The Mind Cannot Go Blind: Effects of Central Vision Loss on Judging One's Crossing Time

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SIGNIFICANCE: This study explored whether people with AMD can accurately judge the time they need to cross the street. The results suggest that AMD-related vision loss does not affect a person’s ability to estimate his/her own street-crossing time, whereas familiarity with the street does.

PURPOSE: The purpose of this study was to assess whether people with AMD could judge accurately their street-crossing time.

METHODS: Fifty-one AMD subjects and 47 age-matched normally sighted subjects (controls) estimated their time to cross a single-lane, one-way street four times (pre-estimate). Then, subjects actually crossed the street four times and subsequently estimated their crossing time four additional times (post-estimate). A linear mixed model with repeated measures for subject was used to determine if the ratio between subjects’ estimated and actual crossing times changed as a function of subject group (AMD vs. control) and whether estimates changed before and after actually crossing the street. Univariate correlations and multiple regression analyses were also performed to determine which of the measured experimental variables were the best predictors of a subject’s ability to estimate his/her crossing time.

RESULTS: No significant difference in crossing ratios were found between the AMD (average, 1.05) and control (average, 1.16) subjects (P = .11). This was true for both the pre-crossing (AMD, 1.09; controls, 1.23; P = .11) and post-crossing ratios (AMD, 1.01; controls, 1.09; P = .17). Both subject groups’ crossing ratios, however, decreased significantly going from pre to post (P < .0001). Increased age, longer actual crossing time, and experience gained from previously crossing the street resulted in less overestimation of one’s crossing time.

CONCLUSIONS: Our data suggest that familiarity with the street as opposed to central vision loss from AMD affects a person’s ability to estimate his/her crossing time.


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Age-related macular degeneration (AMD) affects the central portion of vision, ranging from blurry central vision1 to an area of complete central vision loss known as a central scotoma.2 Unfortunately, there is no cure for vision lost from AMD, and although currently available treatments slow the progression of the disease, they cannot completely reverse the damage.2,3 The changes in vision from AMD can greatly impact a person’s ability to read,4,5 recognize faces,6 or perform activities of daily living,7 including mobility8–10 and driving.11–14 Loss of driving privileges often leads to decreased independence, quality of life, and depression,15,16 and many people with AMD lose the ability to drive because of macular-related vision loss.11,17 If a person with AMD lives in an area where public transportation is not a feasible option or he/she cannot routinely rely on a network of family, friends, or community services for transportation, he/she may be required to walk. If this person is needing to walk to doctors’ appointments, the grocery store, or just to socialize or exercise, there is a high probability that he/she will need to cross the street.

Crossing the street is a dangerous task, even for the general population. In 2017, 5,977 pedestrians were killed by vehicular accidents in the United States, which equates to approximately one pedestrian death every 88 minutes.18 Twenty percent of all pedestrian fatalities reported for 2017 involved people older than 65 years.18 These findings suggest that, when crossing the street, older pedestrians are vulnerable. This level of vulnerability is further increased when older pedestrians have vision loss from AMD, because people with AMD, compared with normally sighted people of similar age, walk slower,19,20 exhibit cautious gait strategy when negotiating curbs,19 are slower to identify crossable gaps in traffic,21 and have lower safety margins in their street-crossing decisions.21

Given that AMD is the leading cause of blindness in western countries and its prevalence is increasing,22–24 we shall see a dramatic rise in the number of older people with AMD who potentially are at risk when attempting to cross the street.

Crossing a nonsignalized street involves four rudimentary tasks: (1) detection of an approaching vehicle, (2) estimating one’s street-crossing time, (3) judging the approaching vehicle’s time to arrival (gap time), and (4) deciding whether the approaching vehicle’s gap time is longer or shorter in duration than the combined times of one’s crossing time and a safety margin. The majority of previous low vision and street-crossing studies,25–27 including those specifically involving subjects with AMD,28,29 have focused either on how well subjects can discriminate different vehicular gap time durations relative to their perceived crossing time (part of task 4),21,26–28 or on the accuracy and safety of...
subjects’ crossing decisions, which involves combining all four crossing tasks into a single decision variable by having subjects indicate when they would cross the street. Therefore, in the accuracy/safety studies, performance in any one of the street-crossing tasks cannot be singled out. Also, a subject’s performance in all of these earlier street-crossing studies was based in part on his/her ability to estimate his/her own crossing time. Because none of these earlier studies assessed how accurate the subject’s estimated crossing time was relative to his/her actual crossing time, it is unknown whether the results of these earlier studies are confounded by a possible discrepancy between the subject’s estimated and actual crossing time. Knowing how well a person can judge his/her own crossing time is important because this task is fundamental to pedestrian safety.

The current study therefore focused solely on the second task when crossing a nonsignalized street—judging the time needed to cross the street. To our knowledge, no study has directly assessed the accuracy and safety of crossing time judgments in people with AMD or any other cause of visual impairment. The few studies that have assessed the accuracy of crossing time judgments have done so in young and/or older normally sighted subjects. In general, these studies have found that older, normally sighted subjects significantly underestimated their imagined street-crossing time compared with their actual crossing time. Holland and Hiji also found that normally sighted subjects aged between 60 and 74 years underestimated their crossing time, but their normally sighted subjects 75 years or older overestimated their crossing time.

It is possible that the tendency of older pedestrians to underestimate their crossing time may be further exaggerated when the pedestrian is visually impaired. This is because any loss of vision may decrease the pedestrian’s ability to properly see the full width of the street, which in turn may lead to an underestimation of distance and, hence, time required to cross that street.

Given the importance of pedestrian safety, especially for older people with central vision loss from AMD; the expected increase in the number of people with AMD; and that no study has assessed the impact of AMD on street-crossing time judgments, the aims of this study were to assess whether people with AMD could estimate their street-crossing time accurately and to determine how the performance of the AMD subjects compared with that of normally sighted subjects of similar age.

METHODS

Subjects and Preliminary Testing

A total of 98 subjects participated in this study. Fifty-one subjects had either wet or dry AMD, and the remaining 47 subjects were age-matched normally sighted control subjects. Subjects were recruited from the local community and through the eye clinics of the Indiana University School of Optometry. Informed consent was obtained from all subjects, and the study followed the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of Indiana University.

The visual acuity, contrast sensitivity, visual fields, and Mini-Mental State Examination were measured in all subjects, and a summary of their results can be found in Table 1. All subjects wore their habitual spectacle or contact lens prescription during these tests, and there was no significant difference in age between the two subject groups (independent t test, t66 = 1.62; P = .11).

Each subject’s binocular visual acuity was assessed using an Early Treatment Diabetic Retinopathy Study acuity chart, which was transilluminated to approximately 85 cd/m². Each subject’s threshold binocular visual acuity was reported as the logarithm of the minimum angle of resolution using the scoring of Bailey and Lovie. The binocular visual acuity of the AMD subjects was significantly worse compared with the age-matched control subjects with normal vision (independent t test, t66 = 7.66; P < .0001).

An Evans letter contrast sensitivity chart positioned at 1 m was used to measure the binocular contrast sensitivity of each subject. The Evans letter contrast sensitivity chart was transilluminated to approximately 85 cd/m² and consisted of eight lines containing two subject groups (independent t test, t66 = 7.66; P < .0001).

Each subject’s binocular visual field was assessed using a Humphrey Field Analyzer (Haag Streit, Mason, OH) with a standard 30-2 testing strategy. The visual field was assessed for each subject in both eyes using a standard 30-2 testing strategy. The visual field was assessed for each subject in both eyes using a standard 30-2 testing strategy. The visual field was assessed for each subject in both eyes using a standard 30-2 testing strategy.

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An Octopus 900 (Haag Streit, Mason, OH) was used to assess subjects’ binocular visual field using kinetic perimetry. The binocular visual field was assessed along 12 meridians (i.e., every 30°), using a 1148e stimulus against a background luminance of 10 cd/m². Subjects were instructed to maintain fixation on the central fixation target throughout testing. If the central fixation target could not be seen because of any scotoma, subjects were instructed to use eccentric fixation presumably with their preferred retinal locus.

The light stimulus was first positioned at the most extreme eccentricity the machine allowed, which was 70° vertically and 90° horizontally. The stimulus was then moved along a straight line toward the central fixation target at a speed of 5°/s. When subjects first indicated seeing the moving stimulus in their peripheral vision, this point represented the subject’s visual field extent for that meridian. The stimulus then continued along that meridian toward the central fixation target in a straight line. Subjects were then

TABLE 1. Subject characteristics

<table>
<thead>
<tr>
<th>Subject group</th>
<th>n</th>
<th>Age (y)</th>
<th>Binocular VA (logMAR)</th>
<th>Binocular CS (log CS)</th>
<th>Av VF extent radius (°)</th>
<th>Av scotoma area (degrees²)</th>
<th>Av remaining VF area (degrees²)</th>
<th>MMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>47</td>
<td>78.5 ± 7.4</td>
<td>0.03 ± 0.1</td>
<td>1.93 ± 0.3</td>
<td>57.65 ± 13.2</td>
<td>0.00</td>
<td>13,248 ± 1747</td>
<td>29.1 ± 1.2</td>
</tr>
<tr>
<td>AMD, no scotoma</td>
<td>34</td>
<td>80.1 ± 8.6</td>
<td>0.36 ± 0.3</td>
<td>1.56 ± 0.4</td>
<td>57.83 ± 11.8</td>
<td>0.00</td>
<td>11,711 ± 2149</td>
<td>28.4 ± 1.7</td>
</tr>
<tr>
<td>AMD, with scotoma</td>
<td>17</td>
<td>83.3 ± 7.8</td>
<td>0.60 ± 0.4</td>
<td>1.27 ± 0.4</td>
<td>56.01 ± 9.8</td>
<td>127.9 ± 141.7</td>
<td>11,181 ± 1501</td>
<td>28.7 ± 1.4</td>
</tr>
<tr>
<td>AMD total</td>
<td>51</td>
<td>81.1 ± 8.4</td>
<td>0.44 ± 0.4</td>
<td>1.46 ± 0.5</td>
<td>57.22 ± 11.1</td>
<td>42.6 ± 100.7</td>
<td>11,543 ± 1963</td>
<td>28.5 ± 1.6</td>
</tr>
</tbody>
</table>

Results are listed as average ± 1 standard deviation. Av remaining VF area = average remaining kinetic visual field area; Av scotoma area = average scotoma area; Av VF extent radius = average kinetic visual field extent radius; binocular CS = binocular contrast sensitivity; binocular VA = binocular visual acuity; MMSE = Mini-Mental State Examination.

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instructed to indicate when they could no longer see the stimulus because of visual loss in that area. If, after indicating that the stimulus was no longer seen, the stimulus continued toward the central fixation target, and the subject would indicate if he/she regained the ability to see the stimulus. If a binocular scotoma was present, it was mapped in at least the eight principal meridians (at the same speed as for the visual field extent), and scotoma area (in degrees squared) was calculated.

The aforementioned procedure was repeated for all 12 meridians. The average visual field extent radius of each subject was calculated in degrees by averaging the visual field extents found across the 12 meridians. The average scotoma area and visual field extent found for each group is listed in Table 1. As expected, no significant difference in visual field extent was found between the two subject groups (independent t test, \( t_{96} = -0.18; P = .86 \)), but scotoma area of the AMD subjects was significantly larger compared with that of the normally sighted subjects (independent t test, \( t_{96} = 2.90; P < .01 \)).

The Mini-Mental State Examination was used to assess cognitive ability in all subjects. Because a score of 23 (out of 30) or lower suggests cognitive impairment,39 it was used as an exclusion criterion. No subjects, however, were excluded from this study based on their Mini-Mental State Examination score. The Mini-Mental State Examination scores of the AMD subjects were significantly worse than that of the age-matched control subjects with normal vision (independent t test, \( t_{96} = -2.20; P = .03 \); Table 1) possibly because of the vision-based components of the Mini-Mental State Examination. However, the average difference in Mini-Mental State Examination score between the two groups was only 0.6, which is not clinically meaningful, and all subjects’ Mini-Mental State Examination scores were well within the normal range despite the small significant difference between the two groups.

Street Location

The nonsignalized street used in the experiment was a 4.62-m-wide, single-lane street in Bloomington, IN. The subjects stood by the curb of the street at a designated crossing point and made their estimation of crossing times as well as their actual crossing from this location. The street had a steady flow of traffic and was located in a quiet residential area away from highways and construction and had minimal foot traffic, allowing minimal visual and auditory distractors.

Estimated Crossing Times

As subjects stood on the curb of the street, they were given instructions from an experimenter on how to estimate their street-crossing times. When the street was free of traffic, they were instructed to imagine themselves stepping off the curb by saying “start.” The experimenter would then start a stopwatch. When subjects imagined themselves stepping onto the curb on the other side of the street, they would say “stop,” and the experimenter would stop the stopwatch. The duration in seconds between when the subject said start and stop was the duration of the subject’s crossing estimate. These estimates were taken four consecutive times and were called the pre-crossing estimates. Once the pre-crossing estimates had been obtained, the subjects crossed the road four times with the experimenter when the road was free of approaching traffic. The time in seconds of the actual crossing was obtained and recorded. After subjects had crossed the road four times, they again estimated their crossing times. These estimates were taken in the same manner as described previously for the pre-crossing estimates, but this second set of crossing estimates was called post-estimate crossings.

To participate in this study, subjects had to be able to cross the street without the assistance of walking aids such as walkers and canes.

Analysis

For each subject, the four pre-crossing estimates and four post-crossing estimates were averaged to form one pre-crossing estimate and one post-crossing estimate. The four actual crossing times were averaged to form one actual crossing time. The subjects’ ability to judge their crossing time was determined by computing each subject’s crossing ratio. This was done by dividing the subject’s averaged pre-estimated or post-estimated crossing time by his/her averaged actual crossing time, creating a pre-crossing ratio and a post-crossing ratio, respectively. If the calculated crossing ratio was less than one, meaning the averaged estimated crossing time was less than his/her averaged actual crossing time, the subject underestimated his/her actual crossing time. Underestimating your crossing time can potentially lead to an unsafe street-crossing decision. This is because the subject would have perceived the time it takes to cross the street to be less than what it would actually take him/her to cross that street. The converse is true for crossing ratios greater than one.

A linear mixed model with repeated measures for subject was used to determine if subjects’ crossing ratios changed as a function of subject group (AMD vs. control) and whether estimates changed with time (i.e., going from pre to post) and for any interaction between these two main effects. The linear mixed model also assessed whether subjects were accurate in judging their actual crossing time (by assessing whether the model-based crossing ratios were significantly different to one). Post hoc analyses were performed whenever significant effects were found from the linear mixed model. To control for multiple pairwise comparisons, \( P \) values were adjusted using a Sidak adjustment.

Given that having a scotoma is one of the hallmark characteristics of AMD, subjects were further divided into one of three groups: age-matched control subjects with normal vision (n = 47 subjects; Table 1), AMD subjects without a binocular scotoma (n = 34 subjects; Table 1), and AMD subjects with a binocular scotoma (n = 17 subjects; Table 1). To assess the effect of having a binocular scotoma on subjects’ crossing ratios, the linear mixed model described previously was repeated but wherein the subject group now had three levels (controls vs. AMD without a binocular scotoma vs. AMD with a binocular scotoma).

Pearson correlations were used to assess for univariate associations between subjects’ crossing ratios and their age, Mini-Mental State Examination, visual acuity, contrast sensitivity, visual field extent, binocular scotoma size, and their actual crossing time. We also performed a stepwise linear multiple regression analysis to determine which factor(s) (age, Mini-Mental State Examination, visual acuity, contrast sensitivity, visual field extent, whether a binocular scotoma was present, binocular scotoma size, and their actual crossing time) were the best predictors of a person’s ability to judge his/her own crossing time.

Safety was an additional factor that was taken into account when considering the street-crossing estimates. Although the safest crossing estimate is one where the estimated crossing time is longer in duration than the actual crossing time, making the crossing ratio higher than one, it is not the only circumstance to have a safe crossing estimate. For the 4.62-m-wide street assessed in this study, a 2.0-m-wide vehicle (the average width of most sport utility vehicles and minivans in the United States40–42) driving down the center of the road leaves approximately 1.31 m of road on either
side of the vehicle (Fig. 1). For a street-crossing estimate to be considered *minimally safe*, one where the pedestrian is still in the street but not in direct contact with a vehicle if an approaching vehicle reached the subject's crossing point (i.e., the location where the subject was crossing), the pedestrian has to cross the first 1.31-m stretch of road and also the vehicle width before the vehicle reached him/her to not be in physical contact with the vehicle. The remaining 28.2% of the road represents the safe portion of the road where a pedestrian is unlikely to experience harm when attempting to cross the street when the approaching vehicle’s gap time is equal to the pedestrian’s estimated crossing time.

Thus, the pedestrian would traverse at least 71.8% of the actual street width by the time the approaching vehicle reaches them. The remaining 28.2% of the road represents the safe portion of the road where a pedestrian is unlikely to experience harm when attempting to cross the street. An illustration of what could be considered as a minimally safe crossing estimate is shown in Fig. 1.

We categorized subjects’ pre-crossing and post-crossing ratios as being either minimally safe or unsafe based on the criterion detailed previously. We then ran a generalized linear mixed model with a forward stepwise procedure to determine which factor(s) (age, Mini-Mental State Examination, visual acuity, contrast sensitivity, visual field extent, whether a binocular scotoma was present, binocular scotoma size, and the subject’s actual crossing time) were the best predictors of the probability of a subject making an unsafe estimation about his/her actual crossing time.

All statistical analyses were performed and figures were generated with SAS for Windows version 9.4 (SAS Institute, Cary, NC).

**RESULTS**

**The Effect of AMD on Judging Crossing Time**

The crossing ratios of the AMD subjects (average, 1.05) were not significantly different to those of the age-matched control subjects with normal vision (average, 1.16; $F_{1,96} = 2.58; P = .11$; Fig. 2). We did find, however, that subjects’ crossing ratios from pre to post) and for any interaction between these two main effects. Post hoc analyses were performed whenever significant effects were found. To control for multiple pairwise comparisons, $P$ values were adjusted using a Sidak adjustment. This model was then repeated to determine the effect of having a binocular scotoma on the probability of making an unsafe estimation by classifying the subjects into the three groups based on having normal vision or having AMD with or without a binocular scotoma.

We also ran a generalized linear mixed model with a forward stepwise procedure to determine which factor(s) (age, Mini-Mental State Examination, visual acuity, contrast sensitivity, visual field extent, whether a binocular scotoma was present, binocular scotoma size, and the subject’s actual crossing time) were the best predictors of the probability of a subject making an unsafe estimation about his/her actual crossing time.
significantly decreased going from pre-crossing to post-crossing the street \((F_{1,96} = 17.01, P < .0001; \text{Fig. 2})\). This trend was true for both subject groups (nonsignificant time \times subject group interaction, \(F_{1,96} = 0.81, P = .37\)). Specifically, the crossing ratios of the AMD subjects decreased from 1.09 to 1.00 going from pre-crossing to post-crossing the street, thus representing an average decrease in crossing ratio of 9\% \((t_{95} = 2.33, P = .02)\). The age-matched normally sighted subjects had a 14\% average decrease in their crossing ratio going from pre-crossing (average, 1.23) to post-crossing the street (average, 1.09; \(t_{95} = 3.48; P < .001\)).

When looking at the effect of having a binocular scotoma on street-crossing estimates, we found that crossing ratios had a tendency to change as a function of subject group \((F_{2,95} = 2.67, P = .07)\). Specifically, the AMD subjects with a binocular scotoma had a tendency to have lower crossing ratios (average, 0.94) compared with the normally sighted age-matched control subjects (average, 1.16), although this difference only approached statistical significance \((t_{95} = 2.31, P = .07; \text{Fig. 3})\). There was not a significant difference in street-crossing ratios between the AMD subjects without a binocular scotoma (average, 1.11) and normally sighted age-matched control subjects (average, 1.16; \(t_{95} = 0.73; P = .85; \text{Fig. 3}\) or between the AMD subjects with (average, 0.94) and without (average, 1.11) a binocular scotoma \((t_{95} = 1.65, P = .28; \text{Fig. 3})\).

We also found that the crossing ratios changed going from pre-crossing to post-crossing the street \((F_{2,95} = 9.58, P = .003)\), and this effect was similar for the different subject groups (nonsignificant time \times subject group interaction, \(F_{2,95} = 1.44, P = .24\)). Specifically, the crossing ratios of the age-matched control subjects with normal vision significantly decreased going from pre-crossing (average = 1.23) to post-crossing the street (average, 1.09; \(t_{95} = 3.50; P < .001; \text{Fig. 3}\) similarly, the crossing ratios of the AMD subjects without a binocular scotoma also decreased significantly going from pre-crossing (average, 1.16) to post-crossing the street (average, 1.04; \(t_{95} = 2.74; P = .007; \text{Fig. 3}\) No significant difference was found between the pre-crossing (average, 0.94) and post-crossing ratios (average, 0.93) for the AMD subjects with a binocular scotoma \((t_{95} = 0.18, P = .86; \text{Fig. 3})\).

### Can People Accurately Judge Their Own Crossing Time?

Before crossing the street, both the AMD and age-matched control subjects with normal vision were inaccurate with their crossing time judgments. Specifically, before crossing the street, the age-matched normally sighted subjects significantly overestimated their crossing time by 23.1\% \((t_{95} = 4.22, P < .0001; \text{Fig. 2})\), whereas the AMD subjects had a tendency to overestimate their crossing time, on average by 9.3\% \((t_{95} = 1.76, P = .08; \text{Fig. 2})\).

After crossing the street, subjects became more accurate in their imagined crossing time. In particular, the age-matched normally sighted subjects overestimated their post-crossing time by only 9.5\% \((t_{95} = 1.74, P = .09; \text{Fig. 2})\), whereas the AMD subjects overestimated their crossing time by only 0.6\% \((t_{95} = 0.11, P = .92; \text{Fig. 2})\).

When breaking down the AMD subjects based on the presence of a binocular scotoma, we found that AMD subjects without a

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**FIGURE 3.** Box-and-whisker plot illustrating crossing ratios for AMD subjects with and without a binocular scotoma and normally sighted subjects before and after crossing the street. Lower and upper T bars represent ±1.5 times the interquartile range; the lower and upper ends of the boxes represent the 25th and 75th percentile, respectively. The line bisecting the boxes represents the median, whereas the round symbol within the boxes represents the mean. Asterisk symbols (*) outside the boxes represent statistical outliers. The dashed line at crossing ratio 1.0 represents a perfect estimation of crossing time; that is, their estimated crossing time was exactly the same as their actual crossing time to give a ratio of 1.0. Crossing ratio scores above and below 1.0 represent overestimation and underestimation of crossing time, respectively. The dashed line below 1.0 represents an unsafe estimation of crossing time. Controls = age-matched normally sighted subjects.
binocular scotoma significantly overestimated their pre-crossing estimates by 16.8% ($t_{95} = 2.64, P = .01$; Fig. 3). Age-related macular degeneration subjects with a binocular scotoma underestimated their pre-crossing street estimates by 5.81%, although this amount of underestimation was not significant ($t_{95} = -0.65, P = .52$; Fig. 3). After having the experience of actually crossing the street, no subject group, regardless of whether there was a binocular scotoma, had a significant amount of overestimation or underestimation of their street-crossing time ($t_{95} > 0.62, P > .12$; Fig. 3).

What Variables Are Associated with and Best Predict a Subject’s Crossing Ratio?

Significant Pearson correlations were found between subjects’ crossing ratios and age, cognition, and various vision variables (Table 2).

From the stepwise linear multiple regression analysis, we found that the best predictors of how well subjects could judge their own crossing time was whether subjects had the experience of crossing the street ($F_{1,97} = 16.77, P < .0001$), their age ($F_{1,97} = 4.98, P = .03$), and their actual crossing time ($F_{1,97} = 4.93, P = .03$). Specifically, as found in the previously reported linear mixed model, subjects’ crossing estimates are predicted to be more accurate after they have the experience of crossing the street compared with before crossing. We also found a general trend where increased age and actual crossing time (i.e., longer crossing duration) corresponded to less of an overestimation of street-crossing time. Collectively, these three predictor variables accounted for only 15.6% of the variability in crossing ratio.

Are Subjects’ Estimates of Their Crossing Time Safe?

After categorizing subjects’ crossing ratios as either safe or unsafe, we found that 9.8 and 11.8% of AMD subjects made unsafe crossing estimates before and after crossing the street, respectively (Fig. 4). This is compared with the 6.4 and 8.5% of unsafe street-crossing estimates made by the age-matched normally sighted subjects before and after crossing the street, respectively (Fig. 4). Although the AMD subjects made a higher number of unsafe crossing estimates compared with the age-matched normally sighted subjects, the difference was not significant ($F_{1,96} = 0.39, P = .54$), and this trend was true for the percentage of unsafe crossing estimates made both pre-crossing and post-crossing (nonsignificant time × subject group interaction, $F_{1,96} = 0.03, P = .86$). Similarly, although both the AMD and age-matched normally sighted subjects made more unsafe estimates post-crossing compared with pre-crossing, the difference was not significant ($F_{1,96} = 0.74, P = .39$). A summary of these results is illustrated in Fig. 4.

Assessing the effect of a binocular scotoma on the probability of making an unsafe crossing estimate, we found that 5.9% of AMD subjects without a binocular scotoma and 17.7% of AMD subjects with a binocular scotoma made unsafe street-crossing estimates before crossing the street, respectively. After crossing the street, it was found that 11.8% of AMD subjects without a binocular scotoma made unsafe street-crossing estimates as compared with 11.8% AMD subjects with a binocular scotoma. The differences in the percentage of unsafe estimations made between the AMD subjects with and without a binocular scotoma were not significant ($F_{2,95} = 0.43, P = .65$). Similarly, no significant difference was found between the percentage of unsafe estimations made going from pre-crossing to post-crossing the street ($F_{2,95} = 0.45, P = .50$), and this trend was true for both subject groups (nonsignificant time × subject group interaction, $F_{2,95} = 1.32, P = .27$).

What Variables Predict Unsafe Street Crossing Estimates?

After running a generalized linear mixed model with a forward stepwise procedure, the only variable that emerged as a significant predictor of a subject’s probability of making an unsafe street-crossing estimate was age ($F_{1,95} = 4.57, P = .04$). Our model suggests that, as people age, they are more likely to make more unsafe

![FIGURE 4. Bar graph representing the proportion of unsafe street-crossing estimations in AMD subjects and normally sighted controls. Error bars represent ±1 standard error. Controls = age-matched normally sighted subjects.](image)

**TABLE 2.** Correlation matrix listing Pearson correlation coefficients ($r$) between subjects’ crossing ratios, age, cognition, vision variables, and actual crossing time

<table>
<thead>
<tr>
<th></th>
<th>Age (y)</th>
<th>MMSE</th>
<th>Binocular VA (logMAR)</th>
<th>Binocular CS (log CS)</th>
<th>Av binocular VF extent radius (°)</th>
<th>Binocular scotoma area (degrees²)</th>
<th>Actual crossing time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-crossing</td>
<td>−0.25*</td>
<td>0.16</td>
<td>−0.16</td>
<td>0.16</td>
<td>0.09</td>
<td>−0.18</td>
<td>−0.30†</td>
</tr>
<tr>
<td>Post-crossing</td>
<td>−0.37†</td>
<td>0.14</td>
<td>−0.20</td>
<td>0.2†</td>
<td>0.16</td>
<td>−0.14</td>
<td>−0.31†</td>
</tr>
</tbody>
</table>

* $P < .05$, † $P < .01$. Av binocular VF extent radius = average binocular visual field extent radius; binocular CS = binocular contrast sensitivity; binocular VA = binocular visual acuity; MMSE = Mini-Mental State Examination.
estimates of their street-crossing time. This model, however, accounted for only 9.6% of the variability in the probability of a pedestrian making an unsafe street-crossing estimate.

**DISCUSSION**

No significant differences in the ability to judge crossing time or the safety of crossing time judgments were found between the subjects with AMD and those of similar age with normal vision. This was true irrespective of whether the crossing judgments were made before or after crossing the street. These findings suggest that having central vision loss from AMD does not affect a person's ability to judge the amount of time he/she needs to cross the street.

Possible reasons as to why no differences in performance were observed between the two subject groups include the fact that many of the AMD subjects in this study had only mild vision loss (on average, 20/55; Table 1). It is possible that crisp, clear central vision is not needed to accurately judge the width of a street or make an estimate on how long it would take them to cross that street. Indeed, visual acuity and scotoma size, the main indices of central vision loss measured in this study, were not found to have any association with street-crossing estimates.

Our finding that crossing time judgments were affected in only those subjects who had a binocular scotoma suggests that greater amounts of central vision loss negatively affect crossing time judgments. The average visual acuity and range (minimum to maximum) of the age-matched normally sighted subjects and the AMD subjects without and with a binocular scotoma in this study were approximately 20/20 (2012-1 to 20/50+1), 20/50-2 (20/16 to 20/160-5), and 20/80 (20/30+2 to 20/500-1), respectively (Table 1). Thus, the subjects in the present study with the greatest amount of central vision loss, the AMD subjects with a binocular scotoma, tended to exhibit the most risky and unsafe behavior because they underestimated their crossing time and had the highest number of unsafe crossing time judgments compared with either the AMD subjects without a scotoma or normally sighted subjects of similar age. Based on these findings, we propose that people with AMD with a binocular scotoma that results in a visual acuity of 20/80 or worse should be educated on exercising caution about not underestimating the time they need to cross the street.

Another possible reason why no significant differences in performance were observed between the AMD and age-matched normally sighted subjects may relate to the fact that all subjects still had intact and full peripheral visual fields. Thus, it is possible that the AMD subjects used their peripheral vision to compensate for their slightly reduced central vision when judging the approximate width of the street and estimating how long it would take for them to cross it. More research is required, however, to confirm this statement because in this study we did not track the eye movements of our subjects.

It is also possible that the AMD subjects in this study were well aware of their visual and physical limitations given the long-term nature of this age-related eye disease. As a result, the subjects in our study may have successfully adopted compensatory strategies for their vision loss and for any possible physical declines associated with normal aging. If so, this may explain why no statistical differences in crossing time judgments were found between the AMD and age-matched control subjects with normal vision. A study by Alexander et al. supports the notion that people with AMD can adopt compensatory strategies because they found that their visually impaired adults with AMD adopted more cautious stepping strategies when negotiating on and off curbs compared with older normally sighted adults.

Adopting compensatory strategies for their visual and physical limitations may also explain why the AMD subjects made more accurate crossing estimates compared with the age-matched normally sighted control subjects. The AMD subjects overestimated their pre-crossing estimate on average by only 9.3%, whereas the age-matched normally sighted controls significantly overestimated their crossing time on average by 23.1%. Similarly, during the post-crossing estimates, AMD subjects overestimated by only 0.6%, whereas the control subjects overestimated by 9.5%. Because the AMD subjects were possibly more aware of their limitations, they may have accounted for these limitations in their estimates. Furthermore, given that inaccurate crossing time judgments can lead to a potentially dangerous, if not fatal, situation, it is not unexpected that older people with vision loss may have been hyperaware of their visual and physical limitations compared with normally sighted people when performing a potentially dangerous task such as making street-crossing judgments.

We did find in this study a significant difference between pre-crossing and post-crossing estimates for both subject groups. Initially, both subject groups' crossing estimates were inaccurate. However, after having the experience of crossing the street, the crossing time estimates of both the AMD and normally sighted subject groups became accurate and faster and were less variable (i.e., the standard deviations of the post-estimates were smaller than the pre-estimates). The exception to this was with the AMD subjects with a binocular scotoma. As previously reported, their crossing estimates did not change significantly with experience.

The trend of a significant decrease in crossing estimates after crossing the street can be explained in part by habituation. When subjects were familiar with the time needed to cross the street, the more accurate, faster, and less variable their street-crossing estimates became. This suggests that subjects used the knowledge gained from crossing the street to refine their post-estimate.

Alternatively, some subjects may have used strategies such as counting steps or heartbeats when they physically crossed the street and applied this technique and knowledge to obtain their post-estimate crossing. If so, this may also explain why subjects' post-crossing estimates became faster, less variable, and more accurate compared with their pre-crossing estimates.

The current study is the first study to assess the accuracy of crossing time judgments made by people who are visually impaired as a result of AMD. Earlier studies evaluating the street-crossing performance of either low vision or, more specifically, AMD subjects have assessed whether they make safe crossing decisions and how well they can discriminate gap times of different durations relative to their perceived crossing time. The experimental tasks in all of these earlier studies therefore required subjects to estimate their crossing time and then use that crossing time estimate when determining when it was safe to cross the street or when discriminating the different vehicular gap times. These studies, however, never assessed how subjects' crossing time estimates compared with their actual crossing time. Thus, it was never known whether the crossing time estimates subjects were using were indeed accurate. The current study therefore provides not only an easy and fast method of assessing the accuracy of one's crossing time judgment but also the results suggest that...
people with AMD are on average quite accurate at judging their own crossing time. Applying the results of our study to the results of these earlier street-crossing studies\textsuperscript{21,25-29} suggests that their findings were not confounded by discrepancies between subjects' estimated and actual crossing times.

The results of this study are in agreement with a previous study assessing the crossing time judgments of normally sighted people. Like in the present study, Holland and Hii\textsuperscript{31} found that normally sighted subjects 75 years or older overestimated their crossing time. Interestingly, a study by Naveteur et al.\textsuperscript{30} found that older normally sighted subjects who had a mobility disability (lower limb disease affecting their ability to walk) also overestimated their crossing time as compared with nondisabled, normally sighted older subjects.\textsuperscript{30} Thus, it is possible that subjects with any type of disability compensate for their limitations by incorporating a greater safety margin when making judgments about the time they need to cross the street.

The findings of this study, however, are not in agreement with Zivotofsky et al.,\textsuperscript{32} who found that elderly normally sighted subjects (mean age, \textasciitilde77.6 years) significantly underestimated their crossing time and, unlike the current study, found that subjects' estimates of their crossing time did not get significantly faster after crossing the street.\textsuperscript{32} A possible reason why our conclusions differ from Zivotofsky and colleagues\textsuperscript{32} may relate to the type of subjects Zivotofsky et al.\textsuperscript{32} recruited. Zivotofsky et al.\textsuperscript{32} specifically targeted elderly subjects who were very active, independent, and high functioning. Indeed, part of their inclusion criteria involved subjects being members of a particular senior citizen's club that required its members to meet certain performance standards in independent functioning, health, mental and physical condition, and social skills. It is therefore possible that such highly functioning subjects may have been overconfident with their actual abilities, which in turn resulted in an underestimation of crossing time. The subjects recruited in the current study were from the general population and may be more representative of the range of abilities seen in older pedestrians when attempting to judge their crossing time.

Studies by Naveteur et al.\textsuperscript{30} and Dommes et al.\textsuperscript{33} have also reported that normally sighted elderly subjects (60 years or older) significantly underestimate their crossing time. However, the discrepancy in results between the current study and the studies of Naveteur et al.\textsuperscript{30} and Dommes et al.\textsuperscript{33} is most likely due to methodological differences. Unlike the present study and the study by Zivotofsky et al.\textsuperscript{32} which were performed using real, outdoor streets, both Naveteur et al.\textsuperscript{30} and Dommes et al.\textsuperscript{33} assessed crossing judgments using a simulated street, which was set up either in a large room or in a long, indoor corridor, and whereas Naveteur et al.\textsuperscript{30} included a "curb" with half of their simulated street assessments, Dommes et al.\textsuperscript{33} did not. It is therefore possible that such an artificial environment, which lacked any natural features and distractors commonly found in real crossing environments, may have resulted in subjects inadvertently speeding up their crossing judgments.

Safety was another aspect investigated in this study. Although it may seem more logical to want a more accurate street-crossing estimate (that is, having a street-crossing estimate as close as possible to the actual street-crossing time), there is a benefit from a functional point of view to overestimate one's crossing time, especially for older subjects. Considering that rushing can cause falls in the elderly population,\textsuperscript{44} overestimation may lead to less pedestrian injury and/or fatality because it allows for additional time than is required for the pedestrian to safely step off and onto the curb and navigate the street. As previously reported, the AMD subjects without a binocular scotoma and the normally sighted subjects always had some level of overestimation in their crossing estimates. In contrast, the AMD subjects with the highest level of visual impairment in this study had a tendency to underestimate their crossing time. It is acknowledged, however, that an overestimation of crossing time can result in more missed crossing opportunities because pedestrians may not accept a vehicular gap time as being long enough to cross because of their perceived longer crossing time. Therefore, although pedestrians may be safer with an overestimation of their crossing time, their travel may be less efficient.

Based on this study's definition of an unsafe crossing estimate (Fig. 1), it was found that there was a tendency that more unsafe estimates were made after crossing the street than before crossing. This result is most likely explained by the finding that subjects' crossing estimates, when familiar with the street, became faster. Also, having familiarity with the street may have caused subjects to have paid less attention to the road width and the task in general. As a result, this may have caused subjects to have a tendency to overestimate their crossing time less on post-crossing compared with pre-crossing.

The effect of street familiarity may therefore be problematic if a person tends to take the same walking route each day. Because we found that subjects' estimate of their crossing time became significantly faster after physically crossing the street, this may lead a person to make faster estimates about the time he/she needs to cross a street if he/she has crossed that same street many times before. If the crossing time estimate becomes faster, the person is at a higher risk of inadvertently underestimating his/her crossing time, which in turn can result in him/her having a higher risk of being involved in a pedestrian accident, injury, and/or fatality. As a result, we recommend that health care professionals providing vision, mobility, and street-crossing rehabilitation educate their patients to exercise caution when making judgments about the time they need to cross a street that they have previously crossed.

We found a large range in abilities of people estimating their crossing time. As seen from Fig. 2 and Fig. 3, both AMD and age-matched control subjects with normal vision demonstrated poor performance. For example, some subjects estimated that they needed more than twice the time they actually needed to cross the street. On the other end of the scale, other subjects from both groups grossly underestimated the time they thought they needed to cross by as much as 50%.

In an attempt to identify the factor(s) that led to good and poor performance and thus help explain the variability observed in our data, we ran a forward, stepwise multiple regression analysis on crossing ratio. The variables that best predicted a person's ability to judge his/her own crossing time was whether the judgment was made before or after actually crossing the street, his/her age, and his/her actual crossing time. As mentioned before, familiarization with the crossing task led to more accurate crossing judgments, with subjects overestimating their imagined crossing time less after crossing the street.

Our multiple regression analysis finding that increased age and longer crossing times were associated with less overestimation of crossing times is most likely explained by the known age-related declines in walking speed.\textsuperscript{45} It is possible that the oldest subjects in this older cohort of subjects may have not fully compensated
for their slowed walking speed like the younger older subjects when making their crossing judgments, hence resulting in the trend of overestimating less with increased age and longer crossing times. Indeed, walking speed\textsuperscript{33,46} and walking time\textsuperscript{31} have all been reported as significant predictors of unsafe street-crossing decisions in older normally sighted adults, and Naveteur et al.\textsuperscript{30} also found that age was one of the two best predictors of crossing time accuracy in their cohort of older, normally sighted subjects.

We also performed a forward stepwise logistic multiple regression analysis to determine which variable(s) were the best predictors of unsafe crossing judgments. We found that, as a person ages, the more likely it was for him/her to make an unsafe crossing judgment. This finding indirectly supports the findings of Dommes and Cavallo,\textsuperscript{46} because they reported that age was one of the significant predictors of unsafe crossing decisions in young and older adults with normal vision.

Collectively, however, the variables that best predicted performance only explained between 9.6 and 15% of the variability in the probability of making an unsafe estimation and of judging crossing time, respectively. It is clear that other variables, not assessed in the current study, contribute to a person’s ability to safely and accurately judge his/her own crossing time. One variable that may better explain the variability in crossing time estimates is the subjects’ propensity to taking risk. A subject with a riskier crossing strategy may tend to underestimate his/her street-crossing time more than a less risky subject.

Even though this study systematically assessed the accuracy of crossing time judgments in people with AMD and normal vision, there are limitations associated with this study. For example, crossing time estimates in this study were measured at a relatively simple crossing environment, that is, a one-lane, one-way street. It is possible that subjects’ performance may differ from what was found in this study if crossing estimates were measured at a wider street or if estimates were taken in the presence of approaching vehicles. Other limitations include that it was assumed that subjects’ imagined walking speeds would not alter during the measurement of their crossing time estimates. Although we instructed subjects to not speed up or slow down within a trial and that trials were conducted with minimal distractors (such as having no approaching vehicles present), we acknowledge that it is still possible that variations in subjects’ imagined walking speeds may have occurred, which would have resulted in variations in their crossing time estimates.

We also acknowledge that there are assumptions in our classification of safe and unsafe crossing ratios. For example, it was assumed in our model where there was an approaching vehicle that had a gap time equal to the subject’s estimated crossing time that subjects would still cross the street at the same pace as when there was no approaching vehicle. Also, it was assumed that the speed of the approaching vehicle in our model would remain constant. Despite these assumptions, we feel that it was important to include this modeled scenario in this study to provide a functional interpretation of our results.

CONCLUSIONS

In summary, the findings of this study suggest that habituation, and not vision loss from AMD, plays a major role in a subject’s ability to make safe and accurate street-crossing estimates. We predict, however, that a person’s ability to judge his/her crossing time worsens with greater levels of central vision loss (the presence of a binocular scotoma with visual acuity 20/80 or worse). Both the AMD and age-matched control subjects with normal vision made more unsafe street-crossing estimates after crossing the street than they did before most likely because their crossing estimates became significantly faster after having the experience of crossing the street. This tendency can be detrimental to a person’s safety if he/she tends to walk the same route repeatedly. We found that increasing age, crossing time, and whether subjects’ estimates were made before or after crossing the street were the best predictors of a person’s ability to estimate his/her own crossing time, whereas age alone was the most important predictor of how well a person could make a safe estimation of his/her street-crossing time.

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REFERENCES