1040-5488/08/8501-0026/0 VOL. 85, NO. 1, PP. 26–36
OPTOMETRY AND VISION SCIENCE

FEATURE ARTICLE ON LINE

Traffic Gap Judgment in People with Significant Peripheral Field Loss

ALLEN M. Y. CHEONG, PhD, BSc(Optom), DUANE R. GERUSCHAT, PhD, and NATHAN CONGDON, MD, MPH

Wilmer Eye Institute, School of Medicine, The Johns Hopkins University, Baltimore (AMYC, DRG), Minnesota Low Vision Research Laboratory, Department of Psychology, University of Minnesota, Minneapolis (AMYC), The Maryland School for the Blind, Baltimore (DRG), Department of Ophthalmology and Visual Sciences, The Chinese University of Hong Kong, Hong Kong SAR (NC)

ABSTRACT

Purpose. Subjects with significant peripheral field loss (PFL) self report difficulty in street crossing. In this study, we compared the traffic gap judgment ability of fully sighted and PFL subjects to determine whether accuracy in identifying crossable gaps was adversely affected because of field loss. Moreover, we explored the contribution of visual and nonvisual factors to traffic gap judgment ability.

Methods. Eight subjects with significant PFL as a result of advanced retinitis pigmentosa or glaucoma with binocular visual field $<20°$ and five age-matched normals (NV) were recruited. All subjects were required to judge when they perceived it was safe to cross at a 2-way 4-lane street while they stood on the curb. Eye movements were recorded by an eye tracker as the subjects performed the decision task. Movies of the eye-on-scene were made offline and fixation patterns were classified into either relevant or irrelevant. Subjects' street-crossing behavior, habitual approach to street crossing, and perceived difficulties were assessed.

Results. Compared with normal vision (NV) subjects, the PFL subjects identified 12% fewer crossable gaps while making 23% more errors by identifying a gap as crossable when it was too short ($p < 0.05$). The differences in traffic gap judgment ability of the PFL subjects might be explained by the significantly smaller fixation area ($p = 0.006$) and fewer fixations distributed to the relevant tasks ($p = 0.001$). The subjects' habitual approach to street crossing and perceived difficulties in street crossing ($r > 0.60$) were significantly correlated with traffic gap judgment performance.

Conclusions. As a consequence of significant field loss, limited visual information about the traffic environment can be acquired, resulting in significantly reduced performance in judging safe crossable gaps. This poor traffic gap judgment ability in the PFL subjects raises important concerns for their safety when attempting to cross the street.
(Optom Vis Sci 2008;85:26–36)

Key Words: gaze, fixation behavior, low vision, street crossing, mobility, decision making

Crossing the street has been reported as a difficult activity for people with visual impairment.[1–4] A study conducted by the Veterans Affairs reported that 64% of subjects with visual impairment did not cross the street on a daily or weekly basis before rehabilitation.[5] In this study, we quantified traffic gap judgment ability and we explored possible reasons for explaining the difficulty in street crossing faced by people with visual impairment because of significant peripheral field loss (PFL).

Crossing the street involves a series of challenges that can be divided into three phases: walking to the curb, standing at the curb, and crossing the street.[6] Each phase requires different orientation, mobility, and decision-making skills. Although deficits in orientation and mobility skills have been well documented in visually impaired people, little is known about their traffic gap judgment ability. Connelly et al.[7] studied traffic gap judgments among 16 school children with normal vision (NV) aged between 5- and 12-year-old. Their results indicated that children above 11-year-old consistently made safe gap decisions regardless of the vehicle speed, indicating that traffic gap judgment ability is developed by the age of 11. We assume that for adults with NV, these skills are constant unless some physical or cognitive impairment compromises this ability. Guth et al.[8] reported that the traffic gap judgment ability in totally blind subjects who rely exclusively on auditory information was significantly impaired with only 20% of crossable gaps being identified by blind subjects at a high-traffic-volume, two-lane roundabout. Knowing the traffic gap judgments of fully sighted and totally blind subjects, we were interested in the effect of visual impairment on traffic gap judgments. Would visually impaired subjects make more mistakes (i.e., expressed that they would cross when it was not safe) or miss more crossing opportunities (i.e., sufficient time to cross but not accepted as crossing opportunities) when compared with the fully sighted? To answer this question we employed the same traffic gap judgment methodology as Guth et al.[8] at an uncontrolled mid-block crosswalk.

To visually identify a safe crossable gap, visual information on the location and speed of moving vehicles and the crossing distance is essential. To compensate for the lack of peripheral information, subjects with PFL might sample the environment with different fixation and scanning patterns.[9,10] In this study, we explored whether visual behavior (eye movements and distributions of fixations) in the PFL subjects was different from the fully sighed subjects and which visual behavior, if any, would affect their traffic gap judgment ability.

Crossing the street carries a risk for an accident which can result in injury or loss of life in severe circumstances; while waiting on the curb entails a loss of time for a suitable and safe crossable gap. Acknowledging a pedestrian's tolerance for risk will affect their street crossing behavior, we measured each subject's selfreported street-crossing behavior when crossing the street using a 5-Likert scale (from very conservative to very liberal) and evaluated the association between street-crossing behavior and performance in traffic gap judgment.

To summarize, the aim of this study was to examine the gap detection ability, visual behavior, and street-crossing characteristics of fully sighted persons and low-vision subjects with significant PFL. We hypothesized that there would be differences in traffic gap judgments and gaze behavior between groups.

METHODS

Visual Function Measures

Visual acuity was measured binocularly using a Lighthouse Early Treatment Diabetic Retinopathy Study acuity chart[11] with a background transillumination of 95 cd/m^2. Visual acuity was scored to the nearest letter and recorded in logMAR (logarithm of the minimum angle of resolution) by deducting 0.02 log units per letter read accurately.[12] Contrast sensitivity was measured binocularly using the Pelli-Robson chart[13] at a testing distance of 1 m, with an average background luminance of 85 cd/m^2. Log contrast sensitivity was calculated by recording the total number of letters read correctly, subtracting three, and multiplying by 0.05.[14,15] For subjects with peripheral field loss (PFL), binocular visual field was measured by kinetic perimetry with a Goldmann perimeter using a V/4e target (1.75° test spot at 320 cd/m^2 on a background luminance of 10 cd/m^2).

Subjects

Thirteen subjects participated in this experiment, among whom five had NV and eight had significant PFL because of retinitis pigmentosa (RP) ($n = 5$) or glaucoma ($n = 3$). Age of the NV subjects ranged from 36.7 to 67.1 years (mean 52.5 ± 12.2) and the PFL subjects ranged from 31.4 to 62.7 years (mean 50.6 ± 10.8) with no significant difference in age between groups ($t = 0.29$, $dF = 11$, $p = 0.78$). Through examination of the medical history and informal clinical evaluation, any subject with physical limitations (e.g., orthopedic) or cognitive limitations (e.g., Alzheimer disease) was excluded from the study. Distance acuities for the NV and PFL subjects ranged from −0.14 to 0.38 (mean 0.05 ± 0.20) and −0.14 to 0.84 logMAR (mean 0.30 ± 0.33), respectively, that were not significantly different ($p = 0.17$, Table 1). Log contrast sensitivity of NV subjects ranged from 1.5 to 1.8 (mean 1.64 ± 0.12) were significantly better than that of PFL subjects whose values ranged from 0.6 to 1.65 (mean 1.24 ± 0.36, $p = 0.04$). Binocular visual field for subjects with PFL ranged from 5.0° to 18.1°.

Informed consent was obtained from each subject after the nature and possible consequences of the study were described. The research followed the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of the Johns Hopkins University School of Medicine.

TABLE 1.
Subjects' background information

Sub ID	Group	Age (years)	Distance acuity (logMAR)	Contrast sensitivity (log unit)	Binocular visual field (deg)
1	NV	67.1	0.24	1.5	—
2	NV	36.7	0.38	1.55	—
3	NV	53.9	−0.14	1.65	—
4	NV	60.5	−0.14	1.7	—
5	NV	44.3	−0.10	1.8	—
6	PFL	50.4	0.08	1.65	8.6
7	PFL	55.5	0.10	1.6	12.1
8	PFL	31.4	0.48	1.15	18.1
9	PFL	53.7	0.10	1.6	11.6
10	PFL	52.9	0.28	1.2	12.0
11	PFL	60.5	0.58	1	5.0
12	PFL	62.7	0.84	0.6	5.9
13	PFL	37.8	−0.14	1.1	13.5
Average (standard deviation)	NV	52.5 (12.2)	0.05 (0.2)	1.64 (0.12)	—
	PFL	50.6 (10.8)	0.30 (0.33)	1.24 (0.36)	10.85 (4.27)

Eye Tracking

The method for obtaining images of the eye and for analyzing fixation location have been fully described elsewhere.[6] Briefly, eye and scene were recorded using an ISCAN ETL-500 headband-mounted eye tracker (Iscan, Burlington, MA) modified to be used as a portable system. Eye movements and view of the scene were recorded on camcorders for later analysis. The camcorders for the eye and scene were synchronized by simultaneously recording a tone on the audio channel and capturing the image of the LED light flash of a tone generator. Calibration was performed at the test site before each trial.

Eye data from the first 3 s while the subject fixated on the central target during calibration was extracted and fitted with a bivariate normal density ellipse. Fixation stability was expressed as fixation area of the ellipse containing 95% of all the eye data. A fixation was defined as the velocity of the eye movement on the scene as $<24°/s$ and was within 1.6° for two consecutive frames (i.e., 67 ms).[16]

Documentation of Crossable Gaps

The subject squeezed a hand held button to indicate when they could cross. The button was connected to an LED system that was illuminated when the button was pressed. The LED was recorded by a stationary digital camera that also recorded the flow of traffic, used to determine the duration of each gap in the traffic. The subject pushed the button whenever they believed they could cross the street and released the button when there was an insufficient gap for street crossing. The videotaping technique made it possible to independently and unobtrusively observe the traffic conditions and the subjects' decision behavior. Fig. 1 is an example of vehicles at the crosswalk and the illuminated LED indicating when the subject believes it is safe to cross. Subjects did not actually cross the street but stood at the curb of the crosswalk and indicated with the press of the button when they could cross.

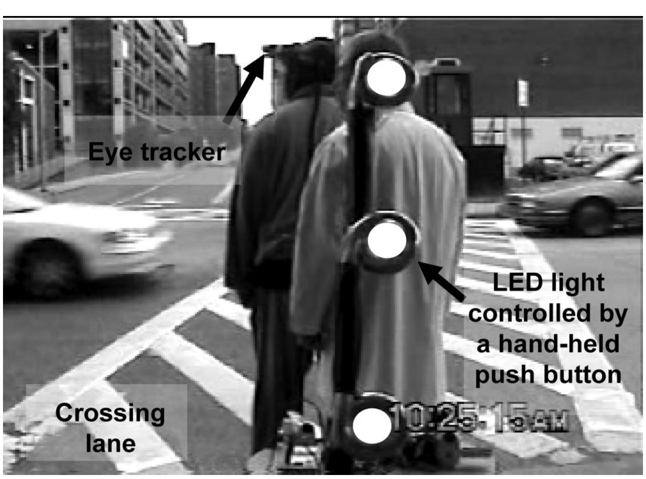

FIGURE 1.
Experimental set up and street crossing environment used in the study. A subject wore a headband-mounted eye tracker (with a green filter to minimize the influence on the image quality of the eye data due to excessive infra-red light) and held a hand held button connected to an LED system. The subject stood at the curb of the street to assess the lanes of traffic coming from opposite directions and squeezed a hand held button (illustrated in the foreground) when a crossing opportunity occurred. The LED system was illuminated when the button was pressed. An experimenter (white coat) stood behind the subject for safety purposes.

Street Crossing Judgment and Behavior

The street selected for this study had four lanes comprised of a parking lane on each side and one lane of traffic in opposite directions. To minimize the amount of differences in the environment across subjects and to ensure a reasonable volume of traffic that included both crossable and uncrossable gaps, the study was conducted between 10 a.m. and 12 p.m. on weekdays. The subject was positioned such that the sun was behind and to the side. An umbrella was held over the subject's head to eliminate any extraneous light from above. None of the subjects was familiar with the mid-block crossing used in this study.

Selfreport Questionnaires

Subjects were asked four questions related to their approach to crossing the street. Specifically subjects were asked to rate: (1) their street-crossing behavior from very conservative to very liberal; (2) their habitual approach to street crossing (independent or dependent); (3) their perceived difficulty in street crossing and traffic gap detection (no difficulty to extreme difficulty; and (4) response to an open question about the visual information they used while making their street-crossing decisions.

Procedures

Subjects were instructed on the use of a hand-held button through the following instructions:

Squeeze the button when you have enough time to walk to the other side of the street at your normal walking speed before any vehicle from either direction gets to the crosswalk. Hold the button down until you can no longer initiate a safe crossing, at which time you release the button. Assume that drivers will not yield. Squeeze the button again when another crossing opportunity occurs.

Practice was given at a different street that was not used during data collection until the subjects fully understood the instructions. Upon arrival at the mid-block crossing, subjects crossed the street two times accompanied by an experimenter. This provided the subjects information about the distance of the crossing lane and provided the experimenters the subjects' walking speed while crossing the street. The subjects were instructed to look straight ahead, with an experimenter indicating when it was safe to cross and then accompanying the subject across the street. The eye tracker was then fitted to the subject and calibrated.[a] The subject was then guided to a specific location 10 cm from the edge of the curb and instructed to look straight ahead until the trial began. Each trial began when at least one vehicle from either direction approached the crosswalk, indicating a definite "unsafe" crossing environment. Each trial lasted for 3 min with 5 trials, totally 15

[a]Subjects were instructed to fixate sequentially at each of five fixation crosses of a "plus" configuration with magnitude of 12.1° at horizontal and vertical directions from the central point on a white board. To reduce head movements, one of the experimenters held the subject's neck which was surrounded by a soft cervical surgical collar. After calibration, the neck collar was removed and the subjects were free to move their eyes or heads without touching the equipment.

TABLE 2.
Results of gap detection ability, eye movement parameters, and fixation allocations

			Traffic			Eye movement parameters			Fixation allocations
			Number of objective crossable gaps	Gap judgment (%)					
Sub ID	Group	Street crossing independently		Accurate gaps	Inaccurate gaps (errors)	Median fixation duration (s)	Median saccadic dist (deg)	Fixation area (deg^2)	Percentage of fixations on relevant tasks[a]
1	NV	Yes	19	86.7	31.6	0.167	5.0	62.1	95.8
2	NV	Yes	24	83.3	35.5	0.167	10.0	52.2	97.5
3	NV	Yes	14	78.6	56.0	0.133	5.9	80.2	90.5
4	NV	Yes	15	93.3	46.2	0.167	3.8	67.7	98.6
5	NV	Yes	5	60.0	25.0	0.25	2.9	79.5	88.2
6	PFL	Yes	12	66.7	60.0	0.133	10.1	21.1	63.8
7	PFL	Yes	18	80.0	38.5	0.133	4.1	36.1	39.0
8	PFL	Yes	15	57.1	63.6	0.10	4.4	40.9	36.3
9	PFL	No	17	70.6	50.0	0.167	5.0	75.7	73.2
10	PFL	No	22	63.6	54.8	0.133	4.8	31.4	72.6
11	PFL	No	6	33.3	93.1	0.133	3.8	30.9	53.2
12	PFL	No	13	27.3	76.9	0.20	4.7	49.8	63.0
13	PFL	Yes	16	62.5	61.5	0.15	3.8	34.6	73.4
Average (standard deviation)		NV	15.4 (7.0)	80.38 (13.6)	38.84 (12.3)	0.18 (0.04)	5.52 (2.8)	68.34 (11.86)	94.12 (4.5)
		PFL	14.9 (4.7)	57.64 (18.2)	62.31 (16.7)	0.14 (0.03)	5.06 (2.1)	40.07 (16.60)	59.31 (15.0)

[a]Relevant tasks include vehicles and crossing elements such as curbs, traffic sign, pavement, crosswalk lines.

min. A new calibration was completed following each trial. Following data collection in the field, each subject answered the four selfreport questions examining their street-crossing behavior and habitual approach to street crossing.

ANALYSIS
Objective and Subjective Gaps

Videotapes captured the traffic conditions and subjects' decision behavior allowing for independent examination of each subject's traffic gap judgment performance. A gap was measured from the back bumper of one vehicle to the front bumper of the next vehicle. An "objective crossable gap" was defined as the duration of time between a vehicle touching the crosswalk and the next vehicle touching the crosswalk that was greater than the subject's walking time (Table 2). For example, if a subject's walking time to cross the street was 10 s, any gap longer than 10 s was determined to be "crossable," while the others were defined as "uncrossable." The total number of objective crossable gaps, their associated times and gap durations (i.e., time frames for the start and end of the gap) were obtained for analysis. A "subjective gap" was defined as the crossable gap identified by the subject who believed there was sufficient time to cross the street. This subjective gap was indicated by the LED lights. The total number of subjective gaps and their associated time (i.e., time frames when the LED was on) were obtained.

We compared the objective and subjective reported gaps in three ways:

1. Percentage of correctly identified crossable gaps[b]: When a subjective gap was identified within the duration of the objective gap, this subjective gap was considered as a "correctly identified gap." We calculated the percentage of correctly identified crossable gaps by dividing the total number of correctly identified crossable gaps by the total number of objective gaps.
2. Percentage of errors: When a subjective gap was identified outside the time frame of those defined as objective crossable gaps, this decision was considered an "error." The percentage of errors was computed by dividing the total number of errors by the total number of reported subjective gaps.
3. Latency in accurate gap identification: Whenever an accurate gap was identified by the subject, the duration between the lead vehicles leaving the crosswalk and the subjects pressing the button for their crossing decision was defined as "gap-detection latency." An example of the analysis for objective and subjective gaps has been described in Fig. 2.

[b]Given that gap opportunities in a test session varied across subjects (depends on subject's walking time and traffic conditions), percentage of correctly identified crossable gaps and errors, rather than absolute numbers was used.

Eye Movement Analysis

Three spatial parameters—saccadic amplitude (or distance), fixation duration, and fixation area were derived from the eye movement data and compared between groups. Saccadic amplitude between each fixation was gauged by comparing the distance (in terms of degrees) of the eye images on the scene camera with a fixed field of view (320° × 240°). Fixation duration was the difference in the elapsed time between the first frame when a fixation was recognized and the last frame before the gaze was shifted to a new point of regard. Fixation area was the area of a bivariate normal density ellipse containing 95% of all fixations.

Fixation Categorization

Movies of the eye-on-scene were generated by superimposing the transformed and calibrated eye position on scene images with a

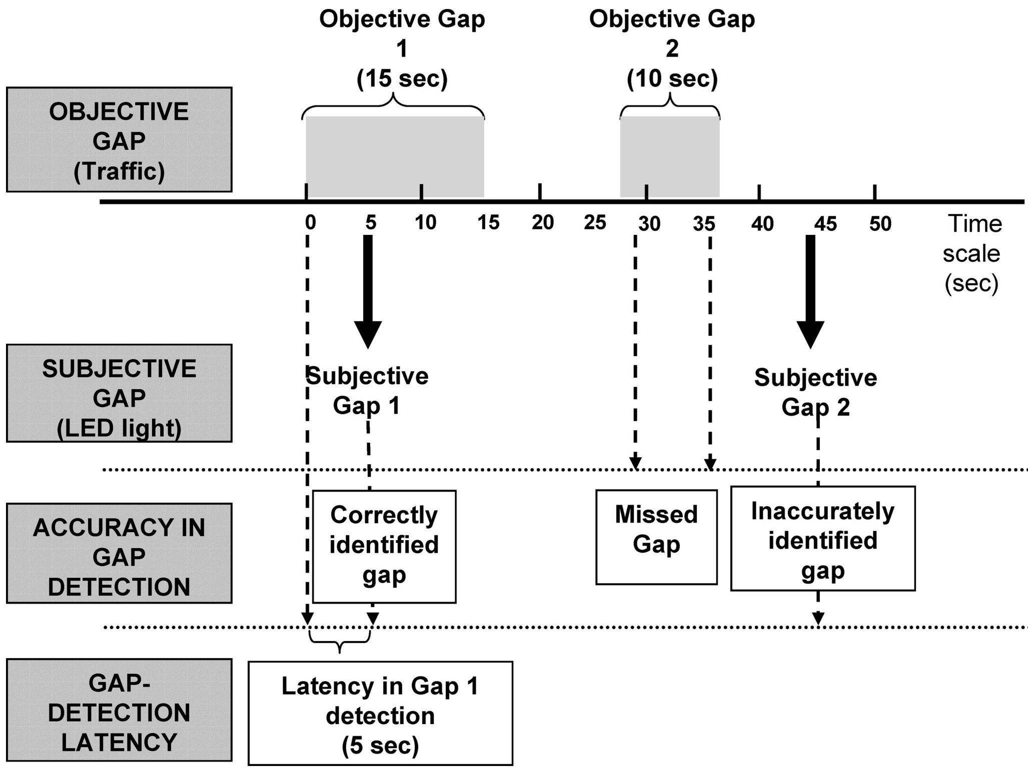

FIGURE 2.

An example to demonstrate how the objective and subject gaps were analyzed and compared. Within the 50 s duration, 2 objective gaps were recognized which were longer than the Sub A's walking time (8 s). The first objective gap was accurately identified by the subject with a latency of 5 s. However, the subject failed to recognize objective gap 2 (i.e., missed gap), but inaccurately identified a gap that was too short or not existing (subjective gap 2).

spatial resolution of 0.25° per pixel for each subject per trial. The process for generating the movie clips (eye-on-scene) has been reported by Turano et al.[16] and Geruschat et al.[6]

Fixation stability, in terms of size of fixation area, analyzed from the data collected in calibration of the eye movement equipment varied from 0.07° to 0.28°. The fixation variability induced by the systemic error of the eye tracking equipment was approximately 0.68°. The sum of subjects' individual fixation stability and the systemic variability of the equipment were 0.75° and 0.96°, which was <1°. Hence, a 1° radius around the fixation center served as the fixation area for fixation classification. Each fixation was categorized into two groups: relevant (including vehicles and crossing elements such as curbs, traffic signs, pavement, crosswalk lines) and irrelevant tasks (including general environment such as trees, sky, buildings, etc.). For three subjects, two independent experimenters categorized the fixation, and the inter-experimenter agreement was 83.5%. When disagreements occurred, the fixation was analyzed by both observers to resolve the disagreement. One person categorized the fixations for the remaining subjects.

Statistical Analysis

Data for vision, traffic gap detection judgment, eye movement characteristics, and fixation behavior were analyzed using the Statistical Package for the Social Sciences (SPSS)—version 13. Descriptive statistics were used to summarize the demographic data results among NV and PFL groups. Results for traffic gap detection performance (percentage of gaps correctly identified, percentage of errors, and latency in gap detection), eye movement characteristics (median of saccadic distance and fixation durations, and mean fixation area), and fixation allocations (percentage of fixation on relevant tasks) were ranked (ties averaged) and analyzed by independent t-test and Pearson correlation to investigate the between-subject variability in each measure.[c] Results of the selfreport questions were analyzed by Chi-square. A probability of <0.05 was taken to indicate statistical significance for all analyses.

Similar to results in many low vision studies, individual results in the PFL group were more heterogeneous than those in the NV group. For a small sample size, the averages and standard deviations computed in the PFL group could be affected by an atypical (extreme) result in one or two subjects, resulting in insufficient statistical power to show a meaningful "failure-to-find" result between groups. To investigate whether the nonsignificant measures between groups were due to this issue, the average data of the measures (saccadic distance and fixation duration) in the NV group was considered as the statistical "norm," which was then used to compute the z-scores for individual data of PFL subject:

$$z = \frac{\bar{x} - \mu}{\sigma/\sqrt{n}}$$

[c]Although multiple comparisons among different measures were conducted, Bonferroni adjustments to the probability level for significance to reduce the chance of Type I errors were not considered necessary as this was a designed experimental study and the statistical analysis was planned to reflect this (comparing results in NV vs. PFL groups), not to develop a predictive model.[17]

where $\bar{x}$ represents the individual PFL data, n is the sample size of the NV group ($n = 5$), μ and σ are the group average and standard deviation in the NV group respectively. When z-scores in individual PFL data were larger than 1.96 or smaller than -1.96, it indicates that the PFL data was statistically different from the "norms" (95% confidence level).

RESULTS

Traffic Gap Judgment Performance

The first question of interest was the effect of visual impairment on the ability to detect crossable gaps. Through the combination of the wide street (4 lanes) and the volume of traffic, on average approximately 3 of the gaps were long enough to be defined as "objective crossable gaps" during each 3 min trial, slightly more than one crossable gap per minute. Combining the 5 three-min trials, there was an average of 15 crossable gaps per subject (Table 2).

Overall traffic gap detection ability for each subject was described by the percentage of crossable gaps accurately identified and percentage of errors made (Table 2). The percentage of crossable gaps accurately identified by the NV and PFL subjects ranged from 60 to 93% (80.4 ± 12.6%) and 27 to 81% (57.6 ± 18.2%), respectively. Although large variations of traffic gap judgment ability within group was found (in particular the PFL group), the PFL subjects identified significantly fewer crossable gaps than the NV subjects by an average of 23% (independent t-test, $t = 2.4$, $dF = 11$, $p = 0.03$). In the PFL group, Sub 11 and Sub 12 identified only 33 and 27% of the crossable gaps respectively, which was much worse than the other PFL subjects.

Of perhaps greater importance are the inaccurate crossing judgments. Since missing crossable gaps may require a longer period of time to cross the street, a missed crossing opportunity does not result in exposure to a safety issue. By comparison, inaccurately identifying gaps which are of insufficient duration may result in serious safety issues. Fig. 3 shows the distributions of safety margins for each subject. Negative values represent gap durations that are insufficient for safe street-crossing and are considered as an "error," whereas positive values represent gaps of sufficient duration for safe street crossing. Fig. 3a shows that the peak frequency of gaps identified by 4 of the 5 NV subjects have sufficient durations for safe street crossing (i.e., the columns are located on the right side of the dashed line), while the peak frequency for one NV subject was shorter than the safe crossable gap. For the PFL subjects, larger variances of gap durations were found (Fig. 3b). Except for Sub 6 and 7, the peak frequencies of gap durations identified by the PFL subjects were insufficient. This poor traffic gap judgment ability was most obvious in Sub 11 and 12, with the majority of their gaps inaccurately identified as crossable gaps. The percentage of errors made by the NV and PFL subjects ranged from 25 to 56% (38.8 ± 12.3%) and 38.5 to 93% (62.3 ± 16.7%), respectively, indicating that the PFL subjects made more errors than the NV subjects ($t = -3.04$, $dF = 11$, $p = 0.01$, Table 2). Similar to the result with accurate gap identification, Sub 11 (93.1%) and 12 (76.9%) made more errors than the other PLF subjects, implying that the overall traffic gap judgment ability for these 2 PFL subjects was worse than the other PFL subjects. Possible reasons explaining their poor traffic gap judgment performance will be explored in the discussion.

When there are opportunities for crossing, it is important to quickly detect the presence of a crossable gap. We calculated the gap-detection latency as the duration between the lead vehicles leaving the crosswalk and the subjects pressing the button for their crossing decisions. Fig. 4 shows the distributions of latency in accurate gap identification for each subject, with ranges from 0.03 to 6.8 s and 0.13 to 8.77 s for the NV and PFL group, respectively. Because of the wide variation in the latency (range from 0 to almost 8 s) and small sample size (i.e., small number of crossable gaps), it was not possible to compare either the mean or median of the latency in each subject to examine the effect between groups (NV vs. PFL). On the basis of the general assessment of Fig. 4, there is no clear evidence that the latency in the NV subjects was different from that in the PFL subjects.

Eye Movements and Distribution of Fixations

Prior to any crossing decision, pedestrians assess the traffic environment to collect sufficient visual information for traffic gap judgment. In this study, subjects were instructed to squeeze the hand-held button whenever a crossable gap was identified. Analyzing the eye movement data and fixation allocation allowed us to understand what visual information was collected when making gap judgments. It is possible that the visual information collected in the "decision making interval," the 4 s-interval defined by Geruschat et al.[6] before gap judgment, might be different from the visual information collected during the entire test (i.e., 15 min). Therefore, we analyzed the data of eye movements and fixation allocation in two ways: (1) The entire test (i.e., 15 min); (2) During the decision making interval (for accurate and inaccurate gap judgment separately). Given that the results analyzed by either method were not significantly different, we report the statistical findings of the eye movements and fixation allocation derived from the entire test (method 1).

Eye movements were quantified as median fixation durations, median saccade amplitude, and fixation area, defined as bivariate normal density ellipse containing 95% of all the fixations. Fixation area in the PFL subjects ranged from 21.1° to 75.7°^{2} and was significantly smaller than that in the NV subjects (ranged from 52.4° to 80.2°,^{2} $t = 3.42$, $dF = 11$, $p = 0.006$). However, no significant difference in fixation durations and saccade amplitudes were found between PFL and NV groups ($p > 0.10$). The secondary analyzes using z-scores showed that the fixation durations for 4 PFL subjects were significantly longer than the "norm," while the saccadic distance for only 1 PFL subject was significantly longer than the "norm." These secondary results demonstrated that these two eye movement parameters for at least one-half of the PFL subjects were not significantly different from the NV subjects, moreover supporting why no significant difference was found between groups.

Distribution of fixation was categorized into two categories: relevant (including vehicles and crossing elements) and irrelevant (including general environment or pedestrians). The NV subjects distributed more than 88% (range of 88.2 to 98.6%) of fixations whereas the PFL subjects distributed no more than 73% (range of 36.3 to 73.4%) on relevant tasks (Table 2). The difference in fixation allocations on relevant task reflected that the fixation behavior in the PFL subjects was significantly different from that in NV subjects ($t = 5.24$, $dF = 11$, $p = 0.001$).

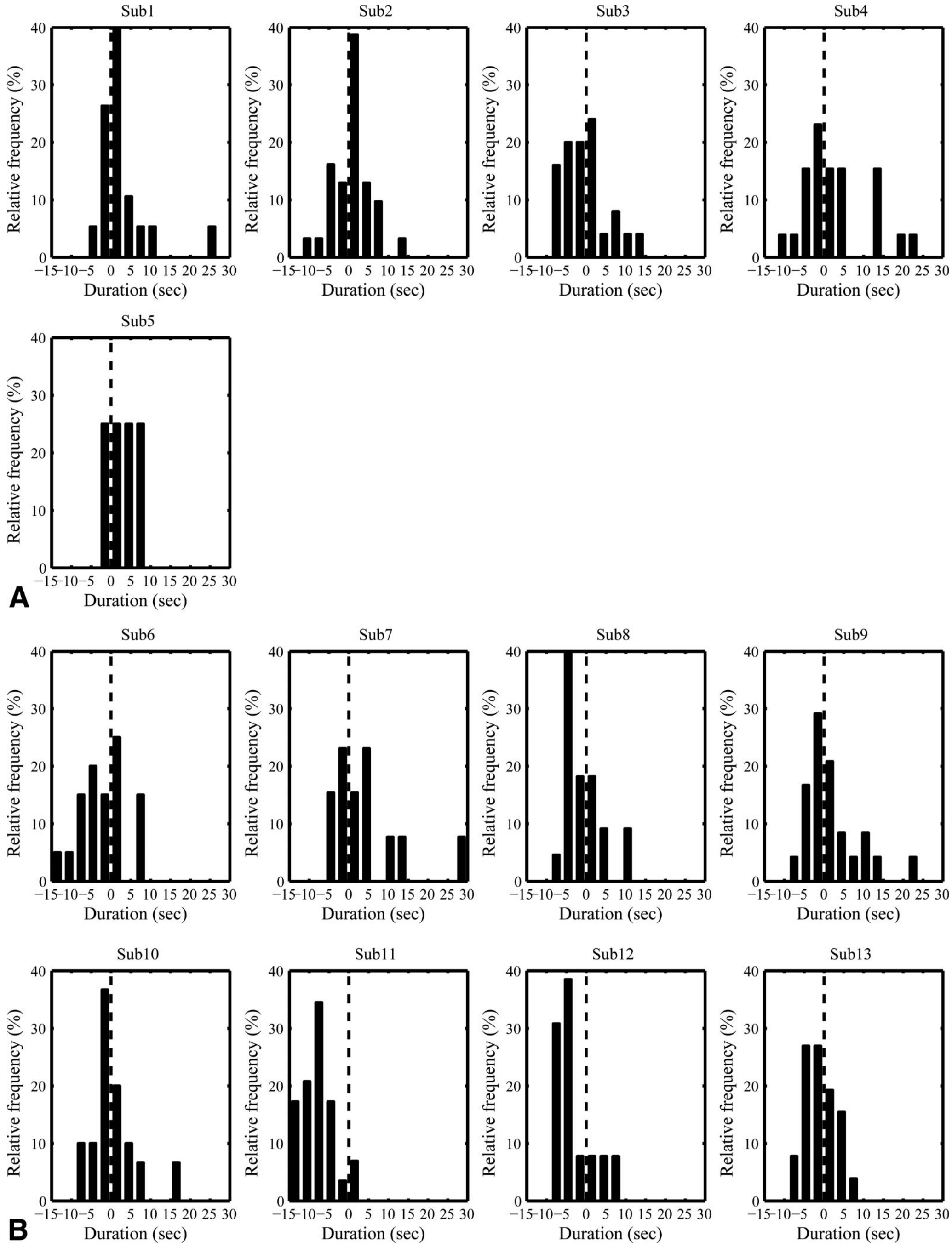

FIGURE 3.

The distributions of safety margin for individual normal vision (NV, Fig. 3A) and peripheral field loss subjects (PFL, Fig. 3B). Negative margin (left of the dashed vertical line) represents gap durations insufficient for safe street-crossing and are considered as an error, while positive margin (right of the dashed vertical line) represents sufficient gap durations for accurate judgment in gap detection.

Selfreported Street-Crossing Behaviors

As a consequence of significant field loss, we might expect the street-crossing behavior of the PFL subjects to be more conservative. Partly supporting our expectations, six PFL subjects rated themselves as "moderately to very conservative" when crossing the street, whereas only one NV subject rated herself "moderately conservative." Although there was a trend showing that the PFL subjects were more conservative than the NV subjects, it was not statistically significant ($\chi^2 = 6.8$, dF = 4, $p = 0.15$). Performance in traffic gap judgment (for accurate gap detection: $r = 0.14$, $p = 0.66$ and errors: $r = -0.27$, $p = 0.37$) was not significantly correlated to the rating on street-crossing behavior.

Results of the questionnaire showed that all NV and 4 PFL subjects could manage independent street-crossing (i.e., independent travelers) whereas the other 4 PFL subjects lost their independent traveling skills and relied on other people for assistance when crossing the street (i.e., dependent travelers, Table 2). Selfreported independent habitual approach to street crossing was significantly correlated with traffic gap judgment ($r > 0.60$, $p = 0.02$). For

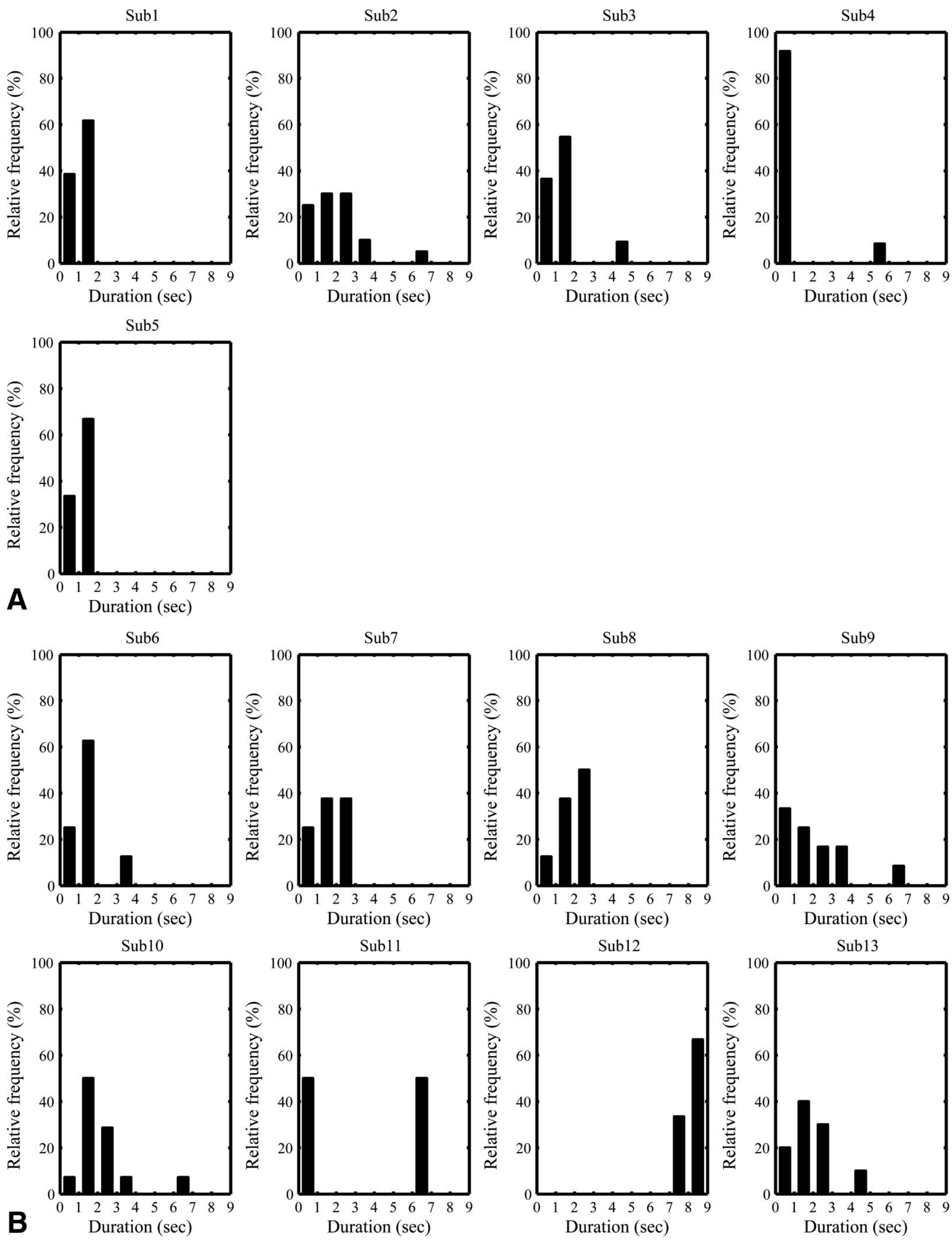

FIGURE 4.

The distributions of latency in accurate gap detection for individual normal vision (NV, Fig. 4A) and peripheral field loss subjects (PFL, Fig. 4B). Despite large variations in latency in gap detection between subjects, this latency does not appear to be significant between NV and PFL subjects.

perceived difficulty in street crossing, 88% of the PFL subjects rated this activity as "moderate to extreme difficulty" whereas all NV subjects rated this activity as having no difficulty, a significant finding ($\chi^2 = 13.0$, dF $= 4$, $p = 0.01$). There was also a significant association between selfperceived difficulty in street-crossing and the ability to detect safe crossable gaps ($r = -0.60$, $p = 0.03$) and errors in gap detection ($r = 0.65$, $p = 0.02$). For difficulty in traffic gap judgment, only 50% of the PFL subjects reported the same level of difficulty (moderate to extreme difficulty) as those perceived in street crossing. The difficulty in traffic gap detection faced by the PFL subjects was not significantly more than the NV subjects who all reported no difficulty ($\chi^2 = 5.1$, dF $= 4$, $p = 0.28$). The discrepancy in selfperceived difficulty in street crossing and traffic gap judgment suggests that the PFL subjects did not perceive that traffic gap judgment was a more difficult task compared with actually crossing the street. No significant association was found between selfperceived difficulty in traffic gap judgment and the ability to detect safe crossable gaps ($r = -0.52$, $p = 0.07$) and errors in gap detection ($r = 49$, $p = 0.09$).

At the conclusion of the data collection, each subject was asked what features they used to make their decisions. Eighty-five percent of all subjects (NV and PFL) relied upon vehicle speed, while more than two third of the subjects (69%) also selfreported that they considered both vehicle speed and distance during the decision making process.

DISCUSSION

Why Is Traffic Gap Judgment Ability Worse in PFL Subjects?

Subjects with significant loss of peripheral field often selfreport problems with mobility, including crossing the street.[1,4] Our subjects were no exception, with all PFL subjects reporting street crossing as "moderate to extremely difficult." To be safe when crossing the street, pedestrians need to identify a crossable gap which involves traffic gap judgment and decision making on the traffic conditions, and then physically crossing the street. This entire process is time dependent because the environment is constantly changing. Our study focused on the first step of crossing the street—traffic gap judgment and decision making. Despite the small sample size, the traffic gap judgment ability in the PFL subjects was significantly worse than in NV subjects with lower accuracy in identification of crossable gaps, combined with a higher percent of gap identification errors (Fig. 3). While missing a crossable gap results in longer waiting time and possible inconvenience, an inaccurate decision, identifying a gap that is too short, creates a serious safety issue. The poor judgment with identifying a crossable gap by the PFL subjects raises important concerns for their safety if they ever do attempt to cross the street. Here, we explored the possible reasons accounting for the poor traffic gap judgment performance in the PFL subjects in two areas: visual and nonvisual.

To understand if visual behavior may account for the gap detection differences between these groups, we compared their eye movements and fixation behavior. The PFL subjects used a different approach to scanning and sampling the environment. Specifically the PFL subjects scanned over a smaller area than the NV subjects by an average difference of 28.3°.[2] This finding was supported by a recent study[10] showing that PFL subjects did not increase their scanning to compensate for missing peripheral vision information during walking. Instead, their horizontal scanning was actually reduced. In addition to a reduced scanning area, the PFL subjects distributed 41% of their fixations on environmental features that appeared to be irrelevant to the task of making accurate gap judgments, with only 59% of their fixations on important features of the environment, the source of the danger (i.e., vehicles), and street crossing elements. The reduced scanning area and fewer fixations on relevant elements may have resulted in insufficient visual information being acquired for making accurate gap judgments, resulting in poor traffic gap judgment ability in the PFL subjects.

The heterogeneous findings of traffic gap judgment in the PFL group showed that Sub 11 and 12 performed much worse than the other PFL subjects. Not only did they identify very few crossable gaps ($<$35%), but also they made many more errors ($>$75%). All PFL subjects had a binocular visual field of $<$20°, but why was the poor traffic gap judgment performance more pronounced in Sub 11 and 12? Vision measures in Table 1 showed that distance acuity ($\geq$0.58 logMAR), contrast sensitivity ($\leq$1.0 log) and visual field ($\leq$6°) for these 2 subjects were worse than the other PFL subjects. The combination of vision deficits in these two subjects might result in a greater reduction of information resolution and a corresponding increase in the challenges of acquiring information. It may be that the combination of deficits on multiple vision measures is an important element affecting their traffic gap judgment ability.

Crossing the street is a high risk activity where an error in judgment can result in injury or loss of life in severe circumstances. Because of the high risk, we hypothesized this activity involves more than visual behavior. In this study, we used selfreport questionnaires to explore the possibility of nonvisual factors such as street-crossing behavior, habitual approach to street crossing, and perceived difficulty in the decision-making process. Our question on street crossing behavior did not enhance our understanding of this issue. However, the other two factors—habitual approach to street crossing (independent vs. dependent) and perceived difficulty (from extreme to no difficulty) were significantly correlated with traffic gap judgment performance. Fewer crossable gaps were identified and more errors were made by subjects who selfreported more difficulty in street crossing as well as in subjects who did not cross the street independently. However, there were 2 PFL subjects who did not follow this association (Table 2). Despite selfreporting extreme difficulty when crossing the street and not crossing the street independently, the traffic gap judgment ability for these 2 PFL subjects (Sub 9 and 10) was not different from the other PFL subjects who did cross independently (e.g., Sub 6 and 7). It is unclear why these 2 PFL subjects do not cross the street. One possible explanation is the fear of not having all the available information required for street crossing, and the associated consequences of a wrong crossing decision. Another possibility is simply that subjects become risk averse to the point where they do not cross the street even though their traffic gap judgment ability is not severely compromised. Moreover research is needed to address these issues.

In summary, our findings reveal that both visual and nonvisual factors significantly account for the poor traffic gap judgment ability in the PFL subjects. It is assumed that as vision loss progresses toward total blindness, some visually impaired subjects will increase their use of auditory information as a cue to assess traffic and make traffic gap judgments. We do not know if, or how, audition affects performance of this task. Before discussing the clinical implications from our findings, we reviewed the limitations in this study.

Contrary to our expectation that very few errors would be made by subjects with NV, our NV subjects made a surprisingly high percentage of errors (39%). Although higher percentage of errors was reported in this study than in Guth et al.,[8] NV subjects in other studies also made some "potentially risky judgments."[18,19] We propose that two reasons for the differences in performance are the complex (traffic from both directions) uncontrolled mid-block crossing, and the more conservative definition of crossable gap adopted in our study. Compared with the roundabout used by Guth et al.[8] which used 2 lanes with one-way traffic, the 4 lanes with two-way traffic in our study was more complex. The introduction of two way traffic introduces the unpredictability of driver behavior, while the increase in the number of lanes increases the difficulty in perceptual judgment in crossing distance and gap duration. Hence, it was not surprising that a higher percentage of errors were found in our NV subjects. In habitual street crossing, pedestrians may define a crossable gap whenever the crosswalk is directly in front of them, rather than the entire width of the crosswalk, is clear of vehicles. By comparison, our study used a more conservative definition of crossable gap, requiring sufficient time to walk to the other side of the street without any vehicles from either direction entering the crosswalk. It is possible that the traffic gap judgment ability is better when a less complex crossing is used and when a less stringent definition of crossable gap is used. The major purpose of our study was to compare the relative differences in gap detection and errors made by the different groups. The significantly higher percentage of errors made by the PFL subjects, which was 1.5 times of that made by the NV subjects, undoubtedly suggests that PFL subjects are at substantially greater risk when crossing the street. It is possible that traffic gap judgments represented by the indicator approach might be different from the result of having the subjects actually crossing the street. This issue has been addressed by Ashmead et al.[18] who reported that results obtained from an indicator-task method were comparable with those from actual street crossing in blind and fully-sighted pedestrians. This indicates that the indicator approach is sensitive enough to reflect subjects' traffic gap judgment decision.

Clinical Implications

Clinical implications of our findings include three areas. First is the awareness of the compromised traffic gap judgment ability by the subjects with PFL. Although PFL subjects reported difficulty when crossing the street, their perceived difficulty in traffic gap judgment was less than their judgment about crossing the street. The underestimated difficulty in traffic gap judgment and the reduced traffic gap judgment performance suggests that clinicians should educate the PFL subjects that their traffic gap judgment ability may be reduced, and that training may be needed to safely manage independent street-crossing. Second is the recommendation that PFL subjects minimize the risk in street crossing. For an uncontrolled mid-block crosswalk used in this study, undetected vehicles might approach the pedestrians during crossing or drivers might fail to stop or yield if the pedestrians intended to rely on drivers to see or avoid them.[20] Hence, the clinicians could recommend that PFL subjects choose to cross at an intersection where there is better traffic control (e.g., a traffic signal or stop sign) or to cross where there is a splitter island, which requires monitoring of traffic from one direction. Third is the referral of PFL patients, in particular those with associated deficit in acuity and contrast sensitivity, to orientation and mobility (O&M) instructors for evaluation of street crossing and mobility performance and perhaps training if required. Four of our eight PFL subjects participated in some O&M training, which involves teaching new skills and techniques for safe and efficient travel to compensate for their perceived difficulty in street crossing. Training details were not assessed in this study, but it appeared that subjects who received training were more likely to safely manage independent-street crossing. Recently, a virtual environment to simulate street crossings has been used to train poststroke subjects.[21,22] The preliminary results with the use of the simulator are promising. When improvements are made to the quality of the simulated environment, this technology could be applied to O&M training for low vision subjects under various types of street crossing scenarios. This training enables the subject to learn the techniques required to be a skilled pedestrian—scanning of the environment to examine traffic conditions, walking speed and personal margin of safety, and to make an accurate crossing decision, while minimizing their risk.

ACKNOWLEDGMENTS

We thank Prof Kathy Turano, Dr Richard Long, and Dr Dan Ashmead for their consultations on our experimental design. We thank the reviewers' for their constructive comments on revising this manuscript.

This research was funded by the National Eye Institute, National Institutes of Health grant EY12984 to Dr Richard Long of Western Michigan University.

Data were presented at Vision 2005, the Eighth International Conference on Low Vision, London, United Kingdom.

Received November 7, 2006; accepted September 18, 2007.

REFERENCES

1. Turano KA, Geruschat DR, Stahl JW, Massof RW. Perceived visual ability for independent mobility in persons with retinitis pigmentosa. Invest Ophthalmol Vis Sci 1999;40:865–77.
2. Turano KA, Geruschat DR, Quigley HA. Getting around with vision impairment. In: 15th Biennial Eye Research Seminar Book. New York: Research to Prevent Blindness; 1999. Available at: http://www.rpbusa.org/library_content.php?document_id=48. Accessed September 20, 2007.
3. Guth DA, Rieser JJ. Perception and the control of locomotion by blind and visually impaired pedestrians. In: Welsh RL, Blasch BB, Weiner WR, eds. Foundations of Orientation and Mobility. New York: American Foundation for the Blind;1997:9–38.
4. Geruschat DR, Turano KA, Stahl JW. Traditional measures of mobility performance and retinitis pigmentosa. Optom Vis Sci 1998;75: 525–37.
5. De l'Aune WR, Welsh RL, Williams MD. A national outcomes assessment of the rehabilitation of adults with visual impairments. J Vis Impair Blind 2000;94:281–91.
6. Geruschat DR, Hassan SE, Turano KA. Gaze behavior while crossing complex intersections. Optom Vis Sci 2003;80:515–28.
7. Connelly ML, Conaglen HM, Parsonson BS, Isler RB. Child pedestrians' crossing gap thresholds. Accid Anal Prev 1998;30:443–53.
8. Guth D, Long RG, Ponchillia P, Ashmean D, Wall R. Non-visual Gap Detection at Roundabouts by Pedestrians who are Blind: A Summary of the Baltimore Roundabouts Study. Washington, DC: U.S. Access Board; 2001. Available at: http://www.access-board.gov/research/roundabouts/research-summary.htm. Accessed September 20, 2007.
9. Turano KA, Geruschat DR, Baker FH, Stahl JW, Shapiro MD. Direction of gaze while walking a simple route: persons with normal vision and persons with retinitis pigmentosa. Optom Vis Sci 2001; 78:667–75.
10. Vargas-Martin F, Peli E. Eye movements of patients with tunnel vision while walking. Invest Ophthalmol Vis Sci 2006;47:5295–302.
11. Ferris FL III, Kassoff A, Bresnick GH, Bailey I. New visual acuity charts for clinical research. Am J Ophthalmol 1982;94:91–6.
12. Lovie-Kitchin JE, Bailey IL. Task complexity and visual acuity in senile macular degeneration. Aust J Optom 1981;64:235–42.
13. Pelli DG, Robson JG, Wilkins AJ. The design of a new letter chart for measuring contrast sensitivity. Clin Vision Sci 1988;2:187–99.
14. Elliott DB, Whitaker D, Bonette L. Differences in the legibility of letters at contrast threshold using the Pelli-Robson chart. Ophthalmic Physiol Opt 1990;10:323–6.
15. Elliott DB, Sanderson K, Conkey A. The reliability of the Pelli-

Robson contrast sensitivity chart. Ophthalmic Physiol Opt 1990;10: 21–4.
16. Turano KA, Geruschat DR, Baker FH. Oculomotor strategies for the direction of gaze tested with a real-world activity. Vision Res 2003; 43:333–46.
17. Rothman KJ. No adjustments are needed for multiple comparisons. Epidemiology 1990;1:43–6.
18. Ashmead DH, Guth D, Wall RS, Long RG, Ponchillia PE. Street crossing by sighted and blind pedestrians at a modern roundabout. J Transport Eng 2005;131:812–21.
19. Guth D, Ashmead D, Long R, Wall R, Ponchillia P. Blind and sighted pedestrians' judgments of gaps in traffic at roundabouts. Hum Factors 2005;47:314–31.
20. Sauerburger D. Street crossings: analyzing risks, developing strategies, and making decisions. J Vis Impair Blind 2005;99:659–62.
21. Boian RF, Burdea GC, Deutsch JE, Winter SH. Street crossing using a virtual environment mobility simulator. Paper presented at the 3rd International Workshop on Virtual Rehabilitation Lausanne, Switzerland, September 16, 2004. Available at: http://www.caip.rutgers.edu/vrlab/publications/papers/2004_iwvr_boian.pdf. Accessed September 20, 2007.
22. Katz N, Ring H, Naveh Y, Kizony R, Feintuch U, Weiss PL. Interactive virtual environment training for safe street crossing of right hemisphere stroke patients with unilateral spatial neglect. Disabil Rehabil 2005;27:1235–43.

Allen M. Y. Cheong
Department of Psychology
University of Minnesota
75 East River Road, N218 Elliott Hall
Minneapolis, MN 55455
e-mail: cheon015@umn.edu