individuals with low vision or total blindness. This is a gap in the literature. It is important to examine benefits of mobility aids specific to central vision loss. Three, a gap in the literature is the lack of analyses to assess the effect of deficits in visual acuity, visual field, contrast sensitivity, color vision and other similar visual measures on an individuals' ability to complete a walking task. Of the 26 articles included in this review, 9 reported visual acuity, contrast sensitivity or visual field. Of these 9 articles, 6 analyzed the relationship between performance and either visual acuity,[56] visual field,[16] or contrast sensitivity.[39] Results suggested that performance measures were most commonly correlated with visual field; greater visual field loss was associated with poorer performance on a task (e.g., foot placement accuracy).[16] Although three studies reported visual acuity, contrast sensitivity, and visual field for each participant they did not examine the relationship between these measures and performance.

Another important consideration that is not clearly addressed in the reviewed literature is the comorbidity of vision loss with age-related ailments and how such ailments also influence mobility. This is important because central vision loss, and low vision in general, typically occur in individuals who are older.[68] For example, hypertension medication has been linked to dizziness and falls in older adults with normal vision.[69] Thus, individuals with both hypertension and vision loss may have greater mobility issues than individuals who have either of these conditions alone. Declines due to aging may also play a role in an individual's ability to navigate and to learn to use a mobility aid because processing speed and performance of movements get slower as age increases.[70] Moreover, because mobility aids partly involve the translation of visual information to another modality, [22] the ability to process and act on the information quickly is important, especially when sensory substitution devices are used to warn the user of approaching obstacles. It is important to disentangle effects of slowing due to cognitive aging apart from effects due to vision loss per se.

In conclusion, this review highlights capabilities and limitations of individuals with central vision loss regarding mobility abilities. Specifically, individuals with central vision loss can successfully complete most mobility task; however, they may complete the task in a different manner than individuals with normal vision. Future research should focus on understanding this alternative way of completing mobility tasks. Further, research focusing on mobility interventions specifically for individuals with central vision loss should be conducted.

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Table 1. Summary of Reviewed Articles.

Citation	Summary Statement
Alexander et al. (2014a)[16]	Individuals with age-related macular degeneration are less likely to accurately step on a target and have a slower gait in low and suddenly low lighting conditions compared to controls. This is especially true for age-related macular degeneration with greater reduced central visual fields.
Alexander et al. (2014b)[47]	Individuals with age-related macular degeneration are more cautious when approaching a curb and take more time to navigate the curb in different lighting conditions.
Timmis & Pardhan (2012)[45]	Individuals with central vision loss overestimate the height of obstacles when stepping over them.
Hassan et al. (2005)[58]	Differences occur in head movement when street crossing for age-related macular degeneration, suggesting that individuals with central vision loss may not fully take the environment into account.
Geruschat et al. (2006)[53]	Age-related macular degeneration tends to focus more on crossing elements than cars and may not see the environment in full.
Hassan & Snyder (2012)[56]	Mobility abilities in central vision loss may be a result of age, rather than visual abilities.
Geruschat et al. (2011)[53]	Individuals with central vision loss can take longer to identify a traffic gap is safe to cross.
Szlyk et al. (2000)[43]	Bioptic telescope did not improve mobility and navigation, their effect was mostly seen in driving.
Almutleb & Hassan (2020)[57]	Results suggest that individuals with central vision loss can cross street with similar abilities as controls.
Turano et al. (2002)[40]	Individuals with central vision loss tend to focus their gaze to the floor rather than on the walls and doors when navigating to find a room number.
Timmis et al. (2016)[46]	Type of central vision loss influences walking speed and ability to estimate a clearance for an obstacle.
Turano et al. (2005)[60]	Central vision loss influences the visual information and adaptation to walking towards a goal.
Hassan et al. (2002)[39]	Observed differences between groups (central vision loss and typical vision) in mobility were a result of age rather than visual impairments.
O'Brien et al. (2014)[52]	Though subjective results suggest that individuals may benefit from an sensory substitution device attached to cane, no significant results were found using described measures.
Kim et al. (2019)[49]	A novel system translating visual information to auditory information could be used to successfully navigate within an environment.
Soong et al. (2001)[23]	Orientation and mobility training did not show significant differences over and above practice effect.
van Rheede et al. (2015)[24]	Though a visual display (which removed unnecessary details from the environment) did improve obstacle avoidance, it created greater hesitancy and slowed walking speed.
Bowman & Lui (2017)[59]	Orientation and mobility training for street crossing in a VR setting can be transferred to a real environment.
Legge et al. (2013)[44]	Individuals can use a handheld device to scan barcodes and find rooms or other areas they which to navigate to.
Neugebauer et al. (2020)[51]	Though participants are still better with a white cane (probably because of years of training), participants can successfully navigate using the sensory substitution device.
Chebat et al. (2011)[50]	A sensory substitution device which presents information on the tongue may be used to successfully identify and avoid obstacles.
Maidenbaum et al. (2014)[22]	EyeCane can provide spatial information to users and thus allow them to navigate as well as notice obstacles.
Chebat et al. (2017)[42]	Spatial information learned within a virtual environment can be transferred to a real environment.
Kuyk et al. (2010)[41]	Individuals who undergo a visual search task training may be able to notice obstacles on a mobility course faster and therefore avoid them.
Buchs et al. (2017)[48]	Individuals can successfully interpret sensory output when using a mobility aid that presents information from obstacles above the waist.
Graber & Hassan (2020)[55]	Age and previous experience, rather than visual ability, led to less overestimation, and thus more accurate, crossing time estimates.

FIGURE LEGENDS

Figure 1. Flowchart of Article Identification and Screening**.**

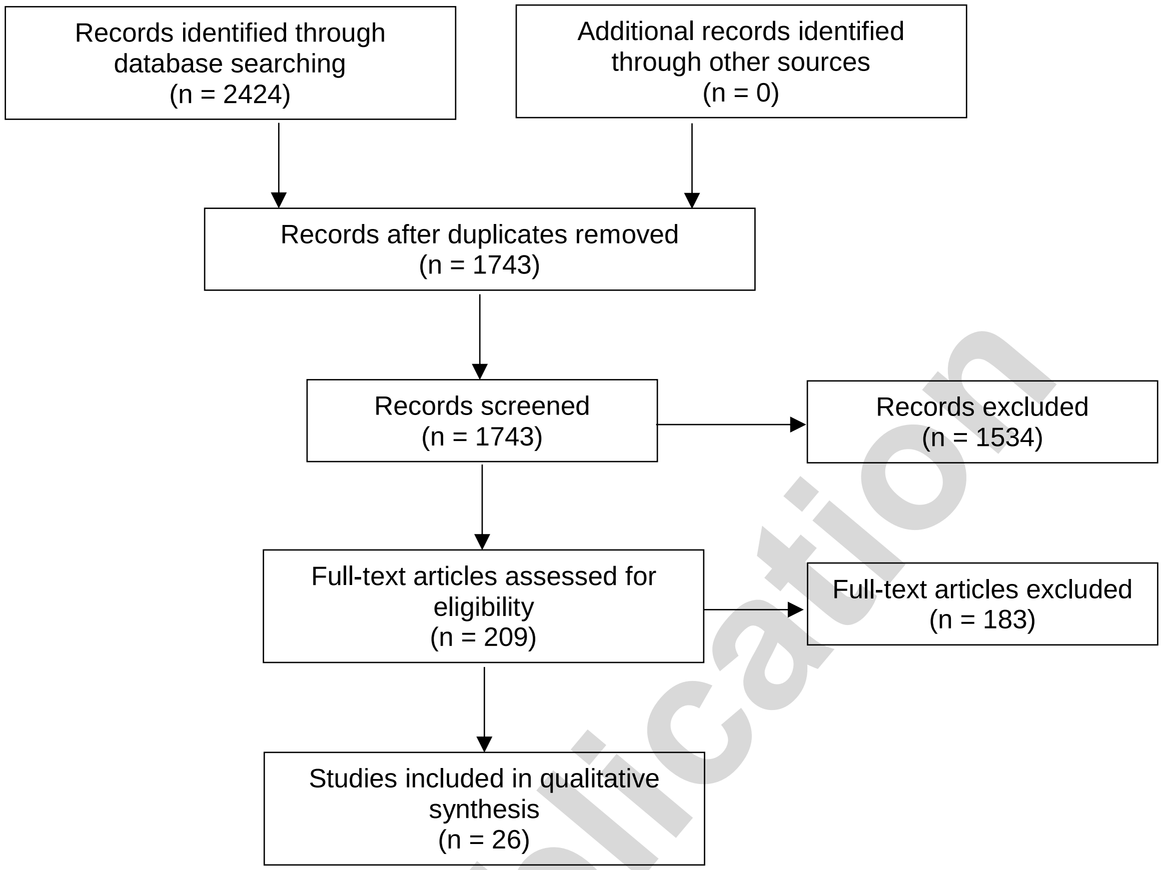

Figure 1 reformattedKAZ