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How Do Vision and Hearing Impact Pedestrian Time-to-Arrival Judgments?

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Abstract

Purpose—To determine how accurate normally-sighted male and female pedestrians were at making time-to-arrival (TTA) judgments of approaching vehicles when using just their hearing or both their hearing and vision.

Methods—Ten male and 14 female subjects with confirmed normal vision and hearing estimated the TTA of approaching vehicles along an unsignalized street under two sensory conditions: (i) using both habitual vision and hearing; and (ii) using habitual hearing only. All subjects estimated how long the approaching vehicle would take to reach them (*ie* the TTA). The actual TTA of vehicles was also measured using custom made sensors. The error in TTA judgments for each subject under each sensory condition was calculated as the difference between the actual and estimated TTA. A secondary timing experiment was also conducted to adjust each subject's TTA judgments for their "internal metronome".

Results—Error in TTA judgments changed significantly as a function of both the actual TTA ($p < 0.0001$) and sensory condition ($p < 0.0001$). While no main effect for gender was found ($p = 0.19$), the way the TTA judgments varied within each sensory condition for each gender was different ($p < 0.0001$). Females tended to be as accurate under either condition ($p = 0.01$) with the exception of TTA judgments made when the actual TTA was two seconds or less and eight seconds or longer, during which the vision and hearing condition was more accurate ($p = 0.002$). Males made more accurate TTA judgments under the hearing only condition for actual TTA values five seconds or less ($p < 0.0001$), after which there were no significant differences between the two conditions ($p = 0.01$).

Conclusions—Our data suggests that males and females use visual and auditory information differently when making TTA judgments. While the sensory condition did not affect the females' accuracy in judgments, males initially tended to be more accurate when using their hearing only.

Keywords

time-to-arrival; street-crossing; gender; normally-sighted; sensory condition

Given the high-risk nature and the complex decision making process involved in forming street-crossing decisions, it could be argued that one of the most dangerous activities of

daily living is crossing the street. As pedestrians are involved in a significant number of motor vehicle accidents every year, it is clear that poor crossing decisions are being made. In fact, the National Highway Traffic safety administration showed that in 2011, a pedestrian was injured every eight minutes and killed every two hours while attempting to cross the street.¹ Moreover, pedestrian fatalities accounted for 14% of traffic fatalities nationally.¹ These statistics represent a 3% increase from what was reported in 2010, demonstrating that this problem is becoming more prevalent.¹ To lower these numbers, it is necessary to not only better understand pedestrian behaviors at street-crossings, but also to identify the perceptual cues that affect the pedestrians' ability to make safe street-crossing decisions.

In order to safely cross uncontrolled intersections, which are intersections not controlled by traffic signals, pedestrians must take several factors into account. Firstly, pedestrians must be able to accurately assess the time-to-arrival (TTA) of approaching vehicles. The TTA is defined as the duration of time it takes an approaching vehicle to reach the pedestrian who is crossing from a given location. Secondly, pedestrians must have an accurate perception of their own crossing time. Finally, pedestrians must incorporate a safety margin, the additional time pedestrians give themselves when comparing the TTA of the approaching vehicle to their own crossing time, into their crossing decision.

Most previous studies have evaluated street-crossing decision making in pedestrians from a holistic perspective, where all three elements of the crossing decision have been combined.²⁻⁵ While these earlier studies are important to understanding pedestrian safety, they fail to explain the underlying cause(s) of unsafe crossing decisions. To determine which element(s) of the street-crossing decision contribute to inaccurate crossing decisions, we examined how well pedestrians made judgments about the first element of the street-crossing decision: TTA judgments.

We also evaluated whether the accuracy in TTA judgments changed when using different sensory systems. The street-crossing environment is a very rich sensory environment where pedestrians can visually access information and hear the speeds of approaching vehicles and other auditory cues such as tire noise and noises from combustion engines. There is also a limited amount of tactile information present in the crossing environment from engine and vehicle vibrations. As a result, pedestrians often presumably sample and combine pertinent information from more than one sensory system when making their crossing decision.

Previous studies have investigated how effectively multisensory information is integrated by subjects to make spatiotemporal predictions about moving objects. Hofbauer et al.⁶ examined how well subjects could make spatiotemporal predictions about a virtually moving object when it was defined by auditory, visual, or audiovisual cues. Hofbauer found that subjects were significantly less accurate when extrapolating the motion of a virtual object that was hidden prior to its arrival under the auditory only condition as compared to the audiovisual condition. In addition, no significant difference in performance was found between the audiovisual and the visual only modalities.⁶ From these results, Hofbauer et al. concluded that subjects' bimodal performance was limited by the visual performance and therefore not enhanced by the additional auditory input.⁶

Schiff and Oldak⁷ also assessed how subjects use multisensory information to make spatiotemporal predictions. In their study, subjects were required to make TTA estimates by watching films of approaching vehicles under audiovisual, visual, and auditory conditions and pressing a button when they thought the vehicle would have reached them after the film stopped. Like Hofbaeur et al, Schiff and Oldak found that when using only auditory stimuli, TTA judgments were significantly less accurate than when using either visual or audiovisual stimuli.^{6,7}

In addition, Schiff and Oldak⁷ found that their subjects tended to be less accurate with increasing TTA, as the amount of underestimation increased with increasing TTA. This result agrees with several other previous studies.^{8,9} Furthermore, in agreement with Neuhooff et al¹⁰, Schiff and Oldak⁷ found that females tended to be significantly less accurate than males when estimating TTA. Schiff and Oldak⁷ found that women tended to underestimate more greatly than men when estimating TTA and attributed this finding to the fact that women either have a more conservative safety margin or inferior spatiotemporal skills.⁷

A common limitation however from these earlier TTA studies is that they been performed in a laboratory setting. While the laboratory enables testing to occur in a controlled manner where experimental factors can be systematically manipulated, the laboratory testing environment is unable to fully replicate all of the natural sensory cues present in the real-world. As a result, laboratory testing does not truly reflect the complexity and sensory richness of street-crossing decision making in the real-world.

Furthermore, little literature exists on how well subjects can make estimates across a broad range of TTA values (e.g. between 0–10 seconds, inclusive). The majority of previous TTA studies have assessed performance either for short (*i.e.* 6 seconds or less) or for only a few selected TTA values—often just assessing performance for only 3–4 TTA categories.^{6–8,11} Assessing performance over a broad range of TTA values is important because most real-world street-crossing situations require pedestrians to make decisions based on much longer TTA values.

Another limitation of the earlier studies is related to their use of a TTA “projection” task. The projection task requires subjects to project time into the future, where the stimulus would disappear completely and subjects would make their TTA estimate by pressing a button when they thought the stimulus would have reached them. However, in the real-world task of actually crossing the street, decisions about the vehicle’s TTA need to be made well in advance of the vehicle reaching the pedestrian. Therefore studies are required that assess subjects’ abilities to judge instantaneously the TTA of approaching vehicles before their arrival at the judgment point. The results of such a study would therefore correlate more directly to the actual decision making process that pedestrians encounter in the real-world.

In the present study, we investigated how well 24 normally-sighted male and female pedestrians made TTA judgments about approaching vehicles under two different sensory conditions within a real-world street-crossing environment. Subjects were asked to use both vision and hearing or just hearing to make their predictions over a wide range of TTA values (1–10 seconds). Based on the results of previous studies, we hypothesized that the female

subjects would not perform as well as the male subjects, TTA judgments would become less accurate with increasing TTA, and subjects would perform better under the vision and hearing condition than the hearing only condition.^{6,7,10,11}

METHODS

Subjects

A total of twenty-four normally-sighted subjects (10 males and 14 females; age ranging from 22–29 years with a mean age of 24.42 ± 1.73 years) participated in the study. Informed consent was obtained from all subjects after the experimental procedures were explained. The study was designed in accordance to the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board (IRB) of Indiana University. Subjects were recruited from the general public and also included graduate students from the Indiana University School of Optometry.

All subjects were required to have normal vision, defined as having a binocular visual acuity (VA) of at least 0.00 Log MAR (20/20), normal Pelli-Robson letter contrast sensitivity (1.70 Log CS), and a full visual field (average VF Extent radii > 60 degrees). An Early Treatment Diabetic Retinopathy Study (ETDRS) chart¹² was used to measure each subject's right eye, left eye and binocular distance visual acuities with using their habitual correction (either spectacles or contact lenses). The ETDRS chart was transilluminated to approximately 100 cdm^{-2} and the VA was reported as the logarithm of the minimum angle of resolution (Log MAR). VA was measured by decreasing the chart distance logarithmically until the subject could read at least the entire first line. Subjects were then required to read letters until four consecutive errors were made and their VA was scored using the method of Bailey and Lovie.¹³

Contrast sensitivity (CS) was also measured monocularly and binocularly using a Pelli-Robson Letter CS chart¹⁴ with overhead illumination of 85 cdm^{-2} at a test distance of one meter. Subjects were required to read until two letters within a given triplet were incorrectly identified. Subjects' CS was scored using the method of Elliott et al.^{15,16}

Right and left monocular visual field (VF) extents were measured with a Goldmann Bowl Perimeter using a III4e target on a background luminance of 10 cdm^{-2} . The VFs were measured over a 90° extent across 28 meridians separated by 10°. Each subject's binocular VF extent (radius) was scored by superimposing the right and left VF plots and then determining the greater VF extent along each assessed meridian. The average radius across all 28 meridians gave an averaged binocular VF extent for each subject. The average results for the vision testing are listed in Table 1.

Inclusion criteria also included normal hearing abilities, which were defined as being able to correctly identify a tone when it was at least 25dB, with the threshold level being 75% correct responses at each frequency (50–4000 Hz).

All subjects were able to walk independently and self-reported that they frequently crossed uncontrolled streets unaided.

Street Test Site

A local two-way street in Bloomington, IN, with consistent morning traffic flow was used for TTA testing. The street had a median strip dividing it into one 4.5 meter wide lane of traffic flowing in each direction. This setup (Figure 1) simplified the experimental task for subjects by limiting approaching traffic to a single direction so that subjects were only making TTA judgments about the approaching vehicles in the lane closest to them. The “judgment point”, where TTA judgments were made by subjects, was chosen along a section of the road where no stop sign or regulatory signals were present so that vehicular speeds remained constant. The judgment point had a long line of sight (approximately 300 meters) and minimal visual and auditory distractors (*i.e.* no billboard signs or audible pedestrian signals) to enable longer TTA values to be tested in our study. In addition, it has been shown that in quiet environments pedestrians are able to hear most vehicles well, regardless of their speed or the level of sound they make under these conditions.¹⁷

Measurement of Actual TTA

A custom-made sensor box and laser system was used to measure actual TTA values of approaching vehicles. The sensor box and laser system design and set up has been previously described in Hassan and Massof.¹⁸ In summary the sensor boxes, positioned on one side of the street, contained a photodetector that detected a laser beam from the opposite side of the street (see Figure 1). When a passing vehicle blocked the laser beam from reaching the photodetector, the event was time stamped and recorded using custom software designed specifically for our study.

Two sets of lasers and sensor boxes were set up during the TTA testing in order to record vehicular speeds. One sensor box was located at the judgment point where subjects made TTA judgments. The second sensor was located to the left of the judgment point (with an average separation of ~15.50 m). The distance between the two sensor boxes was recorded during every session so that the velocity of the vehicle involved in each trial could be calculated. The average vehicular speed of the approaching traffic in this study was $46.01 \pm 7.47 \text{ km}\cdot\text{hr}^{-1}$, which was within the sign-posted speed limit of $48.28 \text{ km}\cdot\text{hr}^{-1}$ (30 mph).

The actual TTA of the approaching vehicles was determined with the custom software by measuring the duration between the time of a prompt signal (see the Experimental procedure below for an explanation of the prompt signal) and when the approaching vehicle first reached the sensor box at the judgment point.

Experimental Procedure

The experimental methodology used to measure the subject’s estimation of TTA of an oncoming vehicle for comparison with the actual TTA has been described previously by Hassan.¹⁹ In summary, subjects made TTA judgments under two sensory conditions: (i) using habitual vision and hearing; and (ii) using habitual hearing alone. The experimental paradigm used for each condition was identical except for the amount of sensory information that was available to subjects when making a TTA judgment. Under the vision and hearing condition, subjects were positioned along the side of the road at the judgment point, wearing a pair of earbuds that played white noise and directing their head forward

with their eyes closed. Thus subjects were initially prevented from either seeing or hearing the approaching vehicles. The experimenter signaled the start of an upcoming trial by pressing a button on the computer program to play a “get ready” signal through the ear buds. At this time, the white noise was automatically turned off and subjects were instructed to turn their heads toward the oncoming traffic in the lane nearest them and to open their eyes in order to view and listen to the approaching vehicle. Subjects were allowed to sample the oncoming traffic for two seconds before a “prompt” tone was generated by the computer. At this point, the white noise was automatically turned back on and subjects were instructed to resume looking straight ahead and to close their eyes so that they were no longer sampling the vehicle's approach. The time of two seconds was chosen as the duration of the sampling period because previous studies have shown that pedestrians take an average of two seconds to make a decision about whether or not to cross the street regardless of whether they have reduced hearing or vision.^{20,21}

Subjects were also instructed to estimate the vehicle's TTA by judging how long they thought the vehicle would take to reach them, to the nearest 0.5 second, from the time of the prompt signal. Subjects gave their TTA judgment with a hand-held trigger button by pressing the button once for each second they thought the vehicle would take to reach them from the time of the prompt signal. In order to enable precision to 0.5 seconds, subjects were instructed to hold the trigger button down longer on the last press to make an estimate to the nearest half second. The trigger devices also allowed us to maintain anonymity of responses across subjects and to record and monitor the reaction time and response time of each subject when estimating the TTA. Response time, or how long it took each subject to use the trigger button to indicate their responses, was limited to 4 seconds to ensure that subjects were not continuing to sample the approaching vehicle or to count out seconds in their head. Reaction time, or how long it took each subject to initiate responding with the trigger button after the prompt signal, was continuously monitored during testing. Any estimate with a reaction time longer than 0.5 seconds was disregarded, as we aimed to measure subjects' initial impressions of the TTA and thus prevent subjects from continually sampling the available sensory information.

The above procedure was repeated under the hearing only condition during which subjects had to make TTA judgments based on auditory cues only. The only difference in protocol was that under the hearing only condition, subjects kept their eyes closed for the entire experiment.

Subjects made TTA judgments under both sensory conditions with the order randomized and counter-balanced across subjects.

The actual TTA of the approaching vehicles assessed in this study encompassed a wide range of TTA values that were both higher and lower than each subject's street-crossing times. The actual TTA values were tested in a random order and chosen based on traffic flow and were categorized into nine different “TTA Categories”. Vehicular TTA values that ranged from 0 to 1 second in duration were included in TTA Category 1, and the final TTA Category of 9 included actual TTA values equal to 8 seconds or longer. At least 10 trials

were recorded for each TTA Category for each sensory condition. The custom computer program recorded subjects' estimated TTA and the actual TTA.

Timing Experiment

Given that the perception of time inherently varies between people and that individuals may not be able to judge time accurately, it was imperative to quantify how each subject perceived time. By assessing each subject's perception of time intervals and thus their "internal metronome", we were able to accurately compare each subject's estimated TTA values in actual, physical seconds. These time interval judgments were assessed in the laboratory using the same custom-written computer program that was utilized out on the street.

During the timing experiment, subjects were asked to estimate the duration of different intervals of time ranging from 1–15 seconds, which encompassed the actual TTA times that subjects encountered during street testing. Subjects were asked to make their estimates by holding down the handheld trigger device for the duration of each interval. The order of these times was randomly predetermined by the experimenter for each subject, and the session was repeated so that two measurements were made for each interval of time. In addition, subjects wore earbuds that played white noise while making these estimates which acted as a mild distractor to prevent subjects from simply counting out the duration of the required interval.

While we acknowledge that the task of measuring subjects' perception of time intervals is different to what subjects were required to do at the street (*i.e.* estimate TTA values of approaching vehicles), it enabled us to measure how subjects perceived time so that we could obtain the most accurate TTA estimates possible.

DATA ANALYSIS

Characteristics of the Internal Metronome

Computing each subject's internal metronome revealed that the metronomes varied greatly between subjects but were very consistent within a single subject. This finding justified the need to scale the individual TTA judgment results to each subject's internal metronome. Figure 2 compares each subject's averaged estimate of the different time intervals to the actual time interval tested. Perfect performance in this task is indicated by the solid black line. The results are plotted such that the "instructed" time interval is the amount of time the subject was asked to estimate, while the "button press duration" is each subject's response. The results from the timing experiment consistently yielded linear estimates for each subject, enabling us to use the slopes of their individual responses to adjust their TTA estimates obtained at the street.

Outcome Variable Calculation

We corrected the 90 estimated TTA judgments each subject made under each sensory condition with the results from the Timing Experiment. The "Corrected Estimated TTA judgment" for each subject under each sensory condition was calculated by dividing each

subject's 90 estimated TTA judgments from the street by the slope of their individual time calibration graph from the Timing Experiment (see Figure 2). By doing this calculation, all subjects' perceived time scales (internal metronomes) were mapped onto the same physical time scale. Using the 90 Corrected Estimated TTA judgments we then calculated the "Log Error in TTA judgment" for each subject under each condition by computing the difference between the Actual TTA and the subjects' Corrected Estimated TTA judgments and then taking the logarithm of the difference.

A general linear mixed model was used to assess how the accuracy of TTA judgments (error) varied with sensory condition, gender, vehicular speed and duration of the actual TTA and for any interactions between these main effects. A mixed linear model was used because there were both fixed (gender, sensory condition, speed, distance, and gap category) and random effects (correlations within each subject due to the repeated measures design of the study). To ensure that the assumptions of normality and equal variance were upheld for the general linear mixed model analyses, data distributions were log transformed, if required, to ensure that all data distributions were normally distributed and had equal variances.

To correct for multiple comparisons during post-hoc testing, a Bonferroni correction was applied to the p-value. Therefore for our study, a corrected p value 0.003 was considered statistically significant for our post-hoc testing.

RESULTS

The Effect of TTA Category on TTA Accuracy

We found that TTA error scores changed significantly with TTA category ($F_{(4039,7)} = 17.97$, $p < 0.0001$) (Figure 3). Overall, TTA error scores were not significantly different from zero up until TTA category 5 ($t_{4039} < 1.76$, $p > 0.08$). After TTA category 5, errors scores were significantly different from zero ($t_{4039} > 1.99$, $p < 0.05$) with subjects underestimating the TTA of approaching vehicles with increasing TTA category.

The Effect of Sensory Condition

TTA error scores changed as a function of sensory condition ($F_{(4039,1)} = 79.59$, $p < 0.0001$). We found that subjects made inaccurate TTA judgments under the vision and hearing condition ($t = 3.31$, $p < 0.001$), but not under the hearing only condition ($t = 1.35$, $p = 0.18$). Under both sensory conditions however, subjects tended to underestimate the TTA regardless of the sensory condition.

The Effect of Gender

While no main effect for gender was found ($F_{(4039,1)} = 1.72$, $p = 0.19$), there was a significant three-way interaction between TTA category x Condition x Gender ($F_{(4039,7)} = 4.96$, $p < 0.0001$) (Figure 4). No significant difference between males and females were found for any of the TTA categories under the vision and hearing condition except at TTA category 2 ($F_{(4039,1)} = 19.79$, $p < 0.0001$) and TTA time category 3 ($F_{(4039,1)} = 12.03$, $p < 0.001$). At these two TTA categories, the male TTA estimates were significantly less

accurate than the female TTA estimates. Under the hearing only condition, no significant differences in performance were found between males and females for any of the TTA categories ($F_{(4039,1)} = 1.30$, $p = 0.25$).

Post-hoc tests also revealed that females tended to be just as accurate in their TTA estimates under the hearing only condition as they were under vision and hearing ($F_{(4039,1)} = 6.66$, $p = 0.01$) with the exception of TTA judgments made in TTA categories 2 ($F_{(4039,1)} = 27.76$, $p < 0.001$) and 9 ($F_{(4039,1)} = 9.65$, $p = 0.002$). In these two cases, TTA judgments were less accurate under the hearing only condition than under the vision and hearing condition.

For males, TTA judgments were more accurately made under the hearing only condition than the vision and hearing condition for TTA categories up to five seconds ($F_{(4039,1)} = 21.47$, $p < 0.0001$). For TTA values greater than 5 seconds, there were no significant differences in TTA judgments between the two sensory conditions ($F_{(4039,1)} = 6.33$, $p = 0.01$).

DISCUSSION

This study aimed to test the generality of laboratory based TTA results in the real-world context of pedestrians judging TTA of approaching vehicles under different sensory modalities. We found that the accuracy of TTA judgments decreased with increasing TTA. These results agree with the laboratory based results of Schiff and Detwiler,⁹ Schiff and Oldak,⁷ and Seward et al.¹¹

Like Gordon and Rosenblum,⁸ Schiff and Detwiler,⁹ and Schiff and Oldak⁷ we also found a general trend that subjects underestimated the TTA of approaching vehicles and that the amount of underestimation increased as the TTA category increased (see Figure 3). We found that subjects on average underestimated the TTA of approaching vehicles by 0.45 seconds, which is less than the amount of underestimation found in previous studies. Previous studies have reported that subjects on average underestimate the TTA of approaching vehicles by approximately 2 seconds.^{7,9} Possible reasons for the discrepancy in results include aspects of our methodology. As our study tested subjects in the dynamic and complex environment of the real-world, it is possible that the amount of error in TTA judgments made by our subjects was less because they were exposed to more pertinent perceptual cues that aided their estimations. In addition, while previous laboratory-based studies had subjects simply hold down a button until they believed a car would arrive, we were unable to utilize this method due to the difficulty of making the stimuli of the real world completely disappear outside of the sampling period. Therefore it was necessary for subjects to make their TTA judgment before the approaching vehicle reach them. Having subjects make instantaneous TTA decisions about approaching vehicles is however more realistic to the actual task of crossing the street than waiting to make the decision until the car reaches the judgment point. Interestingly, when Seward et al.¹¹ used an immersive virtual environment, which may be considered to be more realistic to the real-world than films used in the laboratory based experiments, they found that subjects on average overestimated the TTA by 0.77 seconds, which was similar to our results. Thus it is possible that there is a tendency to have less overall error in making TTA judgments when assessing

performance in a more realistic environment as opposed to testing performance using two-dimensional films.

Although subjects were inaccurate, especially for vehicles that were farther away, it is possible that they would still make "safe" street-crossing decisions. This is because an underestimation of the TTA means that a subject thinks the vehicle will take less time to reach them than it actually does. As a result, they would still have enough time to cross the street, provided that their crossing time is shorter than the actual TTA. Thus from a functional standpoint, it is better for subjects to underestimate the TTA as opposed to overestimating it. Subjects who overestimate the TTA potentially place themselves at greater risk in terms of making an appropriate street-crossing decision if their crossing time is shorter than the actual TTA and/or they underestimate their crossing time.

Our data also suggests that males and females use visual and auditory information differently when making TTA judgments. We found that female subjects made fairly accurate TTA judgments regardless of the sensory condition, with the exceptions of the longest TTA category under the vision and hearing condition and the shortest and longest TTA categories under the hearing only condition. In these cases, TTA judgments made by females were more accurate under the vision and hearing condition than under hearing only, which confirms the results of Hofbauer et al.,⁶ Gerushat et al.,²⁰ and Schiff and Oldak⁷ that the addition of visual information is beneficial when making accurate TTA and street-crossing decisions. In contrast, the male subjects initially tended to be more accurate when using only their hearing compared to using their vision and hearing for TTA values up to 5 seconds. After 5 seconds, performance for the male subjects was not affected by the sensory condition. It is unclear as to why the male subjects were initially more accurate when using only auditory information compared to using vision and hearing when making TTA judgments.

We also found that the female subjects were just as accurate as the male subjects when making TTA judgments, irrespective of the sensory condition. The exception to this was with TTA judgments made under the vision and hearing condition for TTA categories 2 and 3. Under these TTA categories, the female subjects made significantly more accurate TTA judgments than the male subjects. We found no significant difference in performance between males and females under the hearing only condition.

Previous studies have reported that women perform significantly worse than men when making TTA judgments.^{7,10} A possible explanation as for why we found no significant difference in performance between men and women may be related to the spatial-temporal and visuomotor abilities of our female subjects. Schiff and Oldak⁷ argued that females tend to have reduced spatial-temporal abilities compared to males and reported that those females who were not active in sports tended to have worse performance due to their reduced visuomotor abilities than those females who were active in sports. Given that the majority of the female subjects who participated in our study had a science background and self-reported that they were active in sports, it is possible that the female subjects in our study had spatial-temporal and visuomotor abilities that were equivalent to our male subjects.

However, this statement would need to be verified with further research, since we did not measure the spatial-temporal or visuomotor performance of subjects in our study.

Another possible explanation for why our results with regards to gender disagree with the results of previous research may be related to the design of our study. Unlike previous studies which used a projected TTA task within a laboratory setting, our study had subjects make an instantaneous TTA judgment within the rich and dynamic environment of the real-world. It is therefore possible that because our subjects were using the perceptual cues found in the natural environment, both males and females were able to make accurate TTA judgments.

Despite the differences in results for gender, the overall consistency of our results with the results of previous literature cross-validates the laboratory methods used for testing TTA judgments in previous studies with the methods and outdoor field testing used in our study. A limitation of our study however is that the task used to measure each subject's perception of time in the timing experiment was not completely identical to the time estimate task used during the street-testing. Despite these methodology differences, the task used during the timing experiment was the best method to assessing each subject's perception of physical, actual time from which we could directly quantify their "internal metronome".

Another limitation of our study is that the TTA estimations were measured only in young, normally sighted subjects. Future work should therefore include a similar study aimed at characterizing the TTA judgments and street-crossing decision making behavior of the elderly and visually impaired, especially since these sub-sets of the population have been shown to make unsafe street-crossing decisions.^{3,21,22} It is unclear from previous studies as to the cause of these unsafe decisions, as it could be related to inaccurate time judgments, a lack of compensation for slow walking speeds, and/or not incorporating a safety margin into the crossing decision. Applying the results of our study, we might predict that the cause of the unsafe crossing decisions of elderly and visually impaired pedestrians would not be from their TTA judgments, although more research is required to confirm this. Understanding the cause of unsafe crossing decisions is important because it may assist in the development of training programs, mobility devices, and environmental changes designed to improve the safety of visually impaired and elderly pedestrians.

In summary, we found that subjects on average became less accurate in TTA judgments with increasing TTA values, regardless of which sensory condition they utilized. Furthermore, we found that male and female subjects used visual and auditory information differently to make TTA judgments. As females were fairly accurate under either condition, sensory condition did not affect their ability to make accurate TTA judgments. In contrast, male subjects initially tended to be more accurate when using their hearing only to make TTA decisions. However, after 5 seconds, males did not exhibit a significant difference in performance between sensory conditions.

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Figure 1. Photograph of the Experimental Test Site with Equipment. The uncontrolled street used in our study was separated by a median strip, enabling the sensor boxes to be set up on the left side and the corresponding laser on the right side. A color version of this figure is available online at www.optvissci.com.

Figure 2.

Assessing subjects' internal metronome. The results for individual subjects are indicated by each symbol. Subjects had to estimate the duration of instructed intervals of time by pressing a button. Perfect performance is represented by the solid black line.

Figure 3.

The effect of Time-to-Arrival (TTA) Category on Log Error. The error bars represent 1 standard error mean (SEM). A positive log error score means the subjects underestimated the TTA. A negative log error score means the subjects overestimated the TTA.

Figure 4.

The effect of Time-to-Arrival (TTA) Category, Sensory Condition, and Gender on subjects' TTA judgments. The error bars represent 1 standard error mean (SEM). A positive log error score means the subjects underestimated the TTA. A negative log error score means the subjects overestimated the TTA.

Table 1

Subject Characteristics. There were no significant differences in age, visual acuity (VA), contrast sensitivity (CS), and visual field (VF) between the male and female subjects. Results are listed as the mean $\pm$ 1 SD.

Parameter*						
Gender	Age (years)	VA OD (Log MAR)	VA OS (Log MAR)	CS OD (Log CS)	CS OS (Log CS)	Averaged Binocular VF Extent (radius, degrees)
Females (n=14)	24.20 $\pm$ 1.30	-0.10 $\pm$ 0.06	-0.10 $\pm$ 0.06	1.64 $\pm$ 0.04	1.65 $\pm$ 0.05	63.47 $\pm$ 2.96
Males (n=10)	24.72 $\pm$ 2.25	-0.02 $\pm$ 0.18	-0.10 $\pm$ 0.06	1.63 $\pm$ 0.03	1.63 $\pm$ 0.04	60.88 $\pm$ 4.97

* VA, visual acuity; OD, right eye; OS, left eye; Log MAR, logarithm of the minimum angle of resolution; CS, contrast sensitivity; Log CS, logarithm of the contrast sensitivity; VF, visual field