Are Normally Sighted, Visually Impaired, and Blind Pedestrians Accurate and Reliable at Making Street Crossing Decisions?

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PURPOSE. The purpose of this study is to measure the accuracy and reliability of normally sighted, visually impaired, and blind pedestrians at making street crossing decisions using visual and/or auditory information.

METHODS. Using a 5-point rating scale, safety ratings for vehicular gaps of different durations were measured along a two-lane street of one-way traffic without a traffic signal. Safety ratings were collected from 12 normally sighted, 10 visually impaired, and 10 blind subjects for eight different gap times under three sensory conditions: (1) visual plus auditory information, (2) visual information only, and (3) auditory information only. Accuracy and reliability in street crossing decision-making were calculated for each subject under each sensory condition.

RESULTS. We found that normally sighted and visually impaired pedestrians were accurate and reliable in their street crossing decision-making ability when using either vision plus hearing or vision only ($P > 0.05$). Under the hearing only condition, all subjects were reliable ($P > 0.05$) but inaccurate with their street crossing decisions ($P < 0.05$). Compared to either the normally sighted ($P = 0.018$) or visually impaired subjects ($P = 0.019$), blind subjects were the least accurate with their street crossing decisions under the hearing only condition.

CONCLUSIONS. Our data suggested that visually impaired pedestrians can make accurate and reliable street crossing decisions like those of normally sighted pedestrians. When using auditory information only, all subjects significantly overestimated the vehicular gap time. Our finding that blind pedestrians performed significantly worse than either the normally sighted or visually impaired subjects under the hearing only condition suggested that they may benefit from training to improve their detection ability and/or interpretation of vehicular gap times. (*Invest Ophthalmol Vis Sci.* 2012; 53:2593–2600) DOI:10.1167/iov.11-9340

Pedestrian safety is an important issue. Transport authorities are committed to making the task of crossing the street safer and easier for pedestrians, while at the same time ensuring traffic flow is not unduly interrupted. Crossing the street is an “everyday task.” However, it is a complex, difficult, and dangerous task that can be affected by many variables, such as the viewing and auditory environment of the street,¹ number of pedestrians crossing the street, and the previous street crossing experiences of the pedestrian. In the United States alone in 2009, a total of 4,092 pedestrians died in traffic accidents, with 24% of these deaths occurring at an intersection.²

A pedestrian’s safety when crossing a street without a traffic signal relies partially on two main decision variables: (1) the time it will take them to cross the street (i.e., their street crossing time), and (2) the time available before the next vehicle reaches them (i.e., the vehicular gap time). If a pedestrian estimates the two decision variables accurately, they display good street crossing decision-making skills. However, if the pedestrian misjudges either or both decision variables, then they have the potential to make an unsafe street crossing decision or are forced to wait longer by the curb because of missed crossing opportunities.

Many of the earlier street crossing studies are limited by their use of criterion-dependent measures.^{3–6} In these studies, subjects dichotomized vehicular gap times as being either “safe” or “unsafe” to cross the street. A safe gap is a vehicular gap time that exceeds the subject’s street crossing time, while the converse is true for an unsafe gap time. Subjects then were required to indicate which of the presented vehicular gap times they felt were safe and unsafe. The results from these studies, however, will vary across and between subjects because everyone has a different definition of what they believe is safe and unsafe.

Collectively, these previous studies demonstrate that visually impaired⁴ and blind^{3,5,6} pedestrians make significantly more unsafe street crossing decisions and identify significantly fewer crossable gaps compared to normally sighted pedestrians. While these earlier studies show the negative impact of vision loss on a pedestrian’s ability to make safe street crossing decisions, they fail to explain the underlying causes of these inaccuracies. A new metric developed by Hassan and Massof⁷ has an advantage over previous street crossing studies because it can quantify, using criterion-free methods, how well pedestrians can discriminate different vehicular gap times irrespective of their personal decision-making criteria.

In this study, we used our new metric to measure the accuracy (bias) and reliability of street crossing decisions made by normally sighted, visually impaired, and blind subjects under three sensory conditions: (1) visual plus auditory information (V+H), (2) visual information only (V-only), and (3) auditory information only (H-only).

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METHODS

Subjects

A total of 12 normally sighted, 10 visually impaired, and 10 blind subjects participated in the study. The normally sighted and visually impaired subjects' details have been reported previously.⁷ In summary, the normally sighted subjects were recruited from the community or through a relationship with another subject. The visually impaired and blind subjects were recruited from the Wilmer Eye Institute's Low Vision Clinic at the Johns Hopkins University. There were no significant differences in age among the three subject groups (1-way ANOVA, $F_{(2,29)} = 1.91$, $P = 0.17$).

Each subject in this study had their visual acuity (VA), contrast sensitivity (CS), and visual field (VF) assessed. The average results of these tests for each subject group are listed in Table 1. The blind subjects in this study either had no vision (i.e., two prosthetic eyes) or light perception only.

An Early Treatment Diabetic Retinopathy Study (ETDRS) acuity chart⁸ was transilluminated to approximately 100 candelas per square meter (cdm^{-2}) and used to measure each subject's right and left eye VA. The VA's were reported as the logarithm of the minimum angle of resolution (log MAR) using the scoring of Bailey et al.⁹ As expected, the VAs in the better eye of the normally sighted subjects were significantly better compared to the visually impaired subjects (Wilcoxon Rank Sums Test $z = 3.93$, $P < 0.0001$).

Contrast sensitivity in each eye was measured using the Pelli-Robson letter contrast sensitivity chart¹⁰ at 1 m with overhead illumination of 85 cdm^{-2} and scored using the method of Elliott et al.^{11,12} The CS values in the better eye of the normally sighted subjects were significantly better than that of the visually impaired subjects (Wilcoxon Rank Sums Test $z = -3.83$, $P < 0.0001$).

Monocular VFs were assessed using kinetic perimetry with a Goldmann perimeter (III4c target on a background luminance of 10 cdm^{-2}). The VF was measured along 24 meridians from radii of 70° vertically and 90° horizontally. Subjects were instructed to fixate on a central target located inside the bowl of the Goldmann perimeter. Subjects with central field loss were encouraged to maintain steady fixation, presumably with their preferred retinal locus (PRL), during the VF assessment. VF extent and the position of any central scotoma were recorded for all subjects and reported as the average VF extent (radius) across all meridians from the better eye. The VF in the better eye of the normally sighted subjects was significantly better compared to that of the visually impaired subjects (Wilcoxon Rank Sums Test $z = -2.43$, $P = 0.015$).

With the exception of eight subjects, all subjects' hearing was assessed by an audiologist using a pure tone air conduction threshold test in a sound-attenuated room. The hearing assessment required subjects to wear circumaural headphones and press a button whenever they heard a pure tone, which was presented at each of the following frequencies: 500, 1000, 2000, 4000, 6000, and 8000 Hz. The frequency-specific tones were generated by a clinically calibrated portable audiometer (Maico MA; MAICO Diagnostics, Eden Prairie, MN). Each pure tone was presented initially at 40 decibels (dB) with the intensity decreasing by 10 dB steps to determine thresholds (50%

response rate). Normal hearing was defined as pure tone thresholds of 25 dB or less bilaterally for the frequency range measured in this study.

Due to scheduling conflicts, five visually impaired and two blind subjects did not have their hearing assessed. However, these subjects all self-reported having normal hearing and had no history of using auditory assistive devices, or no significant injuries or infections to their ears. An analysis of the street crossing data of the eight subjects who did not have their hearing tested revealed no significant differences in their results compared to subjects who had normal hearing.

For this study, all subjects had to self-report that they crossed streets without assistance regularly and they were unfamiliar with the intersection used in the study. The blind subjects must have had orientation and mobility (O&M) training; however, none of the blind subjects used a guide dog. Through questioning and from informal observations during the course of the study, any subject with a presence or history of a physical or cognitive disorder that affected their walking or cognitive abilities was excluded.

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

Street Test Site

The test site used in this study has been described previously.⁷ In summary, the street selected for this study was located within Baltimore City, Maryland, United States and consisted of six lanes; 3 lanes on either side of a 1.75 m wide median strip (Fig. 1). The outer third lane on either side of the median strip was a parking lane for vehicles. Subjects stood along the curb on one side of the median strip at a location called the crossing point. Therefore, street crossing decisions were made from the crossing point with traffic approaching from just one side of the street. The width of the street from the crossing point to the parked vehicles in the parking lane was approximately 6.5 m. The location of the crossing point did not change throughout the study.

Measurement of Vehicular Gap Times

Four custom-made sensors, positioned approximately 213, 200, 12, and 0 m to the right of the crossing point, were used to compute the vehicular speeds and gap times of approaching vehicles. The sensors' design and methods used to record vehicular speeds and gap times have been described previously.⁷ In summary, each sensor system consisted of a low-powered laser ($<5 \text{ mW}$) positioned along the curb on one side of the street and its beam was aligned with a photodetector positioned along the curb on the median strip. The laser and photodetector were positioned at a height of approximately 50 cm above the curb using tripods. Pilot data showed that at this height, the path of the laser beam was, on average, at the approximate height of a passing vehicle's bumper bar. The two farthest sensors wirelessly sent their recorded information to a portable computer, while the two closest sensors were connected to the same portable computer via serial cables.

TABLE 1. Subject Characteristics

Subject Group	# Subjects	Age (years)*	Parameter in Better Eye*		
			Visual Acuity (log MAR)	Contrast Sensitivity (log CS)	Average VF Extent (degrees)
Normally sighted	12	39.02 ± 16.74	-0.09 ± 0.11	1.83 ± 0.09	65.27 ± 4.16
Visually impaired	10	42.73 ± 12.33	1.04 ± 0.16	0.85 ± 0.54	52.27 ± 15.27
Blind	10	50.36 ± 10.47	Light perception	NA	NA

NA, not applicable.

* Results listed as average ± 1 SD.

FIGURE 1. The street crossing test site used in this study.

Each photodetector was housed within a water- and light-proof box approximately 15 by 15 cm in size. At the front of each box were two identically-sized apertures that were orientated vertically with respect to each other. Positioned behind each aperture were two identical optical systems that directed and focused entering light, by use of a 33 D Fresnel lens and translucent diffuser, through the aperture onto the photodetectors positioned at the rear of the box. The photodetectors continuously recorded the incident light intensity and sent their outputs to a portable computer.

The bottom optical path was exposed to ambient (environmental) light as well as to the light emitted from the laser. The top optical path was exposed to ambient light only. The photodetectors were calibrated so that their recordings were matched for the ambient illumination. During an experimental trial, readings from the top photodetector were subtracted from the intensity readings from the bottom detector, with the difference representing the intensity of the laser light, which improved detection of the interruption of the laser beam by a moving vehicle.

When the path between the laser and photodetector was broken by an approaching vehicle, the event was recorded, time stamped and sent (either wirelessly or by serial cable depending on the location of the sensor) to the portable computer. Vehicular velocity was computed by dividing the known distance separating two adjacent sensors by the time difference between the two sensor signals. The physical gap time was calculated as the difference between the time the prompt signal was given (see Experimental Procedure for an explanation of the

prompt signal) and the time the approaching vehicle was first detected by the sensor system positioned by the crossing point.

Experimental Procedure

The experimental procedure used to record subjects' street crossing decisions has been described previously.⁷ In summary, upon arrival at the test site, subjects crossed the street four times at their usual street crossing pace accompanied by an experimenter. This provided subjects with information about the distance and the time required to cross the street physically. The subject's crossing time also was used when analyzing the accuracy of each subject's street crossing decisions.

Up to four subjects could be assessed concurrently. To ensure that a subject's vision and hearing were not obstructed by another participating subject, each subject's position was staggered around the crossing point such that subjects stood either in front of or off to the side of the subject standing next to them.

While subjects stood by the crossing point, an audible "get ready" signal was given after which subjects were instructed to "view" and/or "listen" to gaps in vehicular traffic for a given period of time. At the end of this period, an audible "prompt" signal was given upon which subjects were required to rate, using a 5-point rating scale, his/her perception of whether or not there was enough time to cross, with a rating of "1" indicating definitely not enough time, "2" probably not enough time, "3" unsure whether or not there was enough time, "4" probably enough time, and "5" definitely enough time to cross at the

time of the prompt signal. By pressing a button the same number of times corresponding to the desired rating number, subjects were able to give their ratings in secret (relative to the other subjects). The button press apparatus was attached to a portable computer, which enabled the number of button presses to be recorded automatically for each subject and trial using custom software.

Safety ratings were collected for eight different vehicular gap times binned in 1 second increments commencing from 0 to 1 second (labeled as gap time category "1") with the final gap time category classifying all vehicular gap times equal to or longer than 7 seconds as gap time category "8." The vehicular gap time was defined as the duration, in seconds, between the prompt signal and when the first approaching vehicle reached the crossing point. The prompt signal was given by the experimenter when he/she judged, from the speed and distance of the approaching vehicle, that the time between when the prompt signal was given to when that vehicle reached the crossing point fell within the gap time bin that was to be assessed. A minimum of 10 trials were collected for each gap time bin.

Ratings for all gap time bins were collected under three sensory modality conditions: (1) habitual vision plus habitual hearing (V+H), (2) habitual vision only (V-only), and (3) habitual hearing only (H-only). For the sensory condition of V+H, subjects stood by the crossing point as they were. For the V-only condition, subjects wore foam ear inserts along with noise-cancelling headphones that played white noise. With this setup, subjects could "see" the street crossing environment but not "hear" any information, except for the get ready and prompt signals, which were delivered through the headphones. For the H-only condition, where subjects could hear and listen to all available auditory information but not "see" any information, subjects stood by the crossing point with their eyes closed. Throughout the duration of the H-only trials, the experimenter constantly monitored and reminded subjects to keep their eyes closed.

Subjects also were instructed to give their rating immediately following the prompt signal (to prevent additional sampling of sensory information), assume that they were crossing the street at their regular walking pace, never assume that the approaching vehicle(s) will slow down or yield to them, and never give a response (rating) when something prevented them from making a judgment (e.g., a lapse in attention or they sneezed).

Experimental trials were run only when the experimenter believed that there was minimal interference from masking sounds, since this could interfere with a subject's ability to make street crossing decisions. If during the trial there was a sudden change in background noise (e.g., a paramedic siren went off during the trial), the trial was aborted by issuing an audible "cancel" signal and not used in any analysis of data.

Practice trials to familiarize subjects with the experimental task were given before the collection of any ratings data. Test sessions were conducted only on days with clear weather and never on days when there was fog, snow, or rain (including drizzle), or when it was dark. All data collection occurred during off-peak traffic hours, typically between 11 AM and 4 PM, and the average $\pm$ SD temperature across all test days was $20.9 \pm 6.9^\circ\text{C}$.

Data Analysis

Each subject's actual street crossing times were averaged and this measure was used later to determine the amount of bias (accuracy) in subjects' street crossing decisions.

The measurement parameters used to assess the accuracy (bias) and reliability in each subject's street crossing decision-making ability have been developed and validated previously.⁷ In summary, Receiver Operating Characteristic (ROC) curves were estimated for all possible gap pairs within each sensory condition for each subject using the street crossing ratings data. The area under each ROC curve then was calculated for all gap pairs and sensory conditions, and the result converted to a z score to give the discrimination ability (d') of the street crossing decision variable for each subject and sensory

condition. There were a total of 28 gap pairs and, hence, 28 d' values for each subject and sensory condition. All 28 d' values for a given subject and sensory condition were inputted into a one-dimensional scaling model (i.e., a Guttman loss function), and the means of each distribution of the decision variable for the eight different gap time categories were estimated relative to a "center of gravity" (COG).

The estimated means of the eight distributions of the decision variable relative to the COG then were plotted against gap time for each sensory condition, and the best fitting nonlinear function was estimated for each subject and sensory condition using nonlinear regression.

Two measurement parameters were calculated from each subject's nonlinear function: (1) the x-intercept, referred to as t_{COG} , and (2) the slope (derivative) of the nonlinear function at t_{COG} . The x-intercept (t_{COG}) represents the gap time at which a subject's response transitions from insufficient to sufficient time to cross (Fig. 2). The slope of the nonlinear function at t_{COG} is an indicator of precision in gap time discrimination. Smaller slope values indicate that relatively larger changes in gap time are needed to obtain a criterion change in the decision variable, and vice versa.

Each subject's level of accuracy in street crossing decision-making was quantified as the amount of bias. Bias was calculated as the difference between a subject's t_{COG} and their measured street crossing time. The closer the bias value is to zero, the better their accuracy. If the bias is positive in value, it suggests less accurate, yet less risky street crossing decision-making ability. This is because subjects classify gap times that are longer in duration than their street crossing time as being "enough time to cross." Conversely, with negative bias, subjects are inaccurate and risky street crossing decision makers, since they classify gap times that are shorter in duration than their actual crossing time as being "enough time to cross."

To assess whether subjects were accurate in their street crossing decision-making, the distribution of bias values for each subject group under each sensory condition was tested if it was significantly different from zero. Multivariate analyses of variance (MANOVA) also were performed to assess for significant differences in bias values between subject groups (normal vision, impaired vision or blind) and sensory conditions (V+H, V-only, and H-only) as well as for any interactions between these factors. Correlations also were performed to assess for any relationship between subjects' bias values and vision measures (VA, CS and VF extent).

The slope of the nonlinear function at t_{COG} was used as an indicator of a subject's reliability in their street crossing decision-making (Fig. 2). A steep slope (large derivative value) suggested a subjects' criterion for crossing shifts quickly over a small range of vehicular gap times. This behavior could be considered as good and reliable street crossing decision-making. The converse was true for subjects with shallow slopes or small derivative values.

To assess the level of reliability in each subject's street crossing decision-making, the distribution of slope values at t_{COG} for each subject group under each sensory condition was tested to determine if there were systematic differences between groups and/or sensory conditions. MANOVA was performed to look for significant differences in slope values at t_{COG} between subject groups (normal vision, impaired vision or blind) and sensory conditions (V+H, V-only and H-only) as well as for any interactions between these factors. Correlations also were performed to assess for any relationship between slope values at t_{COG} and vision measures (VA, CS and VF extent).

From the derived nonlinear functions, the gap times associated with equaling 5% of the lower minimum value (t_{min}) and 95% of the upper asymptote value (t_{max}) also were calculated for each subject and sensory condition. The t_{min} parameter corresponded to the gap time below which was perceived by the subject as representing the same level of unsafe (Fig. 2). Hence, two different gap times that both were shorter than t_{min} were believed to be just as unsafe as each other by the subject, even though one of these gap times was physically shorter than the other. Similarly, t_{max} represented the gap time after which the subject is no longer able to discriminate between different levels of

FIGURE 2. Interpreting the non-linear function as it relates to the experimental task. The center of gravity (COG, of a 1 multi-dimensional scaling model) is the point at which the subject perceives the vehicular gap time is equal to their crossing time. See Hassan and Massof⁷ for more details. t_{COG} , x-intercept of nonlinear function, which is the time at which the COG occurs. t_{min} , time below which subjects do not discriminate different levels of safety with gap time. t_{max} , time above which subjects do not discriminate different levels of safety with gap time.

perceived safety (Fig. 2). All gap times longer than t_{max} were perceived by the subject as being at the same level of safety irrespective of their actual duration. MANOVA was performed to look for significant differences in t_{min} and t_{max} values between subject groups (normal vision, impaired vision, or blind) and sensory conditions (V+H, V-only and H-only) as well as for any interactions between these factors. Similar trends were found for t_{min} and t_{max} values associated with equaling 20% and 10% of the lower minimum value and 80% and 90% of the upper asymptote value, respectively. Consequently, the results of t_{min} and t_{max} values associated with equaling 5% and 95% of the lower minimum value and upper asymptote value respectively were reported in our study.

With the exception of the one-dimensional scaling modeling, which was performed using SYSTAT10 (SYSTAT10, SPSS Inc.), all statistical analyses, including the nonlinear modeling, was performed using JMP 8.0 (JMP8.0, SAS Institute Inc.). Non-parametric statistical analyses were performed on data distributions that were not normal while parametric statistical analyses were performed on normally-distributed data.

RESULTS

Accuracy (Bias) of Subjects When Making Street Crossing Decisions

Table 2 lists the average ($\pm$ SD) bias values for each subject group under each sensory condition. No significant difference in bias values was found between the normally sighted and visually impaired subjects across all sensory conditions (MANOVA, $F_{(1,16)} = 1.22$, $P = 0.73$). Because of this finding, the bias results of the normally sighted and visually impaired

subjects were combined to increase the power of the statistical test assessing whether or not the bias values were significantly different from zero.

The bias values of the combined sample of normally sighted and visually impaired subjects were on average not significantly different from zero under the conditions of V+H ($t_{(1,20)} = 0.83$, $P = 0.42$) and V-only ($t_{(1,19)} = 1.52$, $P = 0.14$). Thus, subjects were relatively accurate at making street crossing decisions under these two sensory modalities, even those subjects who had impaired vision. Under the condition of H-only, however, the bias values of the combined sample of normally sighted and visually impaired subjects were on average significantly different from zero (Wilcoxon Signed-Rank Test, $z = -16.00$, $P = 0.02$). The average bias $\pm$ SD values of the normally sighted and visually impaired subjects under the condition of H-only were -0.35 ± 0.66 seconds and -0.23 ± 0.33 seconds, respectively (Table 2). Because the average bias values were negative in value, this suggests that both subject groups under the H-only condition did not allow themselves enough time to cross.

The blind subjects, under the H-only condition, also had negative bias values (-1.99 ± 1.64 seconds, Table 2) and their bias values were significantly different from zero (Wilcoxon Signed-Rank Test, $z = -16.0$, $P = 0.02$). Thus, like the normally sighted and visually impaired subjects, the blind subjects made unsafe street crossing decisions, since they also did not allow themselves enough time to cross when using only auditory information. Furthermore, the negative bias values of the blind subjects were significantly greater than either the normally sighted (Independent t test, $t_{(1,17)} = -2.67$, $P = 0.03$) or visually impaired subjects (Independent t test, $t_{(1,13)} = -2.96$,

similar across the different subject groups and sensory conditions.

DISCUSSION

The study's findings suggest that normally sighted and visually impaired subjects using V+H or V-only are able to make accurate street crossing decisions. This is supported by our finding that, under these sensory conditions, the bias values of normally sighted and visually impaired subjects were not significantly different from zero. Furthermore, because we found no significant difference in bias and slope estimates between normally sighted and visually impaired subjects, the visually impaired subjects were just as accurate and reliable as the normally sighted subjects in their street crossing decision-making performance, irrespective of whether the visually impaired subjects were using their impaired vision and normal hearing or simply using only their impaired vision to make street crossing decisions.

The performance of the normally sighted subjects in our study agrees with the conclusions of Bond, who found no significant difference in the proportion of unsafe decisions in normally sighted subjects under the sensory conditions of V+H and V-only.¹³

The findings associated with the performance of our visually impaired subjects do not agree with previous studies that assess traffic gap judgments in visually impaired people. Cheong et al. found that people with severe peripheral VF loss made significantly more errors when identifying crossable vehicular gaps than age-matched subjects with normal vision.⁴ Norton and Roberts found that parents with children aged 15 years and younger with reported abnormal vision were four times more likely to have a pedestrian injury compared to children with reported normal vision.¹⁴

A possible reason for the disagreement between our study and that of Cheong et al.⁴ may be differences in the type of vision loss associated with the visually impaired subjects investigated in each study. The average VA and VF extent (radius) in the better eye of our visually impaired subjects were 1.04 log MAR (20/200⁻²) and 52.27°, respectively. In contrast, Cheong et al.'s visually impaired subjects had an average binocular VA and VF (radius) of 0.30 Log MAR (20/40) and 5.4°, respectively.⁴ Therefore, the visually impaired subjects who participated in our study were legally blind because of their VA as opposed to their VF extent, while the opposite was true for Cheong et al.'s subjects.⁴

With moving vehicles being large objects that contain a lot of low spatial frequency information, they are robust to degradations in vision.¹⁵⁻¹⁸ As a result, it is possible that degradations in VA do not affect a person's ability to make street crossing decisions, while a severe peripheral VF loss does. This may explain why we found that our visually impaired subjects still were able to make street crossing decisions accurately and reliably, even when using only impaired vision. This conclusion also is supported by the results of Geruschat et al., who found that subjects with VA loss from age-related macular degeneration (AMD) performed similarly to normally sighted subjects in correctly identifying crossable and short gaps.¹⁹

It also appears that the minimum VF size required to make accurate and reliable street crossing decisions lies between a 5.4° and 52.27° radius – the radii of the VF extents of the visually impaired subjects in the study of Cheong et al.⁴ and our studies, respectively. Further research is required to determine systematically how small the VF extent can be before a person no longer is able to detect crossable vehicular gaps accurately and reliably.

Under the H-only condition, the bias values of the normally sighted, visually impaired, and blind subjects were significantly different from zero. As a result, all subjects were less accurate when their street crossing decision was limited to using only auditory information. We also found that the visually impaired subjects were just as inaccurate in their street crossing decisions as the normally sighted subjects. No significant differences, however, were found in the reliability of decisions made as a function of subject group under the H-only condition. Therefore, while all subjects were consistent in their decision-making behavior, they all were inaccurate with their decisions.

In addition to being less accurate under the H-only condition, all subject groups displayed negative bias values. Since the same street was used for all data collection, we assumed subjects' estimate of their own crossing time would not change under different sensory conditions. Therefore, the negative bias values are interpreted to mean that subjects overestimated the gap time when using only auditory information. As a result, subjects perceived that the gap time was longer than it really was when using only auditory information. Therefore, all subjects under the H-only condition did not allow themselves enough time to cross. We conclude that all subjects displayed less safe street crossing decision-making when using only auditory information.

We also found that the negative bias values of the blind subjects were significantly greater than the bias of either the normally sighted or visually impaired subjects. In fact, the negative bias values of the blind subjects were on average 5½ times worse than that of the normally sighted subjects. These findings suggest that the blind subjects, under the H-only condition, made the least safe street crossing decisions even when compared to normally sighted subjects who had their eyes closed.

Other studies also have shown that, compared to normally sighted subjects, blind people exhibit risky street crossing behavior and make unsafe street crossing decisions. Guth et al.⁵ and Ashmead et al.³ reported that blind pedestrians make a higher percentage of unsafe gap determinations and are more likely to miss detecting a crossable gap compared to age-matched subjects with normal vision. Given the findings of these earlier studies and the results of our study, where the blind subjects previously had received some form of orientation and mobility training, we advocate that the safety of blind pedestrians be increased by referring them for specific orientation and mobility training in the area of street crossing. This street crossing training should aim to improve blind pedestrians' estimate of their own crossing time and/or aim to improve their use of auditory information for the better detection and/or interpretation of vehicular gap times. Additionally, we recommend that modifications be made to the street crossing environment that improves the safety of all pedestrians, including blind pedestrians.

We found no significant difference in street crossing decision-making performance between the sensory conditions of V+H and V-only for the normally sighted and visually impaired subjects. Therefore, it appears that the addition of auditory information did not improve significantly subjects' accuracy and reliability in their street crossing decision-making ability above and beyond that achieved when using only visual information. This result confirms the finding of Geruschat et al., who also found no significant difference in visually impaired subjects' traffic gap detection performance between the conditions of V+H and when hearing was occluded.¹⁹

The nonlinear function describing the relationship between the street crossing decision variable and the vehicular gap time suggests that the decision variable is not discriminable across gap times below and above a certain value (gap time). All gap

times below a certain value, quantified in our study as t_{min} , will be classified by the subject as being “insufficient time to cross.” All gap times above a certain value, quantified in our study as t_{max} , will be classified as being “sufficient time” to cross. We found no significant differences in t_{min} or t_{max} values between subject groups or sensory conditions. On average (across subject groups and sensory conditions), subjects assigned all vehicular gap times that were equal to or less than 2.67 seconds in duration as being unsafe. Even if a vehicular gap time would be significantly shorter in duration than the t_{min} value, subjects would not consider this gap time any less unsafe than a gap time equal to the t_{min} value. Gap times that were equal to or greater than 9.51 seconds in duration (the average t_{max} value across all subject groups and sensory conditions), were perceived on average by subjects as representing the same level of safety. Even if the vehicular gap time were double the duration of the t_{max} time, subjects would not rate this longer vehicular gap time as being safer than a gap time equal to the t_{max} time.

In summary, we found that visually impaired subjects were just as accurate and reliable as normally sighted subjects in making street crossing decisions, even when the quality of the sensory information was reduced significantly by impairment. We found that normally sighted, visually impaired, and blind subjects, while reliable, were inaccurate in making street crossing decisions when using only auditory information. The cause of this inaccuracy under the H-only condition appeared to relate to subjects overestimating the vehicular gap time. We found that blind subjects were the least accurate in their street crossing decision-making and, as a result, significantly overestimated vehicular gap times when using auditory information only. The results of our study, however, were found using one specific type of street, that is a two-lane street of one-way traffic. More research is required to assess whether the results of this study hold true for other types of streets and intersections, such as roundabouts and two-way streets.

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