Evaluation of Vehicle-to-Pedestrian Communication Displays for Autonomous Vehicles

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ABSTRACT

Previous work in human-centered design includes development of interfaces that improve driver effectiveness; however, interfaces designed to communicate to pedestrians based on a vehicle's perceived intent are limited. For the present work, we investigated intent communication for autonomous vehicles by comparing the effectiveness of various methods of presenting vehicle-to-pedestrian street crossing information. A prototype forward-facing display was developed for vehicle-to-pedestrian communication, and an experiment was conducted in a naturalistic setting to compare signaling designs using a simulated autonomous vehicle. In the experiment, a van representing an autonomous vehicle presented information to pedestrians informing them when to cross a street. Participants made crossing decisions from two locations, a marked crosswalk and an unmarked midblock location. Individual differences, including age, gender, crossing location and conscientiousness were predictive of safe crossing decisions. Participant response times were analyzed to determine which display types resulted in the fastest and safest decisions. The results suggest pedestrians will rely on legacy behaviors rather than leverage the information on an external display. A large number of participants, however, believe additional displays will be needed on autonomous vehicles. The results of the experiment can be used to help inform future designs for vehicle-to-pedestrian communication.

Keywords: Human Factors, Pedestrian Safety, Automated Vehicle Control, Signalization, Driverless Cars, External Displays

INTRODUCTION

The impact of autonomous vehicle technologies on safety is potentially enormous given that human error accounts for an estimated 94% of accidents on the road (*1*). Unlike human drivers, autonomous vehicles can eventually be expected to perform at high levels of precision without experiencing decreased performance due to distraction or fatigue. However, while advances in algorithms and sensor technologies continue to improve vehicle performance on roadways and safe operations around other vehicles, interactions with high risk groups, such as pedestrians, remain a concern.

In contrast to motor vehicles, pedestrian behaviors are not particularly constrained by traffic regulations, which makes them unpredictable much of the time (*2*). Previous research observing pedestrian crossing behaviors shows the minority complies with signals, while the majority exhibits “gap-seeking” behavior in which the pedestrian crosses the street when a sufficient break between traffic is available, regardless of the state of the signal (*3*). These behaviors are not without risk, however. Pedestrians who run into the road, fail to yield the right of way and/or otherwise cross improperly account for around 50% of pedestrian fatalities (*4*). In the ten years from 2005 and 2014, while the number of people injured in motor vehicle crashes decreased by 13%, and the number of fatalities decreased by 25%, the number of pedestrian fatalities has remained flat, and has been increasing since a record low in 2009. Pedestrians currently account for about 15% of traffic fatalities, totaling 4,884 in the US in 2014 (*5*).

When conventional cars and trucks are replaced with autonomous vehicles and the occupants are no longer in control (or paying attention), the responsibility for communicating with pedestrians will be allocated to the vehicle. The occupant may not be available to make eye contact or wave a pedestrian ahead, and signaling techniques like the horn or flashing lights, which communicate limited information, can be confused with other messages and warnings. There is a need, therefore, for new methods of vehicle to pedestrian communication to communicate intent information in the immediate area.

Developers of autonomous vehicle technologies have proposed multiple types of displays, including digital road signs, text, audible chimes and voice instructions to communicate intent to pedestrians (*6, 7*). However, the effectiveness of these displays on autonomous vehicles has not been tested empirically. With this in mind, we developed a prototype forward-facing display for vehicle-to-pedestrian communication and conducted an experiment in a naturalistic setting to compare various designs on a simulated autonomous vehicle. In the study, a van representing an autonomous vehicle presented information to pedestrians informing them when to cross a street. Participants representing pedestrians made crossing decisions from two locations, a marked crosswalk and an unmarked midblock location. Participant response times were compared to determine which display types resulted in the fastest and safest decisions. The following sections describe the design of the displays and the subsequent experiment.

DISPLAY DESIGN

The Manual on Uniform Traffic Control Devices (MUTCD) provide guidelines for pedestrian signal indications, including size and shape. For example, the MUTCD indicates that “symbols should be at least 9 inches (23 cm) high” if they need to be understood from 100 feet (30 m) away (*8*). However, these guidelines were designed for stationary signal indicators installed at crosswalks, not displays on moving vehicles. At 25 mph (40 km/h) a car travels 100 feet (30 m) in the time it takes a pedestrian to cross a lane of traffic. That means the pedestrian needs to have detected and interpreted the signal indication and made a decision before the car is 100 feet (30 m) away. Therefore, signals that include symbols or text may need to be larger than current requirements if they are going to be installed on moving vehicles. Indeed, signs aimed at drivers are notably larger. For example, the symbol of a pedestrian on a sign identifying a crosswalk to drivers must be at least 30 inches (76 cm) high when installed on single lane roads and up to 48 inches (122 cm) on highways (*8*).

Human factors guidelines for determining character height on a visual display recommend a minimum of 16 minutes of visual angle (VA) and a preferred VA of 20 minutes according to the following formula (*9*):

$$VA = \frac{3438 \times H}{D}$$

Where H is the height of the symbol and D is the distance. For example, the recommended size of a 20 VA stimulus viewed at 100 feet (30 m) would be 7 inches (18 cm).

For a pedestrian making the decision to cross a street in front of a moving vehicle, it was necessary to increase the size above that of a static display. This means the symbol needed to be large enough for a pedestrian to see and interpret the symbol while allowing enough time to make the decision to cross and physically cross the street. At 25 mph (40 km/h), the speed limit for residential and business locations, a car moves 37 feet (11 meters) every second and requires at least 32 feet (10 m) of stopping distance on dry pavement. A healthy adult pedestrian crosses the street at approximately 4.4 feet (1.3 m) per second, which means the pedestrian can cross a single lane of traffic in approximately 2.7 seconds (*8, 10*). The perception reaction time (PRT) used for design standards by the American Association of State Highway and Transportation Officials (AASHTO) is 2.5 seconds, including 1.5 for perception and decision of the symbol and 1.0 for making a response (*11*). At a speed of 37 feet (11 m) per second, a signal should therefore be readable at 200 feet (61 m). Following these assumptions, a symbol with a height of 20 min of VA at 200 feet would need to be at least 14 inches (36 cm) tall to account for perception, decision and crossing time.

The display in this study used recognized symbols for “Walk” and “Don’t Walk” and numeric data as opposed to text. This was done due to the size limitations of a legible text display. To be visible at 100 feet, a letter would need to be 6 inches tall and approximately 3.6 inches wide. So a screen designed to display a simple message like “safe to cross” without scrolling horizontally would require a screen at least 47 inches (119 cm) wide. At 200 feet (61 m) the same message would need to be over 100 inches (254) wide, which is wider than most cars. Research has also shown that text needs to be twice as tall as symbols to be recognized; so a text display may need to be even larger (*12*).

The symbols used in the experiment appear in Figure 1. The “Walk” and “Don’t Walk” symbols appeared on the advisory display. The advisory display indicated when it was safe or not safe to cross in front of the vehicle (Figure 2, left and middle). ‘”Don’t walk” advice was always provided when the vehicle was in motion. “Walk” was presented only when the vehicle came to a stop. These two symbols were selected because previous work in human factors shows them as recognizable to 95% of the population (*13*). The second display type was the information display (Figure 1, right). The information display presented the vehicle’s speed dynamically.

FIGURE 1 Intent displays including (from left to right) cross advisory, don't cross advisory and information

The two designs provided for a comparison of two types of information. The advisory display made decision recommendations for the pedestrians. In contrast, the information display reported information about the vehicle's behavior to inform the pedestrian's decision. Instead of requiring the pedestrian to use environmental cues to determine whether the vehicle was slowing, the display could indicate to the pedestrian whether the vehicle was maintaining its current speed or slowing down. The symbols on the display were 16.75 inches (42 cm) tall, and viewable at 250 feet (76 meters). The symbols were presented in white on a black background for maximum contrast. The display's backlight, brightness and contrast were also adjusted to their maximum levels (100 on a 0-100 scale) using the setup menu to improve visibility. During pilot testing, a prototype "don't walk" symbol presented in red and a green "walk" symbol did not provide sufficient contrast on the black background in direct sunlight. Once the design was finalized and pilot testing determined the symbols were readable at 250 feet, an experiment was conducted to compare the effectiveness of the two displays against a control condition.

METHODS

Apparatus

The vehicle used for the experiment was a Dodge Sprinter van (Figure 2) reported to participants as an autonomous vehicle. In practice, however, the vehicle was manned by a dedicated driver, as mandated by law, and an observer. Participants were told the vehicle was staffed only for data collection and as a backup to the autonomous control. The driver was responsible for driving the vehicle according to experiment protocols. The observer controlled the display mounted on the front of the van, according to the experiment condition, and communicated via radio headset with two researchers assigned to observe the two participants in each test session.

FIGURE 2 Experiment vehicle in motion, displaying advisory information

A 32-inch (81 cm) LCD was mounted to the front of the van for vehicle-to-pedestrian communication. The forward-facing display presented one of three indicators to participants (Figure 1), including:

1. Advice – A dynamic display indicating when it was safe or not safe to cross in front of the vehicle
2. Information – A dynamic display presenting the speed of the vehicle
3. Off - A blank screen with no additional information.
4. Control – The display hidden beneath a shroud.

In the control condition, participants were told the van was operated by the human driver. In the other three conditions the participants were told the van was operating autonomously. The external display was controlled by the observer inside the van using an Android tablet wired to the display. A custom application installed on the tablet updated the display dynamically based on GPS coordinates.

Procedure

Experiment trials included pedestrian crossing scenarios in which participants initiated crossing in front of an autonomous vehicle at a crosswalk or midblock. The goal of each trial was for the participants to briefly observe the approaching vehicle and indicate when it was safe to cross. Two participants performed each experiment trial, each at different distances from the vehicle's start location. One participant represented a pedestrian crossing at a crosswalk (P1), and the other represented a jaywalker crossing midblock without a crosswalk (P2). Participants were instructed to wait at two separate crossing positions on opposite sides of a street. Figure 3 shows a diagram of the experiment location, including vehicle approach and pedestrian crossing positions.

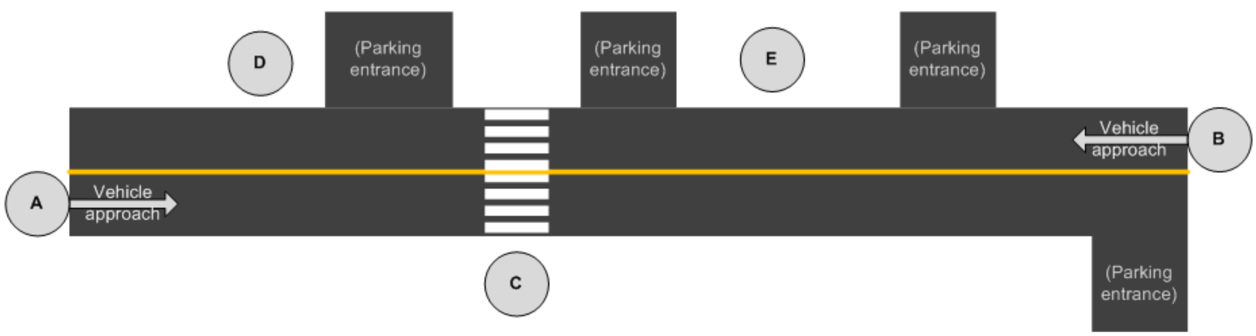

FIGURE 3 Vehicle and crossing positions. Experiment vehicle approaches from positions A and B. Participant 1 crosses at position C using a crosswalk. Participant 2 jaywalks at positions D and E.

Figure 3 shows an approximate layout of the positions. Points A and B identify vehicle approach locations. C identifies the position for P1, and D and E identify the two positions for P2. During each trial, the vehicle approached from points A or B (depending on direction of travel) and slowed to a stop at point C to allow P1 to cross safely at the marked crossing. As Figure 3 shows, the direction of travel also determined whether the vehicle would be approaching from the near or opposite side of the street. After coming to a complete stop, the vehicle continued driving to complete the route. P2 waited at position D or E, whichever was closer to the approaching vehicle. This was done to require the jaywalker to make a decision to cross or not cross in front of a moving vehicle (positioning P2 at or beyond the crosswalk would allow the participant the option to cross when the vehicle was stopped). P2 was directed to change positions after each crossing to maintain a consistent distance from the vehicle.

A researcher was assigned to each participant to start each trial, record the crossing data and prevent participants from walking in front of the vehicle. Both participants were presented with the scenario that they were late for a job interview and getting directions from the experimenter. With the vehicle approaching and the participant's back to the street (facing the experimenter), the experimenter started the trial by pointing to the participant's destination and providing a vocal cue to cross (i.e., "it's there"). The participant would then turn to face the approaching vehicle and indicate when it was safe to cross by walking forward from the start position. The experimenter recorded the time between starting the trial and turning to face the vehicle (the *acquisition* phase) and the time between turning to face the vehicle and beginning to cross (the *decision* phase). The two distinct crossing phases were identified during pilot testing and observed consistently throughout the experiment. A custom Android application was used to record the crossing data. An outward-facing dashboard camera recorded the crossing behaviors of all participants from the vehicle.

The experiment vehicle traveled at one of two predefined speeds, 25 mph (40 km/h) and 15 mph (24 km/h). Each trial began with the vehicle out of view of the participants, driving on the road toward the participants' locations. The distance the experimenter gave the instruction to cross was dependent on the vehicle's speed. At 15 mph (24 km/h), the instruction was given when the van was 150 feet (46 meters) from the crossing position. At 25 mph (40 km/h), the instruction was given at 250 feet (76 meters). This allowed the participant approximately seven (7) seconds between the experimenters' instruction and the vehicle arriving at the participants' position. Following the assumption that a healthy adult pedestrian crosses a single lane of traffic in approximately 2.7 seconds (*8, 10*), participants had approximately four (4) seconds to make the decision to cross safely.

Participants completed a demographic questionnaire prior to participating in the experiment. The questionnaire included questions about street crossing behaviors and perceptions about autonomous vehicles. They also signed an informed consent and completed the NEO™ Five-Factor Inventory-3 (NEO-FFI-3; *14*). The NEO-FFI-3 is brief but comprehensive assessment of five personality domains, including neuroticism, extraversion, openness to experience, agreeableness, and conscientiousness.

Following a brief orientation explaining the procedures and crossing scenarios, the participants were told they would be crossing in front of a prototype autonomous vehicle and to attend to the display on the front of the vehicle. Participants were assigned to one of the two positions (crosswalk or midblock) for the duration of the experiment (i.e., individuals completed all experiment trials at crosswalk or midblock). Each participant completed 16 trials to include all combinations of display (4 types), speed (2 levels) and direction of vehicle travel (2 directions). Presentation order of the 16 speed and display combinations was randomized for each experiment session. At the end of the experiment, each participant completed a structured interview in which they described their crossing strategies and provided opinions about the displays.

The independent variables included the two levels of vehicle speed (25 or 15 mph) and four displays (advice, information, off, control). The dependent variable was the response time. We hypothesized that the symbolic presentations would reduce the time needed to make a decision to cross in front of the vehicle and would therefore improve response times compared to no display.

RESULTS

Participants

Fifty participants between the ages of 19 and 60 (*M*=25.7, median = 22) were recruited for the study, including 17 male and 33 female participants. All participants had experience crossing streets and 96% reported that they cross the street several times a day. Participants were paid $30 for completing the experiment. All participants were required to have 20/20 or corrected to normal vision and no mobility impairments. The Duke University Institutional Review Board (IRB) for Non-Medical Research approved the study.

Response Time

Figure 4 presents the average decision times for participants at the two crossing positions (crosswalk and midblock) for each of the four display conditions. Decision time represented the time between turning to face the vehicle and beginning to cross; therefore, this measure included the earliest point participants were aware of the state of the display.

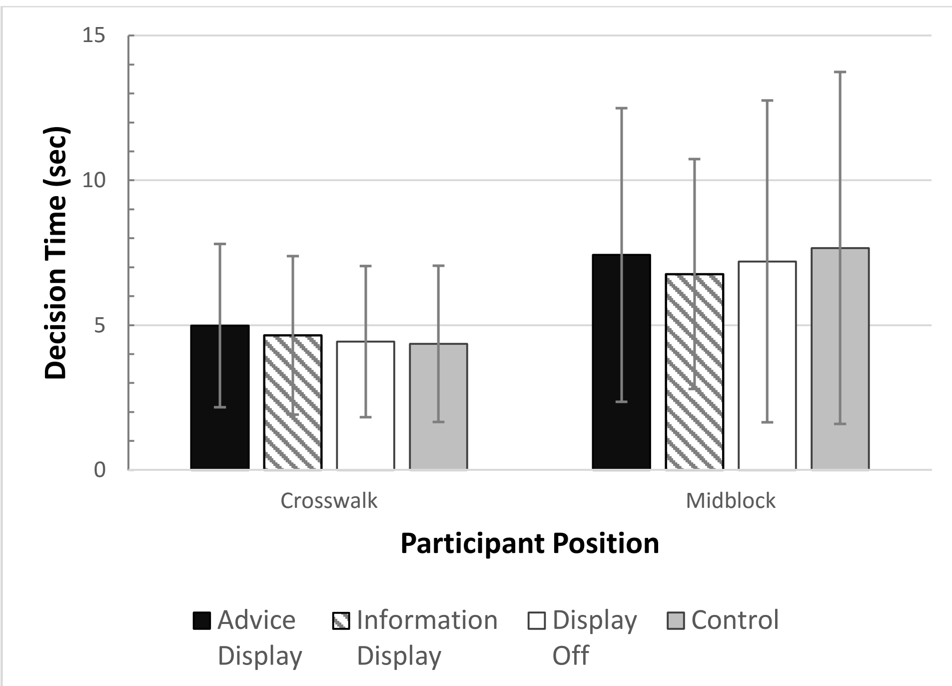

FIGURE 4 Average decision times for the four display conditions for crosswalk and midblock positions. Error bars represent one standard deviation.

Figure 4 shows the lowest average decision time was 4.35 seconds for participants at the crosswalk under the control condition, and the highest was 7.66 seconds for jaywalkers also under the control condition. It is important to note that many participants at the midblock position waited for the vehicle to pass their position before crossing. Participants at midblock positions made the decision to cross after the vehicle passed 56% of the time, while participants at the crosswalk waited until after the vehicle came to a complete stop 28% of the time. This may have extended decision times at the midblock position as participants checked the road a second time to determine if it was clear of other traffic.

Because participants could elect to wait until the vehicle passed to cross, a nested analysis of variance (ANOVA) model was used to both identify significant differences among the display conditions and to identify additional factors affecting decision times. The model included main effects for display, speed, and position, while gender, age and the conscientiousness measure from the NEO-FFI were covariates. These variables were nested in the participants' decision to cross in front of or behind the vehicle.

The ANOVA model failed to reveal any effect due to display ($F(3,27)=0.56$, $p=0.641$); however, other factors were significant. Crossing position had a significant effect on decision times with participants at the crosswalk making faster decisions than the jaywalkers ($F(1,27)=31.86$, $p<0.0001$). On average, crosswalk participants required 4.60 seconds ($SD=2.72$) to make a crossing decision, while midblock participants required 7.26 seconds ($SD=5.22$). This difference is evident in Figure 4. Decision times were significantly faster for participants at the crosswalk, even when accounting for individuals who waited until the vehicle passed ($F(2,27)=633.10$, $p<0.0001$). In other words, even when observing only those trials in which participants crossed in front of the vehicle, crosswalk participants still made faster decisions than midblock participants. This difference could be attributed to participants' expectation that the vehicle would stop at the crosswalk. Participant conscientiousness was a significant covariate on decision time ($F(1,27)=20.00$, $p<0.0001$) with participants with higher conscientiousness scores deciding to cross faster than those with lower scores. Neither age ($F(1,27)=0.063$, $p=0.802$) nor gender ($F(1,27)=2.50$, $p=0.114$) had a significant effect on decision time.

An additional ANOVA was run comparing average acquisition times at the two crossing positions. Acquisition represented the time between receiving the instruction to cross and turning to face the oncoming vehicle and therefore did not include awareness of the display condition. The results showed significant differences due to crossing position ($F(1,10)=20.78$, $p<0.0001$), with jaywalkers ($M=1.23$, $SD=0.49$) turning to face the experiment vehicle faster than participants at the crosswalk ($M=1.49$, $SD=0.67$). This is an expected result since the jaywalking participants were crossing in an unprotected space. Age ($F(1,10)=7.24$, $p=0.007$) and conscientiousness ($F(1,10)=24.17$, $p<0.0001$) were also significant. Gender was significant to acquisition time ($F(1,10)=29.88$, $p<0.0001$), which was in contrast to the decision time results. On average, men had shorter acquisition times ($M=1.25$, $SD=0.51$) compared to women ($M=1.46$, $SD=0.64$).

A logistic regression model was run to identify factors affecting "safe" or "unsafe" crossing behaviors, including the display, position, speed, gender and age. Per the experimental setup, decisions to cross between 4 and 7 seconds after receiving the command to cross were considered unsafe, as crossing during this three-second window would place the participant in the path of the vehicle. The results of the test failed to show any significant differences in the number of unsafe crossings based on display ($X^2(3,N=849)=1.08$, $p=0.782$) or gender ($X^2(1,N=849)=0.19$, $p=0.665$).Vehicle speed was significant ($X^2(1,N=849)=21.87$, $p<0.0001$), with the slower speed condition leading to more unsafe crossing decisions. Age was also significant ($X^2(1,N=849)=9.79$, $p=0.002$). Older participants tended to make more safe crossing decisions than younger participants. Finally, position was also significant to the decision to cross safely ($X^2(1,N=849)=9.09$, $p=0.003$), in that participants made significantly more *unsafe* crossing decisions when the vehicle was on the opposite side of the street.

Subjective Interviews

At the end of each experiment session, participants were asked to identify the most important piece of information needed to cross safely in front of the vehicle and whether the vehicle-to-pedestrian display influenced their crossing decisions. Seventy-six percent of participants reported seeing the display on the front of the vehicle during experiment trials. However, only 12% reported that it influenced their decision to cross, which agrees with the ANOVA results. Distance to the vehicle was reported to be most important in the decision to cross, with 56% of participants noting it as a factor. This is consistent with previous findings that gap distance is the main determinant of a pedestrian's decision to cross (*3*). Speed was reported second in importance (46%), and traffic density in third (24%). Just two participants identified the display as the most important source of information. Despite these results, nearly half of the participants (46%) also reported that having displays like the ones used in the experiment would be helpful when autonomous vehicles become available.

DISCUSSION

Uniform standards for traffic signals have existed in the US for over 90 years (*8*). During that time, regulatory agencies have refined signal designs based on traditional models of surface transportation in which human drivers are expected to attend to a multitude of stimuli. With the development of autonomous vehicles, many of these legacy systems will need to be revisited. For the current work, we developed a preliminary prototype of a vehicle-to-pedestrian communication signal inspired by similar designs (*6, 7*). The design process included many challenges, most importantly the design of a familiar signal that could be interpreted at a substantial distance.

Current guidelines for traffic signals apply to stationary print or illuminated signs. New guidelines will need to be developed if signals are going to be placed on moving vehicles, particularly if they include crucial safety information. The limited time pedestrians have to detect and interpret a signal is going to be an important consideration for the symbol, size and photometric aspects. Messages will need to be simple, salient and familiar. Text messages other than the most recognizable instructions (e.g., STOP) are potentially problematic solutions in situations where decisions need to be made in a few brief seconds. Moreover, signals on moving vehicles will need to account for numerous combinations of vehicles and pedestrians. A vehicle that indicates its intent to stop by announcing "walk" to a pedestrian should not inadvertently instruct the pedestrian to cross in front of another vehicle. A vehicle should be able to give a pedestrian a recommendation to "walk" without giving bad advice to another pedestrian seeing the same information from another intersection. In general, the designs need to scale from the single car and single pedestrian to crowded urban intersections during rush hour, and they need to be consistent across manufacturers.

For this research two types of vehicle-to-pedestrian communication displays were designed and evaluated, including an advice and an information display. The advice display used a familiar design, and the information used a more novel display to communicate vehicle's changing speed. The results of the experiment failed to show any significant differences between the displays, which means they were as effective as the current status quo of having no display at all. Although this result is likely counter to expectations of those companies filing patents for such displays, it still provides practical implications.

The results of the experiment were consistent with previous studies of crossing behavior that indicate gap distance is the main determinant of a pedestrian's decision to cross. The pedestrians recruited for this study all had experience crossing streets, and therefore all of them have developed some sort of crossing strategies. It is likely that these existing strategies were a stronger influence than the novel displays mounted on the front of the experiment vehicle. Furthermore, individual differences including crossing position, personality, age and gender are likely important contributors to an individual's decision to safely cross a road.

Current data on pedestrian injuries and fatalities also show differences among most of these factors (*15*). In 2013, 69% of pedestrian fatalities occurred at midblock positions and 20% occurred at crosswalks. Age groups from 10 to 29 years of age account for the highest pedestrian injury rates, and male pedestrians are more than twice as likely to be killed as female pedestrians. Our results showed that younger participants made more unsafe crossing decisions, and males had shorter acquisition times than females at midblock locations. The results suggest that it may be more important to understand individual differences affecting behaviors than on developing information displays. These will be important design considerations as autonomous vehicles become available.

As research in human factors engineering has shown, all displays (particularly displays presenting safety information) must be tested comprehensively in context to make sure they work as intended. When manufacturers of vehicles and electronic accessories propose vehicle-to-pedestrian displays, it is crucial that they consider the broader implications of the design, and that they incorporate user-centered engineering design and test practices to ensure that autonomous vehicles meet intended safety expectations without introducing a new set of unforeseen hazards.

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