# Gaze Scanning on Mid-Block Sidewalks by Pedestrians With Homonymous Hemianopia With or Without Spatial Neglect

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**Purpose.** The purpose of this study was to investigate gaze-scanning by pedestrians with homonymous hemianopia (HH) when walking on mid-block sidewalks.

**Methods.** Pedestrians with right homonymous hemianopia (RHH), and left homonymous hemianopia (LHH) without and with left spatial neglect (LHSN) walked on city streets wearing a gaze-tracking system. Gaze points were obtained by combining head movement and eye-in-head movement. Mixed-effects regression models were used to compare horizontal gaze scan magnitudes and rates between the side of the hemi-field loss (BlindSide) and the seeing side (SeeingSide), among the three subject groups, and between mid-block walking and street crossing segments.

**Results.** A total of 7021 gaze scans were obtained from 341 minutes of mid-block walking videos by 19 participants (6 with LHH, 7 with RHH, and 6 with LHSN). The average gaze magnitude and scanning rate in mid-block segments were significantly higher towards the BlindSide than the SeeingSide in LHH (magnitude larger by 1.9° (degrees), $P = 0.006$; scan rate higher by 4.2 scans/minute, $P < 0.001$) and RHH subjects (magnitude larger by 3.3°, $P < 0.001$; scan rate higher by 3.2 scans/minute, $P = 0.002$), but they were not significantly different in LHSN subjects. The scanning rate, in terms of scans/minute (mean, 95% confidence interval [CI]) was significantly lower in LHSN subjects (mean = 6.9, 95% CI = 5.6–8.7) than LHH (mean = 10.2, 95% CI = 8.0–13.1; $P = 0.03$) and RHH (mean = 11.1, 95% CI = 9.0–13.7; $P = 0.007$) subjects. Compared to street-crossings, the scan rate during the mid-block segments was lower by 3.5 scans/minute ($P < 0.001$) and the gaze magnitude was smaller by 3.8° ($P < 0.001$) over the 3 groups.

**Conclusions.** Evidence of compensatory scanning suggests a proactive, top-down mechanism driving gaze in HH. The presence of spatial neglect (SN) appeared to negatively impact the top-down process.

Keywords: spatial neglect (SN), naturalistic mobility, visual field loss, mobile gaze, homonymous hemianopia (HH), stroke, brain injury

Where people look is broadly controlled by bottom-up (stimuli sensation driven), and top-down (decision driven) mechanisms. When visual input is impaired, such as in the case of primary visual pathway damage in homonymous visual field loss, it is expected that the top-down mechanism of gaze control will become more prominent.[1,2] In the case of homonymous hemianopia (HH), where one half of the visual field is blind on the same side in both eyes, compensatory scanning, such as looking toward the direction of the missing visual field more often or making larger scans in that direction could benefit mobility.[3–7] Evidence of compensatory scanning in individuals with HH during mobility tasks involves making more and larger gaze shifts (head and eye movement) toward the side of the blind field.[8–20] Much of this evidence is in the context of driving. Most previous studies regarding gaze scanning during walking in natural environments involved normally sighted individuals.[21–23] Studies that involved pedestrians with vision impairment focused on specific scenarios like street crossing[24–26] or on environmental aspects, such as urban design.[27] What little data exist regarding naturalistic gaze scanning in pedestrians with HH, comes from our preliminary analysis of the pilot data[28] from a study of eye-in-head movement of 3 patients with HH,[29] and from our recent report of gaze scanning by the same pedestrians with HH at street crossings, where we found evidence of compensatory gaze scanning.[30]

Our recently published data on gaze scanning by pedestrians with HH focused on street crossings.[30] In this follow-up paper, we present previously unreported findings regarding gaze scanning of the same group of individuals with HH while walking on urban streets in mid-block segments between the street crossings. At street crossings, most people, including normally sighted and visually impaired people, tend to visually scan laterally for cross-traffic. However, it was unknown yet whether pedestrians with HH would proactively scan toward their blind side to compensate for their field loss when walking on mid-block sidewalks. Although not as demanding as street crossings from a traffic safety perspective, mid-block walking may still require active scanning of the environment by pedestrians with HH as a variety of mobility hazards are likely to be present, especially in busy urban sidewalks (where the study was conducted). We therefore hypothesized that a significant degree of compensatory scanning would be observed when pedestrians with HH walked on mid-block sidewalks but might be less than at street crossings. As such, our main analysis was a within-subject comparison of blind side compared to seeing side scanning in pedestrians with HH on mid-block sidewalk segments. If scanning frequency or magnitude was significantly different from the seeing side, this would support the presence of compensatory scanning as a post-impairment adaptation. Each subject's own seeing side was utilized as the control condition. Data from normally sighted individuals was not needed to address the primary research question.

Further, in the case of individuals with HH who also suffer from spatial neglect (SN; also alternatively referred to as spatial hemi-neglect, unilateral spatial neglect, visual neglect, hemi-inattention, and unilateral spatial inattention[31]), the top-down compensatory mechanisms could be impaired in addition to and toward the same side as the visual field loss. The nature of this impairment is such that less attention is paid toward the neglected side, which is likely to manifest in terms of altered compensatory gaze scanning behaviors relative to those without SN. We, therefore, hypothesized that adaptive scanning in pedestrians with SN would be less than that of pedestrians with HH without SN.

Finally, we conducted a secondary analysis to compare the gaze data from mid-block walking to the gaze data from street crossings to test the hypothesis that gaze behaviors exhibited during mid-block walking would differ from those observed at street crossings. Given that top-down environmental cues to scan are greater at street crossings (such as the presence of the cross-street, noise from approaching traffic, and other pedestrians ahead stopping and scanning before crossing) and there is more imminent danger from approaching traffic, we expected that the effect of location (mid-block sidewalks versus street crossings) would be more evident in the SN group than in HH subjects without SN.

## METHODS

The methods are broadly similar to those described previously in our analysis of gaze at street crossings.[30] The data were originally acquired in studies conducted from 2012 to 2014 with multiple visits (up to 4), involving individuals with HH with or without SN using similar experimental procedures.[28,32,33] The study protocols were approved by the Institutional Review Board at Mass Eye and Ear and the USt Army Medical Research and Material Command (USAMRMC), Human Research Protection Office (HRPO). The studies followed the tenets of the Declaration of Helsinki and written informed consent was obtained from all the study participants.

### Study Participants

A total of 22 subjects were enrolled and assigned to one of the 3 subject groups: the left homonymous hemianopia (LHH) group, the right homonymous hemianopia (RHH) group, and the left HH with spatial neglect (LHSN) group. Subjects were further classified as having complete HH or incomplete HH.[34] Complete HH was defined as no greater than 5° (degrees) of sparing within the central 30° above and below fixation.[9,35] Individuals with HH, for more than 3 months, usually due to a cerebrovascular event, were targeted for enrollment. Screening for eligibility included a case history, distance visual acuity, monocular and/or binocular Goldmann visual fields (V4e target), and hemi-neglect screening with the Schenkenberg line bisection test,[36] the Bells cancellation test,[37] and the Catherine Bergego Scale.[38] Cognitive status was quantified with either the Montreal Cognitive Assessment test or Mini-Mental Status Exam (MMSE).[39] Presence of SN was diagnosed by a vision rehabilitation specialist (author K.E.H.) on the basis of formal screening tests, subjective history, review of medical records, and lesion location. Although left SN (due to right hemispheric brain injury) may be predominant, right SN cases are not rare,[40] especially soon after a stroke. We did not have any subjects with right SN in our sample. For participant-level details, please see Supplement S1. Visual field plots of the study participants are included in Supplement S2.

### Gaze Scanning Procedures

During each visit, the study participants walked one of two routes, along the sidewalks on either side of a busy street in downtown Boston (Fig. 1) during daytime. The route order was counterbalanced over multiple visits. Both routes were approximately straight, with a U-turn on each end, and were traversed in both directions (round trip distance of approximately 0.6 miles). During the walk, the participants wore a custom-developed mobile gaze recording setup that consisted of a commercial mobile eye tracker with a scene-camera (Positive Science, New York, NY, USA), measuring eye-in-head movement, and a head tracking system using two inertial sensors (VectorNav, Dallas, TX, USA). The gaze tracking system and its evaluation were previously described.[41] The system was connected to laptops in a backpack worn by the pedestrian, where the scene videos and eye and head movement data were logged for offline processing. The eye tracking setup allowed the participants to wear their habitual refractive correction. Participants were instructed to walk as they normally would, while watching for any potential obstacles, other pedestrians, and cross-traffic. They were not given any specific instructions about scanning, although they were aware that their head and eye movements were being recorded. A researcher followed to ensure the participant's safety.

All the outdoor data collected happened during daytime between approximately 10 AM and 4 PM, when there was usually higher foot and vehicular traffic. We did not explicitly control for time of the day, traffic density, seasons, and weather conditions. However, outdoor walking was avoided during severe adverse weather, such as heavy rain or snow. We also did not take walking speed into consideration.

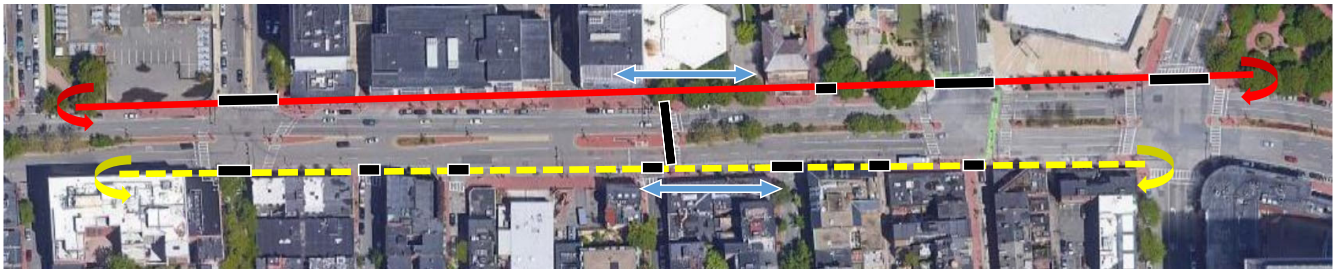

**Figure 1.** The two outdoor walking routes (*solid red line* = route 1 and the *dashed yellow line* = route 2) used in this study overlaid on a Google Maps satellite image. The routes were along the sidewalks on each side of Cambridge Street in Boston, Massachusetts, a busy street with vehicular traffic. Participants walked in both directions along each route (denoted by *blue double head arrows*) with U-turns at each end (denoted by *curved arrows*). Depending on the route chosen, the walking direction, and the side of the pedestrian's vision loss, the main street with vehicular traffic was either located on the side with intact vision (SeeingSide) or on the side with vision loss (BlindSide). The routes included street crossings (shown in *black bars*). Scans recorded in mid-block sections (between street crossings) were analyzed separately from scans recorded during street crossings (credit: This is a modified version of Figure 1 from our previous publication[30]).

## Gaze Data

Gaze shift, in our implementation, was defined as the sum of head and eye-in-head movements that were independently obtained by our gaze tracking system. The eye movement measurements were converted to angular values and synchronized with the head movements.[41] The head tracking unit consisted of one head-mounted inertial sensor and another mounted on the waist-belt. Each sensor output was orientation signals in terms of yaw, pitch, and roll angles. A differential signal was derived from the dual-inertial sensor design, which provided a measure of head orientation with respect to the body trunk (the medial position/heading direction), and also helped mitigate the signal drift due to correlated external interferences (e.g. electromagnetic signals) present in outdoor urban environments. The body/trunk was assumed to be aligned with the walking direction along the walking route (approximately following a straight line). Although it was possible for the entire body trunk to shift with respect to the walking direction, we observed that this typically happened only when the subject was standing (not when walking) – and such segments were excluded from this analysis.

In addition to the inertial head sensor, head orientation angles were also calculated on the basis of the imagery captured by the eye-tracking scene camera, via monocular Simultaneous Localization and Mapping (SLAM).[42] SLAM provided more accurate head orientation estimates, but was prone to intermittent tracking failures, resulting in data loss. The signals from the inertial sensors, on the other hand, were continuously available, albeit noisy and prone to drift. The head orientations obtained via SLAM were fused with those obtained with the inertial sensors to obtain a more reliable head movement signal (see Appendix II of our recently published study[30]). The eye movements were combined with the synchronized fused head movement signal to obtain gaze positions for each video frame (approximately 30 samples/second).

## Gaze Scans

Methodological details for detecting gaze scans from the collected data were described in our study of scanning at street crossings.[30] In that previous study, the street crossing instances were manually identified from the associated scene videos. Here, we extracted gaze data for mid-block walking, defined as the segments of the route between the previously identified street crossing instances, and excluded any sections where the subject was not ambulatory (detected using accelerometer signal; see Fig. 1). Given the nature of the visual field loss (half field missing) and the way neglect manifests – usually one side of the body (left side in our case), the horizontal gaze scans were detected with respect to the body-midline (which was approximately aligned with the heading direction). The scanning side could be toward the hemi-field loss (the same as the neglected side in subjects with SN) – defined as the BlindSide, or toward the side where vision was intact (also the non-neglected side in subjects with SN) – defined as the SeeingSide. A minimum threshold of 20° defined a movement as a gaze scan (dashed line in Fig. 2).[30] There were two main reasons for choosing this threshold: (i) the goal was to evaluate large scans because of their importance in scene understanding and spotting potential mobility hazards, and (ii) recorded natural gaze movement data during outdoor walking tend to be noisy and a minimum threshold for gaze scan peak helps to separate actual scans from noise. The 20° threshold was consistent with the minimum threshold in some of our previous studies (including driving).[30,43–45] Because of the higher speeds involved in driving, the risk of collision is higher for lower eccentricity than it is in walking.[46]

Review of the data revealed two types of gaze scan defined by the relative contributions of head movement to the overall gaze scan: scans with a substantial head movement (>10°) and scans with little head movement. This dichotomy, previously noted for gaze scanning at intersections when walking[30] and driving,[44,45] served as a way to further explore the relative contributions of eye and head movements to gaze in naturalistic walking.

## Outcome Measures

The two main outcome measures were gaze scan magnitude (in degrees) and the scanning rate (number of scans per minute). Some data loss is unavoidable in any naturalistic walking experiment due to technological limitations and other environmental fluctuations which could affect the computation of the scanning rate. In our case, the gaze data loss for a given mid-block segment was always greater than or equal to the head movement data loss. When a gaze scan peak was missing, but the corresponding head scan magnitude was >20°, the scan was counted for the computation

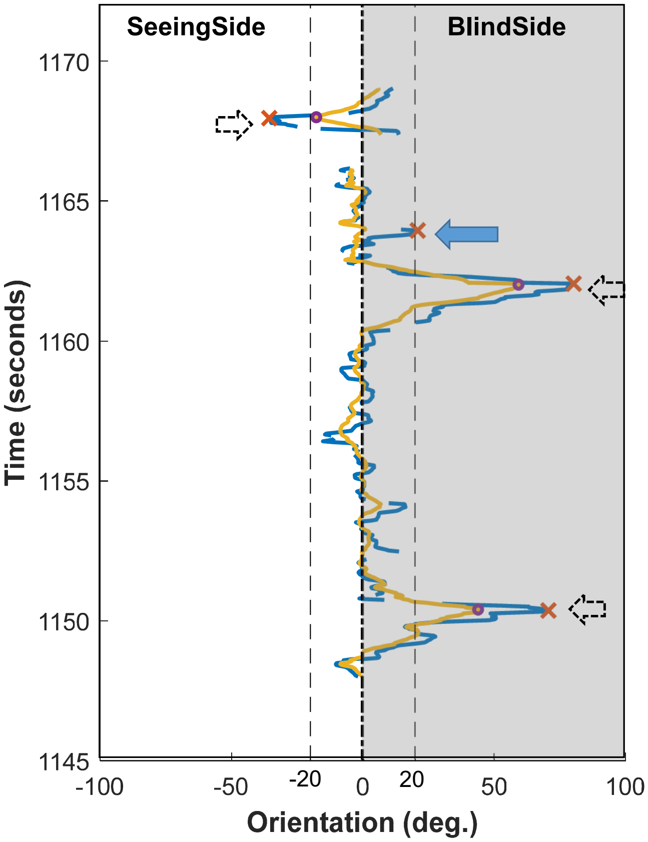

**Figure 2.** Gaze (*blue line*) and head (*yellow line*) orientation recorded during mid-block walking. Gaze scans were detected with respect to the body midline/heading direction (*dash-dot line* corresponding to 0° orientation) and are characterized by a shift of the gaze orientation away from the midline. The threshold for scan detection (peak >|20°|) is shown with *dashed vertical lines*. Two types of gaze scans occurred: (i) scans where the head movement predominantly contributed to the overall gaze magnitude (indicated by *dashed outline arrows*), and (ii) scans with small head movement but relatively large eye movements (*solid blue arrow*). Peaks of the detected gaze scans are shown by a red "x." *Circles* mark the peak of head scans. The side of the hemi-field loss (right side in this example) is the BlindSide. It should be noted that BlindSide-SeeingSide dichotomization is marked with respect to the body midline; however, the blind field shifts with the instantaneous gaze movement.

of scanning rate despite missing the gaze peak (such cases were <2% of all scans). The number of scans per subject were normalized by the duration for which the head movement data were available. For the analysis of gaze magnitude, all available gaze scans with magnitude >20° were considered.

### Statistical Analysis

The overall analysis methods were similar to our previous study of scanning at street crossings.[30] Multilevel mixed-effects regression models were used to determine the association between scanning behavior outcomes and key predictors/fixed effect factors. The factors were scanning side (BlindSide or SeeingSide), subject group (LHH, RHH, or LHSN), the route taken (one of two possibilities), and the side of the street (whether the main street with traffic was on their BlindSide or SeeingSide - see Fig. 1), and subject characteristics (age and time since condition onset). Effect of location – mid-block walking or street crossing segments, was analyzed separately. Visit nested within subjects was modeled as random intercepts. Linear mixed-effects regression was used for scanning magnitude (reciprocal inverse log transformed for better fit, as gaze magnitude was skewed toward smaller angles). For scanning rate (non-normal distribution), the number of scans was modeled as over dispersed count data, with the log of duration of head movement data availability as the offset, in a mixed-effects negative binomial model.[47,48] Testing was not performed to evaluate statistical significance for group-wise differences in participant characteristics because sample sizes were small in each group; however, each of these factors: age, gender, and years since onset, was evaluated as a potential predictor of scanning rate and gaze magnitude in univariate analyses. Significant predictors from the univariate analysis were included in multiple-regression models. The scanning rates and gaze magnitudes were compared between the sidewalk and crossing segments via count and linear regression models, respectively, by including a binary predictor for walking location (street crossings versus mid-block).

Estimated marginal means (back-transformed) with their 95% confidence intervals (CIs) and contrasts obtained from the regression models for scanning magnitude and scanning rate are reported. Incidence rate ratios are reported from the count regression model for scanning rate. *P* values < 0.05 were considered statistically significant. The Benjamini-Hochberg procedure was applied for multiple comparisons within a test. Statistical analysis was performed using statistical packages in R (version 4.0.4).[49–54]

## RESULTS

Out of the 22 enrolled subjects with HH, 3 subjects were excluded from analyses (1 used a motorized scooter and 2 were without recorded gaze data). Analyses were conducted using data from the 19 remaining subjects: 6 with LHH without spatial neglect, 6 with LHH and mild-to-moderate spatial neglect (LHSN), and 7 with RHH (see the Table). All subjects included in the analysis were able to walk independently and did not have vertigo or vestibular dysfunction. Sixteen out of 19 (83%) had complete HH, whereas 3 had incomplete HH with an area of intact vision in the inferior or superior peripheral regions of their blind hemi-field (see visual field plots in Supplement S2).

### Analysis of Gaze Behaviors During Mid-Block Walking

Video data corresponding to midblock walking segments amounted to a total of 341 minutes across 19 subjects, from which 7021 gaze scans were obtained. Gaze or the corresponding head position was >|20°| for about 20% of the available data samples. About 1.2% of gaze scans had missing gaze peak magnitude, but the corresponding head scan magnitude was >20°, so they were included when computing scanning rates. However, scans missing gaze peak magnitudes were excluded when analyzing gaze magnitude (leaving 6936 scans for this analysis). In about 46% of gaze scans, the head-movement (>10°) was the major contributor (mean ± SD gaze magnitude: 47° ± 20°). Gaze scans, where eye-movements were the major contributor, tended to be smaller in magnitude (33° ± 12°) with little

**TABLE.** Characteristics of the Participants and the Gaze Scanning Data During Mid-Block Walking

| | Overall | Left Homonymous Hemianopia (LHH) | Left Hemi-Spatial Neglect (LHSN) | Right Homonymous Hemianopia (RHH) |
|---|---|---|---|---|
| *N* | 19 | 6 | 6 | 7 |
| Age, y Median [25th–75th percentile] | 53 [46–73] | 50 [46–59] | 50 [39–66] | 63 [53–73] |
| Males; *N* (%) | 14 (74) | 3 (43) | 6 (100) | 5 (83) |
| Years since onset*; Median [25th–75th percentile] | 2.4 [1.2–4.19] | 3.0 [2.2–3.9] | 3.5 [1.7–12.8] | 1.3 [0.8–1.8] |
| MMSE scores†; Median [25th–75th percentile] | 28 [25.5–29] | 29 [29–29.8] | 26.5 [25.3–27] | 27 [24–28.5] |
| Head movement data loss, %; Median [25th–75th percentile] | 12.4 [10.5–16.5] | 12.4 [10.9–17.3] | 10.4 [9.8–12.4] | 14.1 [11.6–17.8] |
| Duration in min (avail. data) | 341 | 83 | 136 | 122 |
| No. of gaze scans (gaze magnitude analysis) | 6936 | 1890 | 2255 | 2876 |
| SeeingSide | 3124 | 751 | 1148 | 1225 |
| BlindSide | 3897 | 1139 | 1107 | 1651 |
| Gaze magnitude, degrees; Median [25th, 75th percentile] | 35 [26, 48] | 37 [27, 52] | 33 [26, 46] | 35 [26, 48] |
| SeeingSide | 33 [25, 46] | 34 [26, 52] | 33 [26, 47] | 32 [25, 42] |
| BlindSide | 36 [27, 50] | 38 [28, 51] | 33 [26, 44] | 38 [27, 52] |

* Data missing for one patient with LHH.

† Scores for two subjects converted from Montreal Cognitive Assessment based on the conversion table in Kim et al.[55]

head movement. The overall gaze magnitude distribution was skewed toward smaller values (<40°).

Scanning rate declined significantly with advancing age, by about 1.6% per year increase in age (incidence rate ratio [IRR] = 0.984, 95% CI = 0.977–0.992, $P < 0.001$). The scanning rate denoted in terms of scans/minute throughout) was also significantly lower on the south side of the street (route 2; mean = 7.9, 95% CI = 6.7–9.5) compared to the north side (route 1; mean = 10.7, 95% CI = 9.4–12.3, $P < 0.001$). Adjusting for participant age and the route, the BlindSide scanning rate was significantly higher than the SeeingSide scanning rate in LHH (SeeingSide: mean = 8.6, 95% CI = 6.4–10.9, BlindSide: mean = 12.5, 95% CI = 9.7–16.3, $P < 0.001$), and RHH subjects (SeeingSide: mean = 9.6, 95% CI = 7.7–12.1, BlindSide: mean = 12.8, 95% CI = 10.2–16.0, $P = 0.002$). However, there was no significant difference between the BlindSide and SeeingSide scanning rates in subjects with LHSN (SeeingSide: mean = 6.8, 95% CI = 5.4–8.7, BlindSide: mean = 7.1, 95% CI = 5.6–8.9, $P = 0.7$; Fig. 3A). Comparing among the subject groups, the scanning rate was significantly lower in subjects with LHSN (mean = 6.9, 95% CI = 5.6–8.7) than LHH (mean = 10.2, 95% CI = 8.0–13.1, $P = 0.03$) and RHH (mean = 11.1, 95% CI = 9.0–13.7, $P = 0.007$) subjects. Thirteen out of 19 subjects (6/6 with LHH, 3/6 with LHSN, and 4/7 with RHH) made more scans toward the BlindSide compared to the SeeingSide (and therefore

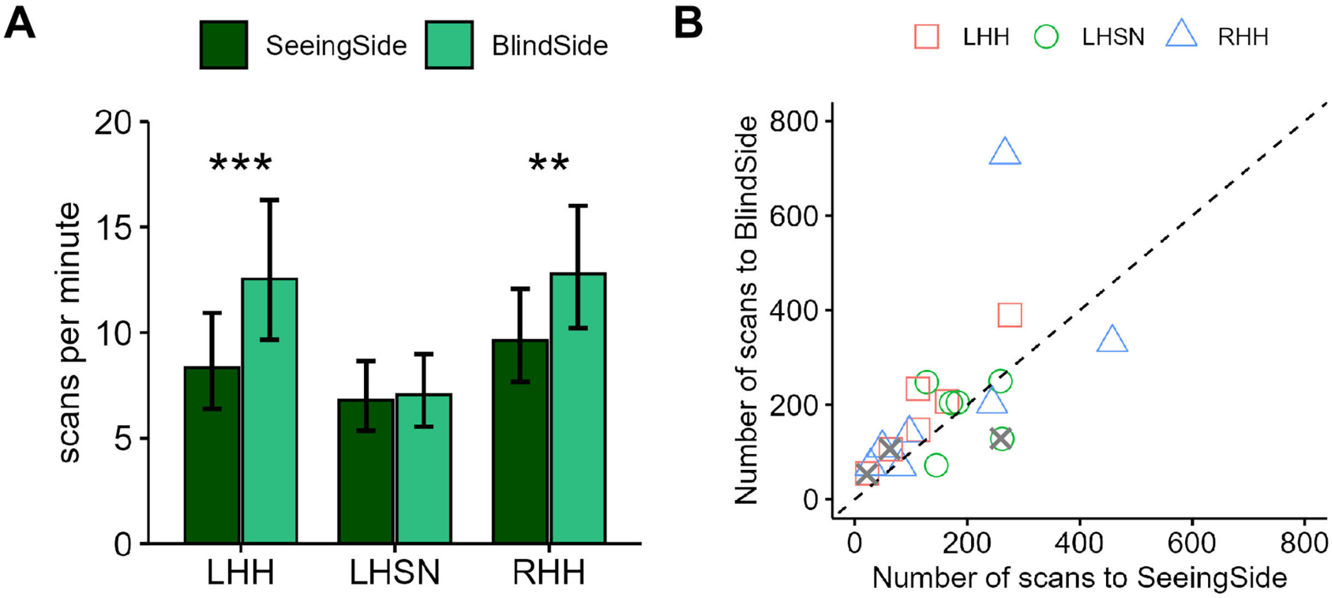

**FIGURE 3.** (**A**) Comparison of the average scanning rate between the BlindSide and the SeeingSide for the three subject groups (reported as estimated marginal means from the count regression model). Error bars indicate the 95% CI of the mean. Significance levels: *** : $P < 0.001$, ** : $P = 0.001$ to 0.01, and * : $P = 0.01$ to 0.05. The $P$ value adjustment method: Benjamini-Hochberg (BH) procedure. (**B**) Scatter plot of the total number of scans to the BlindSide versus the SeeingSide for each participant. Points lying above the diagonal indicate more scans toward the BlindSide. Symbols with a gray "×" indicate subjects with incomplete HH (some residual vision in the blind hemi-field).

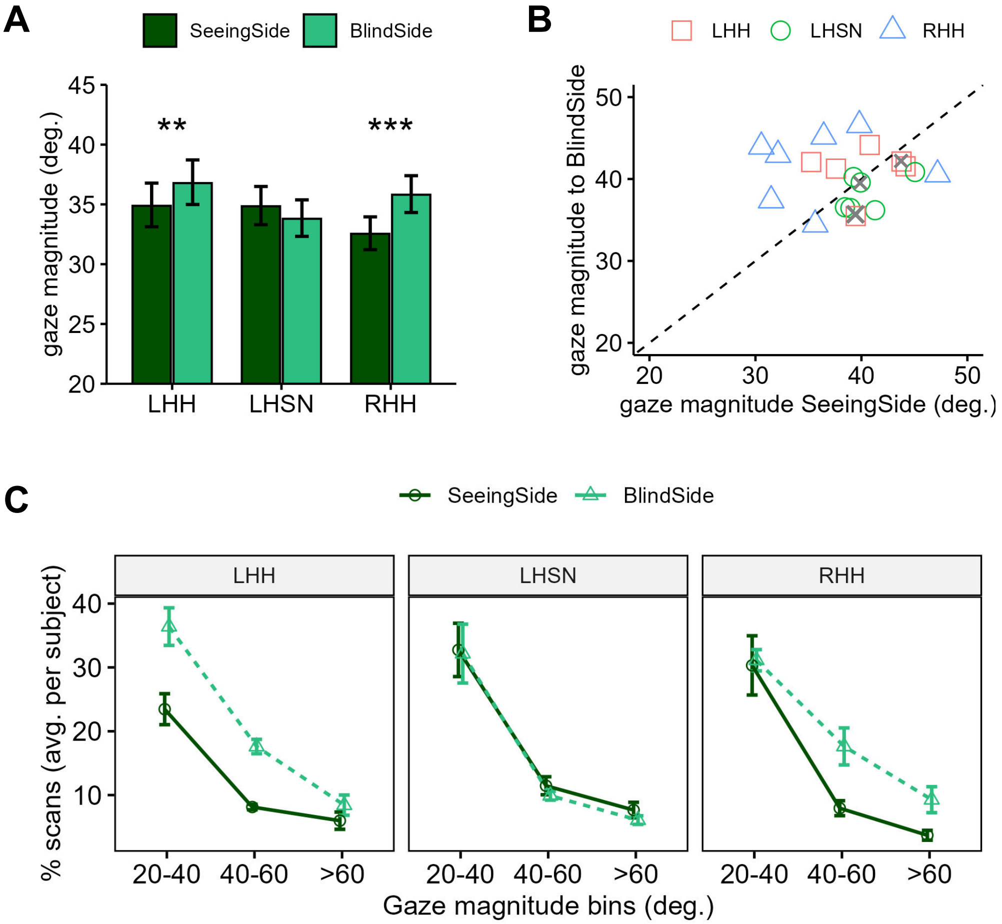

**Figure 4.** (**A**) Comparison of the average gaze magnitude between the BlindSide and the SeeingSide for the three subject groups (reported as estimated marginal means from the linear regression model). Error bars indicate the 95% CI of the mean. Significance levels: *** : $P < 0.001$, ** : $P = 0.001$ to 0.01, and * : $P = 0.01$ to 0.05. The *P* value adjustment method: Benjamini-Hochberg (BH) procedure. (**B**) Scatter plot of the mean gaze magnitude towards the SeeingSide versus the BlindSide for each individual participant. A point lying above the diagonal dashed line (equal magnitude line) indicates higher average gaze magnitude towards the BlindSide by that subject. Symbols with gray "×" indicate subjects with incomplete HH (some residual vision in the blind hemi-field). (**C**) The percentage of scans made toward the BlindSide compared to the SeeingSide over three gaze magnitude bins (covering the entire range of gaze magnitudes) for each of the three subject groups. The relative percent of scans to both the sides was similar across the entire range of gaze magnitudes for the LHSN group.

had higher scan rates towards the BlindSide; Fig. 3B), which could be considered as evidence of compensatory scanning.

The gaze magnitude was significantly larger toward the BlindSide than the SeeingSide in subjects with LHH by 1.9° ($P = 0.006$) and in subjects with RHH by 3.3° ($P < 0.001$), but was not significantly different in subjects with LHSN (Fig. 4A). Nine out of 19 subjects (3/6 with LHH, 1/6 with LHSN, and 5/7 with RHH) demonstrated larger average gaze magnitude toward the BlindSide compared to the SeeingSide, which could be interpreted as compensatory scanning (Fig. 4B). In total six subjects with HH without SN (3 with LHH and 3 with RHH) showed evidence of compensatory scanning in both scan rates and scan magnitudes, with more scans and larger toward the BlindSide.

To further investigate differences in BlindSide and SeeingSide gaze scan magnitudes, the percentage of scans to each side (over all recorded scans to both sides), was computed group-wise for 3 gaze magnitude bins: 20° to 40°, 40° to 60°, and >60° (Fig. 4C). In subjects with LHH, there was a higher percentage of scans toward the BlindSide for gaze magnitudes below 60° (larger differences seen for gaze magnitudes in the range of 20° to 60°). In subjects with RHH, there was a higher proportion of scans towards the BlindSide for gaze magnitudes above 40°. In subjects with LHSN, the relative proportion of scans were similar for both sides throughout the entire gaze magnitude range. No other factors or variables, including age, had significant effects on gaze magnitude.

## Comparing Gaze Behaviors During Mid-Block Walking and at Street Crossings

We compared gaze behaviors during mid-block walking to street-crossing data (previously reported separately) for the same cohort of subjects. The SeeingSide scanning rate (in scans/minute) was significantly higher at street crossings compared to mid-block walking segments in all three subject groups. However, the BlindSide scanning rate was not significantly different between the two locations, except in the case of subjects with LHSN (crossings: mean = 12.0, 95% CI = 8.8–16.4, mid-block: mean = 8.0, 95% CI = 5.9–11.0, $P = 0.002$; Fig. 5A). Across all three groups and the

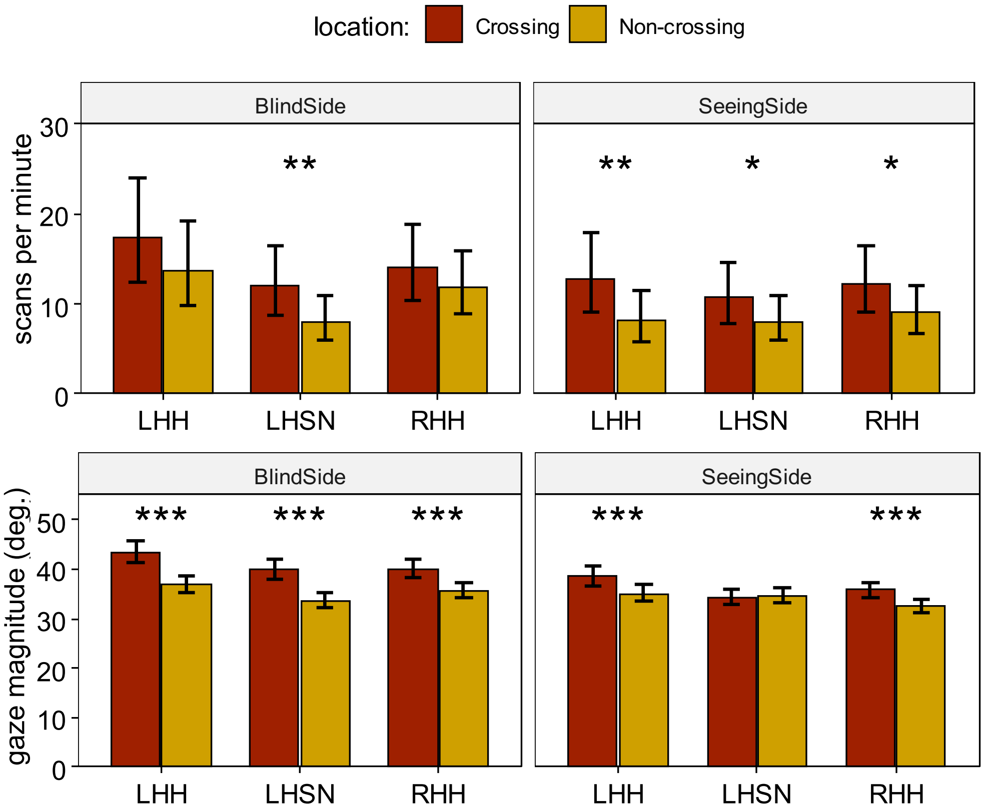

**FIGURE 5.** Comparison of mean scanning rate (*top row*) and mean gaze magnitude (*bottom*) between street crossings and mid-block walking among the three subject groups towards the BlindSide and the SeeingSide. The overall scanning rate and gaze magnitude were significantly larger at street crossings than in the mid-block walking. Significance levels: *** : $P < 0.001$, ** : $P = 0.001$ to 0.01, and * : $P = 0.01$ to 0.05. The $P$ value adjustment method: Benjamini-Hochberg (BH) procedure. Error bars show 95% confidence interval of the mean.

two scanning sides, the average scanning rate was significantly higher at street crossings (mean = 13.0, 95% CI = 11.0–15.3) than at mid-block segments (mean = 9.6, 95% CI = 8.1–11.3, $P < 0.001$). The overall gaze magnitude was significantly larger at crossings (mean = 38.5°, 95% CI = 37.5–39.5°) than in the mid-block segments (mean = 34.7°, 95% CI = 33.9–35.5°, $P < 0.001$). The BlindSide gaze magnitude was significantly higher at street crossings than non-crossing segments in all three groups. The SeeingSide gaze magnitude was significantly higher at street crossings than the mid-block segments in subjects with LHH and RHH, but not in the subjects with LHSN (Fig. 5B).

## DISCUSSION

We studied the gaze scanning behavior of people with HH with and without SN during mid-block walking on busy urban sidewalks. HH pedestrians without SN used compensatory scanning, evidenced as higher average gaze magnitude and scanning rate toward the side of visual field loss compared to their own seeing side, with no significant differences between LHH and RHH. However, the LHSN group behaved differently. Their overall scanning rate was not greater to their blind side and was significantly lower than that of the RHH and LHH groups, and so we conclude that there was lack of compensatory scanning in the LHSN group. These findings during mid-block walking were broadly consistent with those we previously reported for the same cohort of subjects when scanning at street crossings (except in the LHSN group), but with lower overall scanning rate and gaze magnitude compared to the crossing segments. Together, these findings from our analyses of both mid-block segments and street crossing segments,[30] suggest top-down mechanisms of gaze scanning are at play in outdoor walking mobility of pedestrians with HH, with the neglect condition acting as scanning behavior modulator/suppressor.

People with normal vision and an intact binocular visual field deploy their gaze through a combination of bottom-up and top-down mechanisms that are difficult to separate during naturalistic viewing. However, for people with large and dense visual field loss, it is likely that the top-down mechanism is mainly in play, making it easier to reveal. People with tunnel vision (concentric peripheral field loss) were observed making saccades (eye-in-head) that landed outside their pre-saccadic field-of-view almost every second during outdoor walking.[1] Such top-down eye movements are presumably needed for obstacle detection and circumnavigation. Similarly, top-down gaze shifts were observed in the case of HH without SN (LHH and RHH groups) while walking, with three to four more scans/minute towards the BlindSide (33% to 45% increase). Attention is tightly linked to eye movements, and proactive compensatory eye/gaze shifts are preceded by an attentional shift.[56,57] Such attentional shifts can be toward a position outside the visual field.[1] Because people with SN have attention and movement execution deficits toward the neglected side (the same as the Blind-

Side), they did not scan to the BlindSide as often or with the same magnitude of those without SN. In fact, the BlindSide and overall scan rates were higher by about 78% and 54%, respectively, in the HH without SN group than the LHSN group.

The average gaze magnitude difference between the BlindSide and SeeingSide was not large in any group, despite being statistically significantly larger towards the BlindSide in the LHH and RHH groups. However, there were group-wise variations in gaze scan magnitude distributions (see Fig. 4C), with clear differences in the relative percentage of BlindSide and SeeingSide scans of large magnitudes between participants with and without SN. Thus, although the average difference in gaze magnitude between the blind and seeing sides was small, there were substantially more large magnitude gaze scans made toward the BlindSide in the LHH and RHH groups. Interestingly, when evaluating gaze behaviors for each participant, compensatory scanning was more evident in terms of the scanning rate than the gaze magnitude (see Figs. 3B, 4B). Greater evidence of compensatory behaviors in scan numbers rather than scan magnitudes was also reported for drivers with HH in a driving simulator.[10]

Scans where eye movement was the predominant contributor to the overall gaze magnitude, constituted slightly more than 50% of all the scans analyzed in mid-block walking. Because their average magnitude was 33° and because typical eye movement saccades in naturalistic viewing tend to be limited to around 15°,[58] this potentially indicates the presence of multiple eye movement saccades within a single gaze scan. This was previously reported in gaze scanning of individuals with HH when driving in a simulator.[43,45]

The finding that the average gaze magnitude and scanning rate were lower during mid-block walking than at street crossings (by 3.8° or 10% and by 3.4 scans/minute or 26%, respectively) was consistent with our expectations. Large and more frequent scans at street crossings are intuitively needed and also a result of life-skill training at a young age for most people, especially in busy urban areas like that of our study site. Whereas the average gaze magnitude difference of 3.8° between mid-block and street crossing segments may seem small, the average BlindSide difference was 5.7°. We previously demonstrated that the head contribution to the overall gaze was significantly higher at street crossings than during mid-block walking over the entire gaze magnitude range.[59] The scanning behaviors during mid-block walking showed some interesting group-wise differences not seen at street crossings. Statistically significantly higher scanning rates and gaze magnitudes toward the BlindSide were observed in all three groups at street crossings,[30] but only in the RHH and LHH groups during mid-block walking. Our results suggest that the presence of SN impacts scanning differently at street crossings and during mid-block walking, consistent with the idea that mid-block walking and street crossing are cognitively different mobility tasks, and should be considered separately when evaluating mobility outcomes.

Although there is ample evidence of compensatory scanning by HH individuals in the context of driving[8–18] or at street crossings,[30] this study details the scanning behaviors of HH and SN pedestrians during naturalistic mid-block walking on urban streets. Our current findings show deficits in compensatory scanning in patients with SN compared to those without SN. This finding is relevant to current clinical practice in the rehabilitation of patients with SN and HH, which primarily relies on blindside cueing under the guidance of an occupational therapist (OT). The OT practice standard dictates provision of reminders to the patient to look to the blind/neglected side, and, in the process, teaching the patient to self-implement this top-down strategy. This may be effective for patients with SN during mobility tasks where the patient is engaging top-down strategic systems, such as at signalized crossings; however, our findings might suggest a breakdown of this approach in mid-block sections where hazards are not expected but still could occur. Interventions that target bottom-up mechanisms of leftward attention and movement, such as peripheral prisms[60] or alerting sensors, may potentially benefit patients with SN.[61]

One of the perceived limitations to our analysis may be the absence of normally sighted control subjects. However, because the main focus of this work was on compensatory scanning in patients with HH defects, gaze scanning behaviors of normally sighted subjects were not needed to interpret the findings, which were primarily within-subject comparisons between the blind side and the seeing side. Lack of control of hazards was both a benefit in the sense of being ecologically valid yet a limitation in that participants were not exposed to the exact same environment. In addition, most but not all subjects had complete HH which could be considered a limitation; however, the behavior of the three subjects with incomplete HH was well within the range of those with complete HH (see Figs. 3B and 4B).

In conclusion, the findings of this study suggest that compensatory gaze scanning is used by HH pedestrians (especially those without the SN), when walking on sidewalks in urban environments. Compensatory scanning behaviors could be either increased frequency of scanning toward the BlindSide, or larger BlindSide gaze scan magnitude, or both. Presence of SN significantly altered the gaze scanning behaviors, suggesting the role of top-down mechanisms driving the gaze in HH pedestrians without SN. The next step will be to conduct a study to investigate the association between gaze scanning behaviors and successful detection and avoidance of hazards when walking. Ultimately, the goal is to address the question of whether HH pedestrians who demonstrate compensatory scanning have safer walking mobility than those who do not demonstrate such scanning behaviors.

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