Risk of pedestrian collision for persons with peripheral field loss: A computational analysis

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SIGNIFICANCE: People with peripheral field loss report colliding with other pedestrians on their blind side(s). We show that, in dyadic collision scenarios between persons, one with field loss, such as homonymous hemianopia, and the other normally sighted pedestrian, collisions occur only if the persons with homonymous hemianopia are overtaking the pedestrians, and the collision risk is concentrated at farther bearing angles than previously suggested.

PURPOSE: Prior work computed the risk of collision while simulating both pedestrians as points and did not consider the ability of the other pedestrian's normal vision to avoid the collision. We extended the model to better characterize the open space collision risk posed for persons with homonymous hemianopia by normally sighted pedestrians where both have volume.

METHODS: We computed the risk of collision with approaching pedestrians using a model that simulates approaching pedestrians as volumetric entities without vision, volumetric entities with vision, and as points for comparison with the prior work. Collision risk of approaching pedestrians is characterized for all three conditions through spatial collision risk maps and collision risk densities as a function of bearing and radial distances.

RESULTS: The collision risk for volumetric pedestrians is slightly different from that of point pedestrians. For volumetric pedestrians simulated with normal vision, the risk of collision was reduced substantially, as the other pedestrians could detect and avoid most impending collisions. The remaining collision risk is from pedestrians approaching at higher bearing angles (>50°) and from shorter radial distances (<2 m). Thus, collisions occurred when the pedestrians started in front of the person with homonymous hemianopia that was overtaking the pedestrian.

CONCLUSIONS: The probability of collisions between pedestrians and the person with peripheral field loss is low and occurs only when the person with peripheral field loss is walking from behind the pedestrian at faster speed, thereby overtaking them. Such collisions occur with pedestrians at higher bearing angles, which should be monitored by assistive aids to avoid collisions. The same collision risk applies not only in homonymous hemianopia but also in other peripheral field loss such as monocular vision loss or concentric field loss, as common in retinitis pigmentosa and glaucoma.

(*Optom Vis Sci* 2024;00: 00–00)

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Submitted: January 5, 2024
Accepted: July 15, 2024
Funding/Support: National Institutes of Health (EY023385; to EP) and The Margaret and Leo Meyer and Hans M. Hirsch Foundation (to EP).
Conflict of Interest Disclosure: EP has patents for peripheral prisms assigned to Schepens Eye Research Institute and licensed to Chadwick Optical. The other authors have no financial conflict of interest.
Author Contributions: Conceptualization: NMK, SM, EP; Formal Analysis: NMK, SM, EP; Funding Acquisition: EP; Investigation: EP; Methodology: NMK, SM, EP; Project Administration: NMK, EP; Resources: EP; Software: NMK; Supervision: EP; Validation: NMK, EP; Visualization: NMK, EP; Writing – Original Draft: NMK, SM, EP; Writing – Review & Editing: NMK, SM, EP.
Supplemental Digital Content: Direct URL links are provided within the text.

ISSN: 1040-5488/24/0000–0000
DOI: 10.1097/OPX.0000000000002175

People with peripheral visual field loss frequently report reduced mobility and subsequently decreased vision-related quality of life.[1–4] They report the need for a sighted guide due to the risk of collisions.[5,6] In unstructured open walking spaces, it is difficult to avoid collisions with other pedestrians approaching from the unseen area of the visual field. Navigating while walking in open space requires planning a path to reach a specified goal location along with active adjustments to the path to avoid obstacles in the planned path.[7] Obstacles encountered during navigation can be static or dynamic, specifically, other walkers.[8] Avoiding collisions with static obstacles requires identifying the obstacles (tripping hazards at the lower field), determining the risk of collision, and maneuvering to circumvent the obstacles.[9] Avoiding collisions with other pedestrians requires each walker to avoid colliding with the other walker through interpersonal coordination.[10]

Collisions occur in such open spaces when two walkers' positions coincide at a future time, and they continue to approach the collision (coincident) point without changing their speed or heading. This is likely only when both walkers cannot see each other. In a potential collision scenario involving two normally sighted walkers, one or both pedestrians identify the impending collision by estimating their future locations[11–13] and avoid collision.[14,15] If one of the pedestrians has field loss, avoiding potential collision scenarios becomes challenging. For example, persons with homonymous hemianopia, who have lost one-half of their visual field in both eyes, report difficulties with avoiding collisions with walkers on their blind side.[1,16]

Collision scenarios involving dyadic pedestrians have been extensively studied through modeling and experimental studies.[9,11,15,17–20] When two pedestrians are approaching a collision point at a constant speed (but not necessarily the same speed), the angle between the pedestrians' headings (bearing) stays constant.[8] Similarly, in maritime and aerial navigation, two entities traveling in straight lines are considered to be on a collision course if their bearing is constant while the distance between them reduces, resulting in looming. Considering this, Peli et al.[21] calculated the risk of collision for persons with field loss posed by other pedestrians, as a function of the pedestrian's bearing angle using a collision risk model. That model was a closed-form geometrical model using geometrical equations to calculate the risk of collisions from any point in the space under the speed constraints. From the collision risk derived by that model, Peli et al.[21] calculated the collision risk density as a function of the bearing angle. They found the collision risk density to be low for lower bearings, increasing gradually to peak at 45° bearing, and dropping substantially for higher bearings. This collision risk analysis has informed the development of mobility aids. Prismatic devices that expand the visual field by shifting the view from the blind side have been developed to cover up to 45° without the requirement of scanning and 60° with scanning to monitor the eccentricities with the highest risk of collision.[22] However, the model[21] has limited face validity, as it simulated both pedestrians as points without volume and did not consider the ability and social obligation of the approaching pedestrian to use their normal vision to avoid collisions.

In the current work, we extended the collision risk model from Peli et al.,[21] to consider pedestrians with physical volume and with volume and normal vision. Collision risk posed by pedestrians approaching from the blind side of a patient with homonymous hemianopia was characterized using spatial collision risk and collision risk densities for each pedestrian characteristic. We found that the highest risk of collision is concentrated at higher bearings than previously determined. Furthermore, we found that collision between persons with homonymous hemianopia and normally sighted pedestrians occurs only when the pedestrian is being overtaken by the person with homonymous hemianopia. These findings can be generalized for other peripheral field losses such as monocular vision, glaucoma, and retinitis pigmentosa. We discuss the relevance of our findings for the mobility of persons with peripheral field loss and the development of assistive devices for collision detection.

METHODS

Simulation of collision scenarios

Dyadic collision scenarios consisting of a person with homonymous hemianopia and a normally sighted pedestrian were simulated in MATLAB (MathWorks, Natick, MA). The simulated person with homonymous hemianopia heads straight ahead from their start location (0,0) to their goal location (0,5) meters away at a speed of 1 m/s (2.2 mph). Simultaneously, pedestrians start from various start locations in the open space and head to intercept the person with homonymous hemianopia anywhere along the path. Both the person with homonymous hemianopia and the pedestrian were simulated to walk in straight paths maintaining the same heading from their start position and maintaining a fixed speed. All pedestrians' start locations are simulated from the right, behind, and ahead of the person of homonymous hemianopia's path. Pedestrians were not simulated from the left side as they would be seen by a person with right homonymous hemianopia and will not pose any risk of collision. For the persons with left homonymous hemianopia, the same risk of collision will be posed by the pedestrians approaching from the left. Hence, this model only simulated right homonymous hemianopia scenarios. Pedestrians' start locations for each scenario that ended with a collision were determined by the radial distance (distance between person with homonymous hemianopia and pedestrian's start locations) and the bearing angle (angle between the person with homonymous hemianopia's heading and the line connecting the two starting positions) (Fig. 1A). The bearing angle is equal to the eccentricity of the pedestrian on the retina of the person with homonymous hemianopia who is looking straight down the heading path. Collision scenarios simulated pedestrians starting systematically by varying the bearings (0° to 180°) and radial distances (0.02 to 10 m for point pedestrians; 0.6 to 10 m for volumetric and volumetric + vision pedestrians). Bearings were sampled with steps of 0.1°, whereas radial distance was sampled in steps of 0.02 m. Pedestrians were allowed to head in any direction in the range of 90 to 270° from their start positions in each scenario. All collision scenarios were simulated to be completed within 5 seconds; that is, the pedestrian must collide with the patient before or at the 5-second mark. Consequently, the pedestrian had 5 seconds to intercept the person with homonymous hemianopia. The pedestrian's speed was determined by their starting location and consequently the distance they needed to cover to reach the person with homonymous hemianopia's path before the person with homonymous hemianopia reached the goal location in 5 seconds. We also simulated collision events where the collision scenarios were limited to be completed in either under 2 or 7 seconds (see Appendix Fig. A1, available at http://links.lww.com/OPX/A760). Both the person with homonymous hemianopia and the pedestrian were simulated to walk at a constant speed along their paths, but not necessarily at the same speed, from their respective start to their goal locations. Throughout all collision scenarios, the person with homonymous hemianopia walked at a constant speed of 1 m/s. The pedestrian's speed was limited within lower and upper bounds of 0.7 and 1.5 m/s, respectively. To examine the effect of the speed constraints on the collision risk, additional ranges of speed criteria's were simulated (lower and upper bounds: 0.5 to 1 m/s, 1 to 2 m/s; Appendix Fig. A2, available at http://links.lww.com/OPX/A760).

Dyadic collision scenarios were simulated with pedestrians as points (to replicate Peli et al.,[21] reported results using our current discrete model), with volume, and with volume + vision. The geometry of Peli and colleagues' collision risk model included a wedge diagram, where the person with homonymous hemianopia's current location, end location, and the pedestrian's current location were vertices that formed a collision triangle (see Fig. 1 for examples of such dyadic scenarios with different conditions, but where all collision scenarios are of a pedestrian starting from the same bearing angle and radial distance). In this illustration, not all headings of pedestrians will lead to a collision. We divide these into three categories: colliding, noncolliding as the speed criteria are not met, and noncolliding as collision is not possible. For example, if the pedestrian is heading in a direction that does not cross the person with homonymous hemianopia's path within 5 seconds, collision is not possible (Fig. 1, represented as gray-shaded region). In some collision scenarios, although the collision is possible where the paths of the pedestrian and patient do cross, the pedestrians cannot intercept the patient in time based on the limitation imposed on the speed of the pedestrian (Fig. 1, represented as green-shaded region). Therefore, not all headings of the other pedestrian would result in collisions. Only the collision scenarios where collision is possible based on the crossings of paths and the speed constraints are considered to pose a risk of collision (Fig. 1, represented as red-shaded region). Throughout the scenario, the angles of the collision triangle remained constant as the speeds of the pedestrian and the person with homonymous hemianopia were fixed. As a result, for collision scenarios involving point pedestrians, both point pedestrians completely overlapped at the end of the scenario. Consequently, throughout the collision scenario, approaching pedestrians stayed at a constant bearing from the person with homonymous hemianopia start location (Fig. 1A, left panel) to the end of the collision scenario simulation. This type of collision path resulting in a complete overlap was labeled center-to-center collision path.

We extended this model to include cylindrical pedestrians with a body diameter of 0.6 m for the volume and volume + vision conditions. When pedestrians are simulated with volume, the collision can occur before the complete overlap of the pedestrian and the person with homonymous hemianopia. When both the pedestrian and the person with homonymous hemianopia have volumes, an approaching pedestrian can collide with the person with homonymous hemianopia by brushing with their side. For example, collision is signaled when the person with homonymous hemianopia and the pedestrian's volumes touch before overlapping partially or completely. This can happen even when the pedestrian is not heading directly toward the person with homonymous hemianopia's location, which we refer to as a shoulder-to-shoulder collision path (for example, see Fig. 1B, marked using rounded corner rectangles). During such collision scenarios, approaching pedestrians do not necessarily stay at a constant bearing throughout the scenario (see black curves in Fig. 1E). For the condition involving pedestrians with vision, the person with homonymous hemianopia was simulated with right homonymous hemianopia and the pedestrian with nominal normal visual field (180° lateral visual field; 90° on each side of the heading direction). The person with homonymous hemianopia and the normally sighted pedestrians were simulated to have their gaze fixed on their path (no head or eye scanning). In this condition, scenarios that would be collisions based on the speed criteria may turn into noncolliding, as the pedestrian can see the person with homonymous hemianopia during such scenarios (Fig. 1C, represented as yellow-

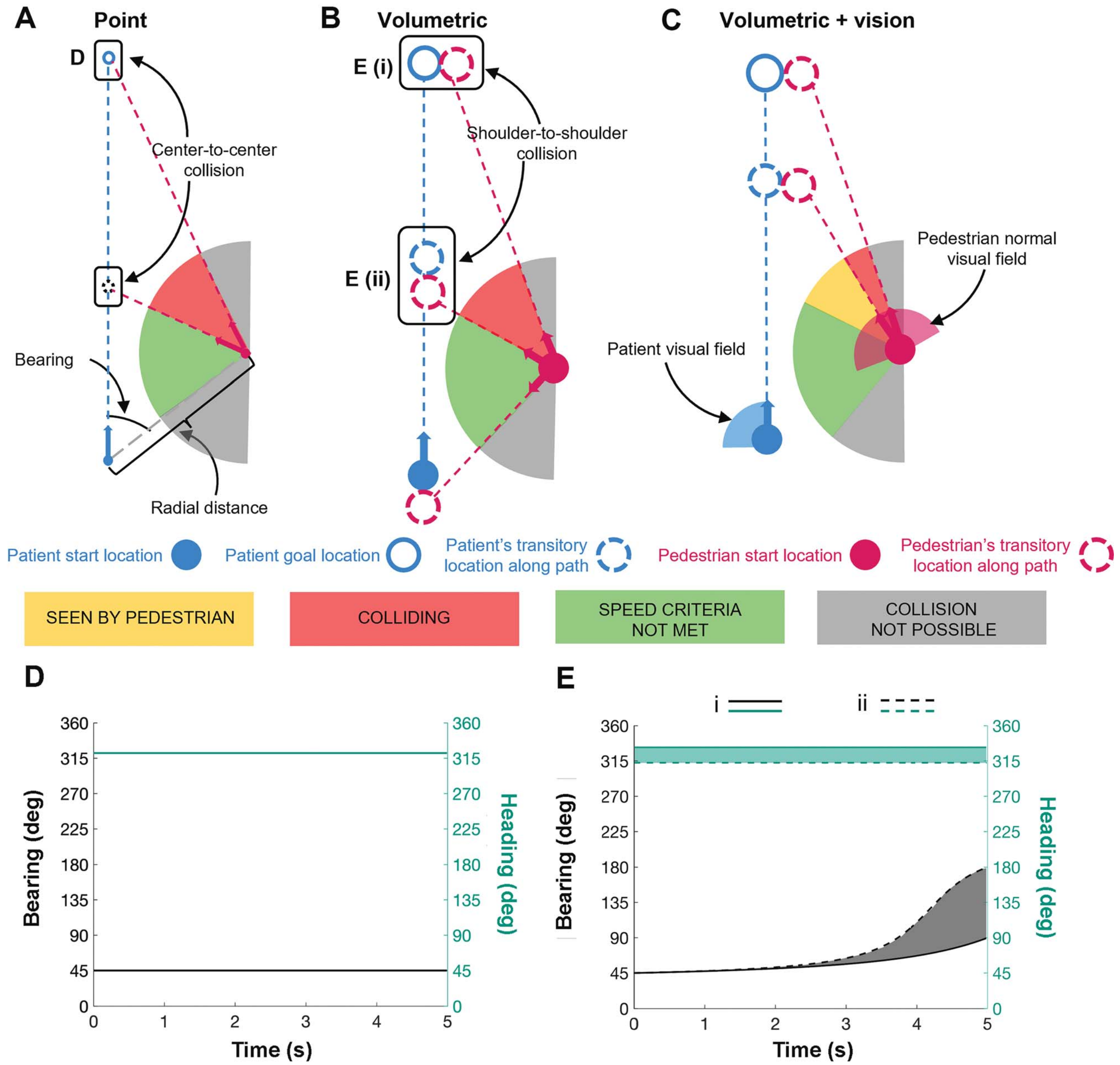

FIGURE 1. Examples of dyadic collision scenarios for (A) point pedestrians, (B) volumetric pedestrians, and (C) pedestrians with volume and vision. All scenarios shown depict the approaching pedestrian at a 45° bearing angle and starting at a 2.5-m radial distance but walking at different headings. The bearing angle is computed as the angle between the line connecting the center of the person with homonymous hemianopia to the center of the pedestrian and the heading of the person with homonymous hemianopia. The risk of collision is represented as the range of headings that can result in collision (shaded red). The green-shaded region represents collision scenarios that might result in a collision if the pedestrian travels faster or slower than the speed constraint imposed. The gray-shaded region represents scenarios where collisions cannot occur. When the pedestrian and person with homonymous hemianopia are simulated as points (A), it results in a center-to-center collision path, in which the pedestrian stays at a constant bearing (D, black line) while walking at a constant heading of 320° (seafoam green line). When pedestrians are simulated with volume (B and C), shoulder-to-shoulder collision paths occur, and the pedestrian is not along a constant bearing (E) even though they are traveling at a constant heading. Two of the extreme cases in an example collision scenario are depicted (B). In one case, the pedestrian heads at 330° and, by the end of the scenario, collides with the patient by brushing their left shoulder with the right shoulder of the person with homonymous hemianopia (E, i). In the other extreme case, the pedestrian heading at 300° collides with the person with homonymous hemianopia by brushing their right shoulder to the back of the person with homonymous hemianopia (E, ii). Note that, in the model, all collision scenarios that lie in between these two extreme conditions are also counted. Hence, the oncoming pedestrians' bearing for the collision scenarios can change anywhere in between the two extreme cases by the end of the scenario (E, represented by dark gray–shaded region) while they head in any direction in between the two extreme cases (E, represented by seafoam green–shaded region).

shaded region). For example, the scenario where a pedestrian collides with a person with homonymous hemianopia by approaching from behind the patient (Fig. 1B, marked E, ii) can be a successful collision when both pedestrian and person with homonymous hemianopia are volumetric but without vision. Then again, when pedestrian normal vision is added, the overtaking pedestrian approaching from behind the person with homonymous hemianopia can see the person with homonymous hemianopia within their visual field and can avoid the collision. Many such collision scenarios were categorized as noncolliding, reducing the total number of possible collision scenarios.

Collision triangle

At the start of each collision scenario, a collision triangle is created using the start locations of the person with homonymous hemianopia and pedestrian, and the collision location of the two, as three vertices of the triangle. The vertices are recomputed to form the angles of the triangle at each time point. The headings of both the person with homonymous hemianopia and the pedestrian are simulated to be constant for all time points in a scenario so that they walk in straight paths. Based on this simulation, the speeds of the pedestrian and the person with homonymous hemianopia are used to calculate the future corresponding locations of both the person with homonymous hemianopia and the pedestrian. At each time point sample, once the location of the person with homonymous hemianopia and pedestrian is computed, a new collision triangle is created to compute the vertices and the angles of the triangle. For conditions involving volumetric pedestrians, as explained earlier, a collision can occur when the pedestrian is approaching on shoulder-to-shoulder collision paths. To identify collision when the two volumetric pedestrians touch, signaling collision, the computation of collision scenario was terminated when the radial distance between the pedestrian and the person with homonymous hemianopia was equal to or less than the sum of radiuses of the pedestrian and the person with homonymous hemianopia. For conditions involving volumetric pedestrians with vision, the bearing of the patient with respect to the pedestrian is used to classify if the person with homonymous hemianopia is inside the normal visual field of the pedestrian. If the bearing of the person with homonymous hemianopia with respect to the pedestrian is above 90° before a collision occurs in the scenario, the scenario is categorized as noncolliding, as the person with homonymous hemianopia is inside the field of view of the pedestrian and can be detected. For point pedestrians, the collision triangles are similar triangles having the same angles at any time. For volumetric pedestrians, the bearing angles vary over time, and the detection of the person with homonymous hemianopia by the pedestrian may happen at an intermediate time during the walking scenario.

Spatial collision risk computation

Pedestrians starting from a given location could head in any direction in the range of 90 to 270°. Despite this, the pedestrian cannot realistically reach all locations where the person with homonymous hemianopia can be present at any given time allocated for the collision. To filter out unrealistic collision scenarios, a speed limitation was imposed on the pedestrian's speed such that they could only travel faster than 0.7 m/s or slower than 1.5 m/s. Given these speed constraints, only a fraction of headings from the pedestrian's start location could result in successful collisions. The speed limitations prevent a range of headings from achieving collisions (Fig. 1B, marked by a green-shaded triangle). For conditions involving pedestrians with vision, an additional constraint was imposed where collision scenarios were only counted in which both the normally sighted pedestrians and the person with right homonymous hemianopia could not see each other throughout the scenario until the collision occurred. If either of them saw the other, it was assumed that they could anticipate and avoid the imminent collision. Collision risk was computed as the range of headings that resulted in a collision (the angular width of the red wedge in Fig. 1), given that the pedestrians met the speed criteria, to the total range of headings possible by the pedestrian (180° = red + green + yellow + gray wedges). For the conditions involving pedestrians with volume and vision, collision risk was computed as the range of headings that resulted in a collision and where the pedestrian and the person with homonymous hemianopia were not able to see each other until the collision occurred in the scenario to the total headings possible by the pedestrian. Collision spatial risk was computed for each starting location of the pedestrian that resulted in collision. The magnitude of the spatial point risk was color coded in Fig. 2.

Bearing and radial risk computation

To characterize the collision risk as a function of bearing (β) and radial distance (r), bearing risk and radial risk densities, respectively, which represent the collision risk from a colliding pedestrian in the visual field of the person with homonymous hemianopia fixating on their path ahead, were computed. Each polar coordinate (r, β) was sampled in steps of 0.02 m of r and 0.1° of β. Bearing risk at a given bearing was computed as the sum of collision spatial points risk magnitude along each sampled polar coordinate point multiplied by r and divided by the total point risks for that given bearing. This represents the normalized collision risk posed by pedestrians approaching from a given bearing, β. Similarly, radial risk is computed as the sum of collision point risk magnitudes at each given r, multiplied by β and divided by the total point risks for that given radial distance. This represents the normalized collision risk posed by pedestrians approaching from a given distance.

Collision risk density computation

To determine the percent of collision risk within a range of bearing angles, we further normalized the bearing and radial risks so that the area under the bearing and radial curves is 1, resulting in risk density as a function of bearing and radial distance, respectively. Collision risk density as a function of the bearing is achieved by summing the bearing risks in the range of 0 to 90° and dividing each bearing risk by the total bearing risk to get the contribution of each bearing relative to the total bearing risk. The percentage area under the risk density curve between any two bearing angles represents the percentage of total risk that a window of visibility in that angle range would monitor for the person with homonymous hemianopia. Such a window may be provided by a visual aid. Similarly, collision risk density as a function of radial distance is achieved by summing the radial risks in the range of 0 to 5 m and dividing each radial risk by the total radial risk to get the contribution of each radial distance relative to the total radial risk.

RESULTS

Spatial collision risk

The risk of collision from pedestrians starting at all spatial locations to the right of the heading of the person with right homonymous hemianopia was computed for pedestrians simulated as points, with volume, and with volume + vision (Figs. 2A to C, respectively). The spatial collision risk was anisotropic and varied largely with bearing at each radial distance, and less so with bearing at each radial distance across the three conditions. The collision risk obtained from our discrete model for the point pedestrian condition was identical to the results reported by Peli et al.,[21] which used closed-form calculations, validating both models. For the volumetric condition, the spatial point risk distribution (Fig. 2B) was slightly different from the distribution derived for the point pedestrians (Fig. 2A). When the other pedestrian was simulated with a nominal normal visual field,

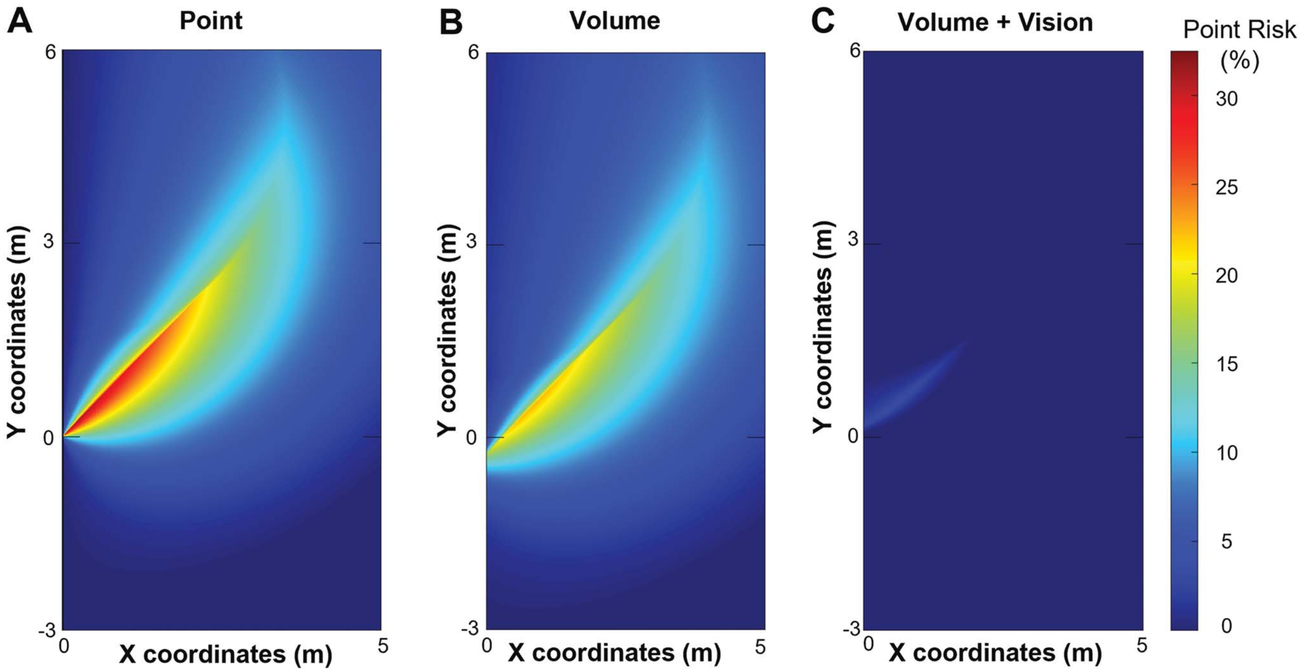

FIGURE 2. Spatial collision point risk for a person with right homonymous hemianopia with other pedestrians in open space. The person with homonymous hemianopia starts from ([*x*, *y*] = [0, 0]) and walks in a straight line toward ([*x*, *y*] = [0, 5]) while the pedestrians approach from the right of the starting position of that person with headings in the range of 90 to 270°. Headings that result in a collision between a person with homonymous hemianopia and a pedestrian, where the pedestrian's speed is between 0.7 and 1.5 m/s, are counted as collisions. Spatial collision risk is computed for each starting position of the pedestrians as the ratio of the range of headings that resulted in collisions to the total range of headings simulated (180°). Three conditions were simulated in which (A) both pedestrians were simulated as points (replicating the condition of Peli et al.[21]), (B) both pedestrians with volume, and (C) with volume and the pedestrian with normal vision. Spatial collision point risk is represented in the spatial Cartesian coordinate form (*x* and *y*). Each point represents the risk posed by the pedestrian starting from that position, color coded for magnitude of risk.

the risk of collision of the person with homonymous hemianopia with another sighted pedestrian while walking in an open space was found to be substantially lower (Fig. 2C). The normal vision of the other pedestrians (as expected in the real world) allowed them to avoid many collisions where they could see the person with homonymous hemianopia rendering such collisions scarce. This shows that the likelihood of collisions for persons with homonymous hemianopia with approaching pedestrians having normal visual field (most situations in daily life) is low and not likely to be frequent. It is also notable in Fig. 2 that the bearing angles of the collision with vision (Fig. 2C) are higher than the bearing angle of the volume (without vision) condition (Fig. 2B). The latter effect and its consequence become clearer below. The vision condition is the most important to consider as it is the only condition with face validity. When the other pedestrians were simulated with volume, but without vision, the distribution of spatial collision risk shifted slightly downward, and the calculated risk was higher below the starting point of the person with homonymous hemianopia. Although interesting and explainable, this is not relevant effect, as this condition representing collision with a blind pedestrian is not realistic.

In all the collision scenarios for the condition involving volumetric pedestrians with vision, the pedestrians were walking slower (0.7 to 0.85 m/s; Fig. 3, right box) than the person with homonymous hemianopia (1 m/s) and thus started in front of the person with homonymous hemianopia before walking toward their goal location. They were not seen by the person with homonymous hemianopia as they were in their blind hemifield. Furthermore, when the relative speed of the pedestrian was restricted to be higher than that of the patient (1 to 2 m/s; see Appendix Fig. A2, available at http://links.lww.com/OPX/A760), the spatial collision risk was eliminated. This indicates that, in all scenarios that resulted in a collision, the person with homonymous hemianopia was walking faster than the pedestrian and, having started from behind them, overtook the pedestrian and, in the process, caused a collision during the scenario.

To further examine the impact of the parameters of the model, we computed spatial collision risk with two additional levels of maximum allowable time for collision for volume + vision condition. Peli et al.[21] previously reported such results for the point pedestrian condition, and we expected similar results for the point and volumetric pedestrian conditions with our model. Decreasing the maximum allowable time for collision from 5 to 2 seconds eliminated the spatial collision risk (Appendix Fig. A1, available at http://links.lww.com/OPX/A760). However, increasing the maximum allowable time for collision to 7 seconds increased the spread of spatial collision risk but did not affect it as a function of bearing. We also changed the range of speed restrictions to evaluate its impact on the spatial collision risk. Decreasing the range of speed restriction to 0.5 to 1 m/s shifted the peak collision more centrally (lower bearing angles), whereas increasing the range of speed restriction to 1 to 2 m/s resulted in a peak at higher bearing angles (Appendix Fig. A2, available at http://links.lww.com/OPX/A760), which is consistent with previous results.[21] This shows that the spatial collision risk as a function of bearing is dependent on the limits of the speed restrictions imposed on the pedestrian.

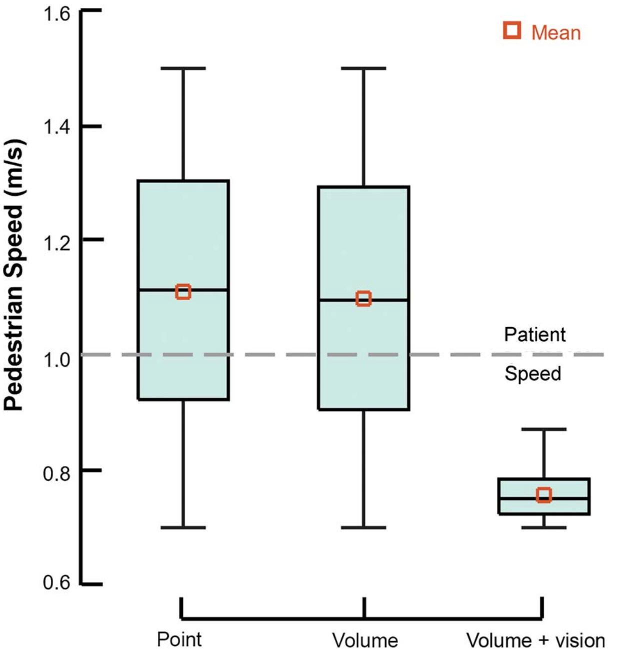

FIGURE 3. Distribution of speeds of pedestrians colliding with the person with homonymous hemianopia in three conditions. The box plots represent the median (horizontal line) and interquartile range, and the whiskers extend from the interquartile range to the furthest observation. Although, for both point and volume conditions, the speed distribution is similar, for the volume + vision condition, the speeds of the pedestrians that cause collisions were limited to be below the speed of the patient (represented by the dashed gray horizontal line).

The inclusion of volume and vision in the current computation extends the previous model, resulting in more realistic collision scenarios. Peli and colleagues' model considered pedestrians as points resulting in the collision scenarios ending when the pedestrian and person with homonymous hemianopia completely overlapped. In these scenarios, the pedestrian stays at a constant bearing as their end position is the same as the patient. In reality, pedestrians have volume, and collisions occur when they just touch (Fig. 1B). When pedestrians were simulated with volume, the pedestrian had to reach a collision point where they touched the person with homonymous hemianopia. Therefore, the pedestrian can cause a collision by touching the person with homonymous hemianopia with their front, right shoulder, or left shoulder, depending on their heading direction (Fig. 1B). On these paths, the pedestrian is not always at a constant bearing with respect to the person with homonymous hemianopia throughout the collision scenario (shoulder-to-shoulder collision), as they do not overlap at the end of the collision (Figs. 1D, E). This is especially important as the approaching pedestrian drifts further into the blind field of the person with homonymous hemianopia rather than staying at a constant bearing. As a result, avoiding collisions in such scenarios is especially challenging even if the person with homonymous hemianopia employs scanning strategies or optical aids that shift images from a defined eccentricity to acquire information from the blind side. For example, when a pedestrian is approaching on a collision course from a bearing of 45°, they do not stay at a constant bearing throughout the collision event but drift further into the blind field of the person with homonymous hemianopia. If the person with homonymous hemianopia is wearing the multiperiscopic prisms (which expand their visual field by 42°) or is employing gaze scanning (usually scanning is up to 40° into the blind field), they will not be able to spot the pedestrian.

Collision risk densities

The collision risk densities as a function of bearing and radial distance to the start location of the pedestrians were computed for each condition (Fig. 4).

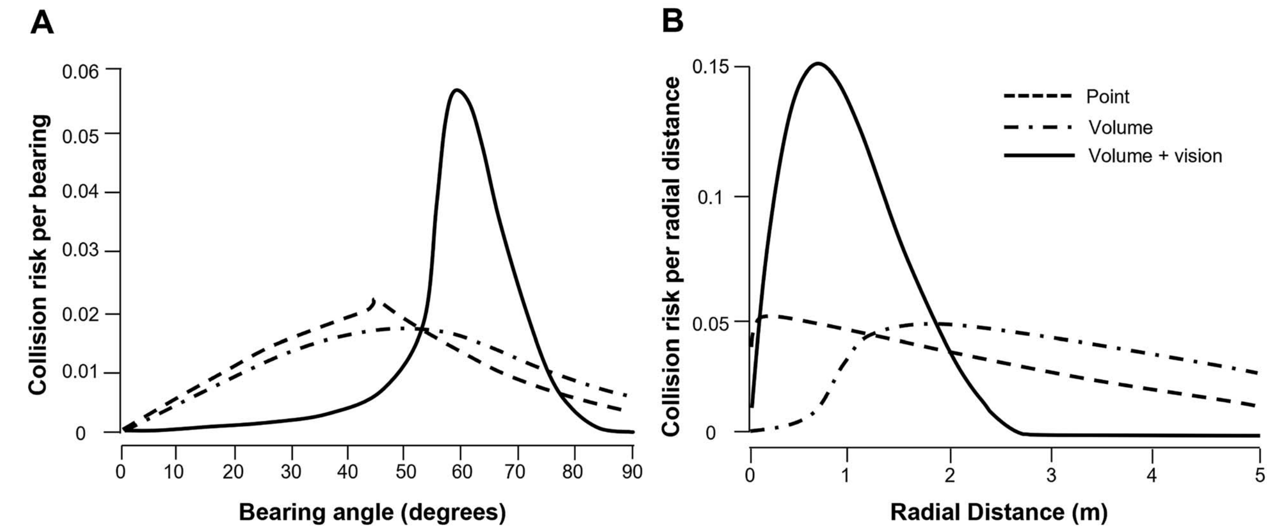

FIGURE 4. Collision risk density as a function of (A) bearing angle and (B) radial distance. Collision risk density was computed for collisions involving point pedestrians (dashed line), pedestrians with volume (dash-dot-dash), and pedestrians with volume and vision (solid line). All densities are normalized distributions as the area under the curves equates to 1.0. Although the collision risk density as a function of bearing was calculated up to 180°, it is illustrated here up to 90°. Pedestrians starting from behind the person with homonymous hemianopia and heading toward the path of the person with homonymous hemianopia will see the pedestrian and will not pose any risk. Similarly, the collision risk density as a function of radial distance is computed up to 10 m but is illustrated only up to 5 m. This was done as pedestrians starting from farther distances do not pose any risk until they get closer to the person with homonymous hemianopia.

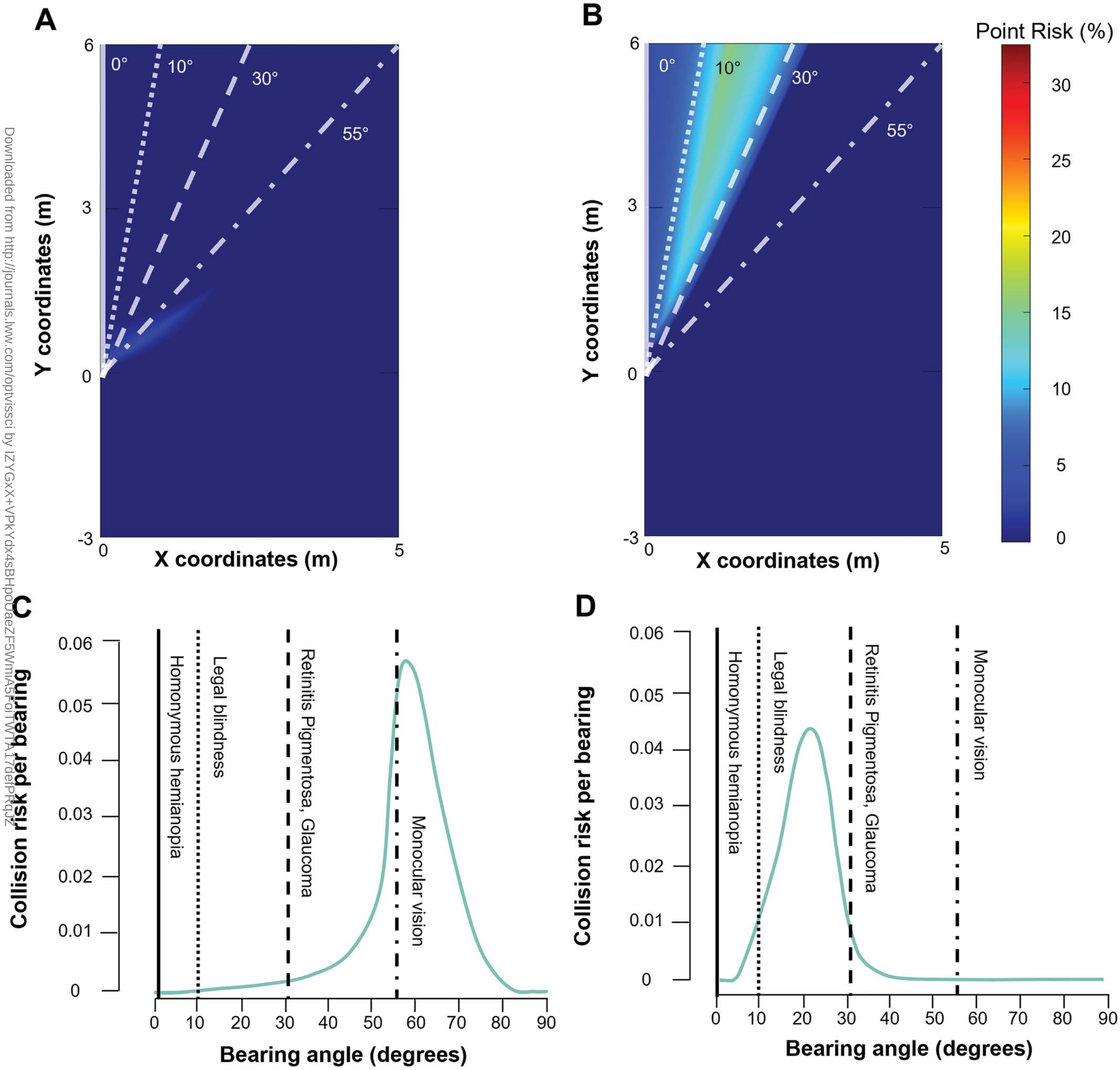

FIGURE 5. Collision risk of a person with homonymous hemianopia when walking (A) and cycling (B) in an open space with other normally sighted pedestrians. The homonymous hemianopia walker and bicyclist and the pedestrians were simulated with volume. The homonymous hemianopia walker was simulated to walk at 1 m/s, and the homonymous hemianopia bicyclist was simulated to travel at 4.4 m/s, or 10 mph, in a straight line and had the same volume as the other pedestrian. Pedestrians walked toward the person with homonymous hemianopia paths from various headings and speeds in the range of 0.7 to 1.5 m/s. During walking (C), persons with peripheral field loss who have residual fields, such as acquired monocular vision and retinitis pigmentosa, cannot monitor the peak of the collision risk calculated for the person with hemianopia. However, when they are traveling at higher speeds, such as the cycling condition (D), they can monitor the pedestrians at the peak of their collision risk. These relationships are presented in the angular domains in (A) and (B) using the same line types as in (C) and (D), respectively.

Collision risk density as a function of bearing angle (Fig. 4A) for point and volumetric pedestrian conditions is similar. The pronounced peak observed for point pedestrians at bearing ~45° is smoothed out for the volumetric pedestrian condition, and the bearings with the highest collision risk per bearing are in the higher bearing range of ~40 to ~60°. For the realistic scenarios with volumetric pedestrians with vision, the collision risk density function is narrow and peaks at bearing ~60°, with minimal risk for small bearings (<30°).

Collision risk density as a function of radial distance (Fig. 4B) shows that, for point pedestrians, as might be expected, pedestrians starting at a closer radial distance pose a higher risk. For volumetric pedestrians, the risk is shifted to the higher distances (Fig. 3B). For conditions with volumetric pedestrians and vision, the risk peaks at a radial distance of ~0.8 m and is concentrated at near radial distances. With a radial distance above 2.8 m, the risk is diminished. This indicates that pedestrians who start closer to the location of the start of the homonymous hemianopia patient pose the highest risk.

DISCUSSION

This article aimed to extend the findings of Peli et al.[21] to address the two limitations of the prior analyses. In particular, it was important to determine the impact of the other pedestrian's normal visual field on the risk of collision with persons with homonymous hemianopia. Second, it was thought that replacing the point pedestrians with realistic pedestrians that have volume may change the interactions. To include these aspects, the type of modeling had to be modified from the closed-form geometrical equations to discrete sampled modeling. The consideration of the normal visual field of the other pedestrians had a large impact on the risk of collision, resulting in a substantial reduction in the risk of collisions, as might have been anticipated. On the other hand, the addition of the volume to both pedestrians resulted in only modest changes in the risk of collisions. The combinations of both changes revealed that the only scenarios that led to collisions were those where the person with homonymous hemianopia overtook the other pedestrian coming from behind that pedestrian and walking faster than the other pedestrian. All other scenarios permitted the other pedestrian to detect the person with hemianopia and avoid the collision. Thus, all face-to-face (pedestrians facing each other) scenarios should not result in collisions.

To consider the impact of the relative speed of the person with field loss relative to the normally sighted pedestrian, we also simulated the persons with homonymous hemianopia, with volume + vision condition, in situations where their speeds might be higher than walking, such as cycling. In many jurisdictions, persons with homonymous hemianopia are prevented from driving. However, they are not prohibited from riding bicycles, and many of them do, for commuting as well as recreation. When riding a bicycle on recreation trails or on sidewalks, persons with homonymous hemianopia share the space with pedestrians who are walking much slower than the bicyclists. Under these conditions, persons with homonymous hemianopia are exposed to substantially increased collision risk with pedestrians when overtaking them (Fig. 5B). With their higher speeds, bicyclists with homonymous hemianopia can collide with pedestrians over a broader range of distances (Fig. 5B). Moreover, the spatial collision risk concentrates at lower bearing angles than in the dyadic pedestrian collision condition. That relation is more apparent when the risk density function is derived (Fig. 5D). This effect is due to the relation between the relative speeds of the pedestrians with the homonymous hemianopia bicyclist, limiting the pedestrians from reaching the path of the bicyclist in a given time (T_{max} = 5 seconds). Moreover, this effect means that, for a pedestrian with monocular vision, although the collision risk is not different from that for a person with homonymous hemianopia, the risk of collision for a bicycle rider is much higher. However, the person with monocular vision in cycling condition can monitor most of the risk yet cannot monitor the majority of the risk in the walking condition.

With the increased speed, the homonymous hemianopia bicyclist is exposed to more risk of collisions. This underscores the importance of the speed relationship between the persons with homonymous hemianopia and other peripheral field loss and the other pedestrians for collision risk in open space. With higher speeds of the persons with homonymous hemianopia, they are exposed to higher collision risk. Furthermore, in all collision scenarios, the pedestrian is always in front of the person with homonymous hemianopia and thus cannot see the person with homonymous hemianopia heading toward them from behind and be able to avoid collision.

The disability impact of any constant partial vision impairment is usually intermittent and may be infrequent, as was found here. This is an important consideration for vision rehabilitation for most types of vision loss (not just field loss). Visual loss impairs function always but causes disability only when it interferes with the patient's ability to perform a certain task. Even persons who are totally blind can perform many tasks successfully. With partial sight and specifically with field loss, people are rarely unable to function, and indeed, many of them never even know that they lost a substantial part of their visual field.[23] Yet, persons with field loss but with good visual acuity, who hardly report visual difficulties, anecdotally report difficulties with walking in crowded situations. They report colliding with pedestrians approaching from their blind side, whom they perceive as *overtaking* pedestrians. Additionally, they also report of embarrassment for being called out for the collision by the other pedestrian. This description is unexpected because an overtaking pedestrian is coming from behind the patient; such pedestrian can see the patient and has the responsibility and the ability to avoid a collision. Individuals with field loss might erroneously interpret these to be overtaking events, as they detect the colliding pedestrian they have *overtaken* only at the instant of collision and misperceive the situation. Being called out for the collision by the other pedestrian further supports their misinterpretation, which could only happen as the responsibility to avoid collision is borne by the person doing the overtaking. Such experiences could have adverse consequences on quality of life as they erode self-confidence or serve as a deterrent to a person with homonymous hemianopia aspiring for independent mobility. However, these collision scenarios are not exclusive to persons with homonymous hemianopia. The collision risk is concentrated at high bearing angles in the range of ~50 to ~75° (Fig. 4A). This range of eccentricities is mostly invisible not only for persons with homonymous hemianopia but also for persons who have larger residual vision such as monocular vision. We show that people with monocular vision and more restricted central fields such as retinitis pigmentosa cannot monitor the majority of collision risk without any aids (Fig. 5C). This explains the difficulty with mobility reported not only by people with complete hemifield defects but also by other visual field losses, such as acquired monocular vision, which is not considered substantially disabling (people with acquired monocular vision are legally permitted to drive in almost all jurisdictions) and moderate peripheral field loss, which is not disabling enough to be considered legal blindness. Hence, understanding the situation resulting in a collision is essential in devising solutions and explaining them to people with peripheral field loss.

It has been reported that people with visual field defects naturally alter their preferred walking speeds to be slower than other normally sighted individuals when navigating unstructured walking spaces alone as opposed to being accompanied by a sighted guide.[6,24,25] This natural behavior is attributed to the need to process the space with a limited visual field and determine how to navigate obstacles.[26] With persons with homonymous hemianopia walking at slower speeds, a collision could occur only if the pedestrians were walking in front of and slower than the person with homonymous hemianopia. This reduced walking speed could serve as a natural temporal filter to limit collision with an overtaken pedestrian. We recommend that walking studies that attempt to understand the benefit of devices designed to aid mobility in persons with peripheral visual field loss should consider the inclusion of the overtaken pedestrian as a test of efficacy. Qiu et al.[27] and Jung et al.[28] evaluated the efficacy of prisms for pedestrian detection in retinitis pigmentosa and acquired monocular vision, respectively. They employed virtual reality walking scenarios, in which the simulated pedestrians approached from in front (opposite to the heading of the patient), who were not representative of the overtaken pedestrians shown to pose collision risk through the current model. Jung et al.[28] included pedestrian at high bearing angles but these were not overtaken pedestrians either. Hence, the virtual walking scenarios employed in these studies might not be representational of actual possible collisions. In a recent pilot study, we employed pedestrians who are approaching on shoulder-to-shoulder collision paths to evaluate the functionality of peripheral prisms in aiding the detection of potential collisions with overtaken pedestrians walking in an open space in a virtual environment.[29] Through this, we aim to evaluate the performance of vision aids, such as peripheral prisms to detect the overtaken pedestrians, where pedestrians come into contact (shoulder-to-shoulder) but not pass through (center-to-center). We designed such a detection test to be a realistic representation of more risky collision situations for persons with homonymous hemianopia and serve as a good performance measure of the effectiveness of peripheral prisms.

The pedestrians' collision risk is highest for angles ~50 to ~75°, which cannot be monitored actively during dynamic walking situations without an aid. Devices that create artificial islands of vision to target these areas of highest risk for collision would prove beneficial during such situations. Jung et al.[28] have shown that optical aids fitted for expanding the visual field of patients with acquired monocular vision can be beneficial in detecting pedestrians on the blind side beyond 60°. Currently, available optical aids for homonymous hemianopia[22,30] and tunnel vision[27] do not provide visual field expansion beyond 60° eccentricities on the blind side and cannot serve to monitor this area of high risk, unless the wearer combines their use with scanning head movements. Although scanning into the blind side is beneficial for collision avoidance, knowing when to scan is difficult. Hence, better optical devices that can monitor more peripheral eccentricities without the need for scanning are required to avoid collisions while walking.

People with peripheral field loss are at risk of collision with pedestrians in an open space. Although we analyzed the risk of collision for homonymous hemianopia, our findings suggest that any person with residual fields of <50° cannot monitor the peak of collision risk. Moreover, in all these scenarios, the person with field loss can only collide with pedestrians in front of them who are walking slower than the person with field loss. Otherwise, one or both can see each other and thus can and are obligated to avoid the collision. As both pedestrians cannot see each other during collision scenarios, optical aids that create artificial islands to monitor such large eccentricities are necessary to avoid collisions with other pedestrians and provide confidence in independent mobility for people with peripheral field loss.

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