Using a Virtual Environment to Examine How Children Cross Streets: Advancing Our Understanding of How Injury Risk Arises

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Abstract

Purpose To examine how risk of injury can arise for child pedestrians. **Methods** Using a highly immersive virtual reality system interfaced with a 3-D movement measurement system, younger ($M = 8$ years) and older ($M = 10$ years) children's crossing behaviors were measured under conditions that introduced variation in vehicle speed, distance, and intervehicle gaps. **Results** Children used distance cues in deciding when to cross; there were no age or sex differences. This increased risk of injury in larger intervehicle gaps because they started late and did not monitor traffic or adjust walking speed as they crossed. In contrast, injury risk in smaller intervehicle gaps of equal risk (i.e., same time to contact) occurred because crossing behavioral adjustments (starting early, increasing walking speed while crossing) were not sufficient. **Conclusions** Dependence on distance cues increases children's risk of injury as pedestrians when crossing in a variety of traffic situations.

Key words: children; crossing behaviors; pedestrian injury; risk.

Unintentional injuries are the leading cause of mortality for youth <19 years of age, accounting for approximately 830,000 deaths annually worldwide (World Health Organization [WHO], 2008). Pedestrian injuries are especially concerning, with >30,000 children killed annually worldwide (Toroyan & Peden, 2007). Examining pedestrian injuries by age, elementary school children are at particular risk and account for a disproportionate number of injuries (National Center for Injury Prevention and Control [NCIPC], 2013). A number of environmental factors influence children's risk of pedestrian injury, including traffic speed and volume (Mueller, Rivara, Lii, & Weiss, 1990; Roberts, Norton, Jackson, Dunn, & Hassall, 1995). However, *how* children cross streets also can increase their risk of injury (Hoffrage, Weber, Hertwig, & Chase, 2003; Wazana, Kreuger, Raina, & Chambers, 1997). The aim of the current study was to examine measures of crossing behaviors under different traffic conditions to advance our understanding of how

behavioral risk of injury arises for children when they cross streets.

Road crossing is a complicated and highly skilled task that implicates cognition, perception, and motor abilities. It comprises several component and interrelated skills. Selecting a safe place to cross and attentively monitoring approaching traffic are essential skills. One also must perceive traffic-based information about car speed, distance, and intervehicle gap sizes, as well as integrate this information over time for traffic coming from different directions. In addition to appraising traffic conditions, one must judge whether there is sufficient time to cross before the next car arrives and appropriately time the implementation of a crossing. Adapting locomotion behaviors based on traffic information as one implements a crossing is also essential for safety. A change in an approaching car's speed, for example, may necessitate an adjustment in crossing speed to avoid being hit.

Past research with children has examined a number of these component skills (for a more extensive review, see Schwebel, Davis, & O'Neill, 2012). Attention to traffic seems to emerge early in development. For example, by 7 years, children have been shown to recognize the importance of looking to traffic and they do so to the same extent as adults and adolescents (Schwebel, McLure, & Severson, 2014). With regard to location, young children frequently select high-risk situations for crossing, such as busy intersections and mid-block areas between parked cars (Agran, Winn, & Anderson, 1994; DiMaggio & Durkin, 2002). Although both vehicle speed and distance affect one's ability to cross safely in traffic, children aged 5–12 years seem to rely more on vehicle distance than speed in making roadside crossing decisions (Connelly, Conaglen, Parsonson, & Isler, 1998). Research on children's abilities to judge whether they can safely cross a road when presented flowing traffic with different intervehicle gap sizes has yielded mixed results that seem to relate to the methods used.

When children are visually presented traffic situations (e.g., films, videos, virtual reality traffic simulations) and asked to indicate (e.g., button press, verbal response) when they would initiate a crossing, they often make riskier choices than adults (Pitcairn & Edlmann, 2000). For example, children have been shown to delay their crossing longer than adults for similar sized gaps, which can increase risk of pedestrian injury when crossing (Schwebel et al., 2012). One limitation of these kinds of methodologies, however, is that what is measured is the crossing *decision* (e.g., when they say they would cross) and the safety consequences of the decision are extrapolated based on typical or individual mean walking speeds. Although studies of crossing start decisions are important, recent evidence suggests that when actual crossing behavior is measured in real time (i.e., motor-perceptual coupling is intact) using an immersive virtual reality simulator, then children adjust their walking speed to compensate for greater risk owing to traffic conditions. This evasive action resulted in three times fewer hits when compared with simulated crossings by the same children based on start decisions (Morrongiello, Corbett, Milanovic, Pyne, & Vierich, 2015). When tested in ways that naturally couple perceptual and motor performance, therefore, children sometimes demonstrate greater pedestrian capabilities than are evident when other testing methods are used. The importance of considering task demands is highlighted too by the finding that verbal decisions do not necessarily closely align with actual judgments to cross streets (teVelde, van der Kamp, Barela, & Savelsbergh, 2005).

The pattern of these findings generally supports Gibson's Ecological Theory of perception, which

emphasizes the importance of testing in ways that provide individuals the perceptual-motor coupling that they naturally experience in real-world situations (e.g., crossing in actual traffic situations). According to Gibson (1979), crossing in traffic depends on perceiving *affordances* or the relation between properties of the pedestrian and the traffic environment. For safe self-movement in relation to traffic, perceivers presumably judge intervehicle gaps in terms of time to act, and a gap is considered to *afford* crossing if the time needed to cross is less than the temporal intervehicle gap (Lee, Young, & McLaughlin, 1984). Of course, road crossing typically involves dynamic affordances because possibilities for action change over time owing to ongoing variation in vehicle speed and changes in the individual's location as s/he crosses (Plumert & Kearney, 2014). Nonetheless, according to Gibson, the same basic principle applies in all crossing situations, namely perceivers calibrate self-movement based on the immediate perceptual-based information.

To safely cross in traffic situations, perception of time of arrival of the cars in a gap (i.e., time to contact, TTC) is important because one can use this information both to decide *when to initiate* a crossing (i.e., determining whether the temporal gap between cars is sufficient to pass through safely and avoid being hit), as well as to determine whether one needs to *adjust speed* of movement during the crossing to avoid being hit. Judging TTC relies on estimation of speed and distance, and research has explored both methodological and traffic-based factors that affect performance (Hancock, 1998; Hancock & Manser, 1997; Manser & Hancock, 1996). Although an extensive review of research on TTC is beyond the scope of this article (see Hecht & Savelsbergh, 2004), studies examining TTC judgments as a function of intervehicle temporal gap sizes reveal findings relevant to the current study. Specifically, psychophysics studies examining adult accuracy in judging TTC reveals greater difficulty as temporal gap size increases (Schiff & Detwiler, 1979; Seward, Ashmead, & Bodenheimer, 2007). For example, adults have greater difficulty discriminating a 1-s difference between a 7- and 8-s gap for vehicles traveling 50 km/hr than between a 2- and 3-s gap at 50 km/hr. Moreover, for larger gap sizes (e.g., 7 s or more), estimating TTC particularly degrades, indicating that it is much more difficult for adults to judge arrival time of a vehicle that is at a farther than closer distance from the viewer (Seward et al., 2007). Although we are not aware of any studies that have explored these issues directly with child observers, detection of visual looming (i.e., optical expansion as an object approaches) contributes to judgments of TTC and has been examined (Wann, Poulter, & Purcell, 2011). Results reveal that children show the poorest

performance in TTC judgments for more distant moving objects.

Applying these findings to the current study of children's crossing behaviors, it was hypothesized that if difficulty in judging TTC is relevant to children's injury risk when crossing in traffic, then several patterns should emerge in their crossing data. First, one would expect to see longer start delays for those traffic conditions they find more difficult to judge TTC; related to this, it was hypothesized that greater distance conditions will be more difficult for judging TTC than shorter distance conditions. Second, one would expect to see less time to spare and/or more hits for traffic conditions children find difficult to judge TTC. Studies of adult pedestrians in real-world traffic situations show that longer temporal gap sizes involving cars at greater distance are more difficult for adults to judge and are associated with small margins of safety of only 1–2 s (Ashmead, Guth, Wall, Long, & Ponchillia, 2005); no comparable data exist for children.

To assess for these patterns, children in the current study were tested using a highly immersive virtual reality environment (i.e., complete perceptual-motor coupling) and a 3-D movement tracking system. They were asked to cross a street under three temporal gap conditions (3-, 5-, 7-s gaps between vehicles), with each of these presented at three speeds (30, 50, 70 km/hr) and corresponding distances; note that if temporal gap is constant, then varying speed of the traffic varies distance from one car to the next. We reasoned that if distance does not affect children's judgments of TTC, then we should see similar pedestrian performance whenever the temporal gap size is the same even if distance varies (i.e., 3-s gap at 30 km/hr [small distance] vs. a 3-s gap at 70 km/hr [large distance]). In contrast, if children perform like adults, then poorer performance should be seen for larger than smaller gap sizes because TTC estimation is poorer for vehicles at farther than closer distances. To explore these issues, the current study examined how different traffic-relevant characteristics (temporal gap, distance, speed) relate to crossing indices, including: start delay, change in walking speed, hits, and time left to spare (TLS).

Method

Power Analysis

Based on past findings examining children's crossing behaviors, we anticipated obtaining at least medium effect sizes (e.g., η_p^2 of .20+) when conducting analyses of variance (ANOVA) tests comparing means across different conditions (Morrongiello et al., 2015). With alpha level set at .05 and power set at .80, this resulted in an estimated total sample size requirement of 65 (Cohen, 1992).

Participants

A total of 95 English-speaking children were recruited throughout the local community, including 51 in the *younger* group ($M = 8.00$ years, $SD = 0.51$ years, range: 7.50–8.5 years; 51% male) and 44 in the *older* group ($M = 10.13$ years, $SD = 0.55$ years, range: 9.60–10.60 years; 52% male). All children were developing normally (as reported by parent) and had no immediate family member who had ever been injured by a car as a pedestrian. The sample comprised predominantly middle-upper income families (71% earned >\$60,000), with 71% of parents having some/completed college/university, and nearly all of the participants Caucasian (97%). All measures and procedures were reviewed and approved by the university research ethics board, and both the child and one parent granted independent written consent before testing began.

Materials

Screening Questionnaire

The Simulator Sickness Questionnaire was completed over the phone before booking an appointment to ensure the child was not at an increased risk for sickness while wearing the virtual reality headset. The questionnaire, which was designed originally to be given after a simulator session, assessed the child's history of migraine headaches, claustrophobia, motion sickness, and dizziness/nausea (Kennedy, Lane, Berbaum, & Lilienthal, 1993). Anyone reporting these symptoms was excluded from the sample ($N = 2$).

Virtual Reality and Movement Tracking System

The system was constructed in an 8 m $\times$ 5 m room using an eight-camera optical-motion tracking system (PPTH by Worldviz) to feed position data to specialized software (Vizard), using a high-level scripting language (Python) to accomplish many low-level graphics and hardware interfacing actions. Participants viewed the virtual environment through a Virtual Research Systems 1,280 $\times$ 1,024 resolution stereoscopic head-mounted display (HMD) with a 60 degree diagonal field of view, weighing 840 g. Mounted on the HMD is an Inertia Cube 3, which was used to track children's head movements: this is a 3 degrees of freedom (i.e., X, Y and Z coordinates) orientation-tracking system that uses accelerometers and gyroscopic and magnetic sensors to track the orientation of a participant's head, such that the imagery corresponding to changes in head orientation are rendered in real time in the HMD virtual environment. All movement and orientation data are captured at a rate of 60 times per second.

The virtual environment is a two-lane street (2.75 m/lane) with a double yellow line down the

center, and sidewalks with houses set back from the road. The virtual environment's realism is enhanced visually by trees, shadows, and textures, and aurally by realistic sounds of traffic movement (e.g., engine sound becoming louder as cars get closer). Children control the direction they walk and their speed of movement, so they have the ability to adjust their walking to try to evade an approaching vehicle. Traffic flowed from the left of the participant and in the closest lane only, and crossing indices were taken as the child crossed this one lane.

Crossing Measures

The crossing measures that were taken are explained in [Table I](#) and included start delay (in seconds), walking speed (in m/s), TLS (in seconds), hits, and checking traffic (proportion score indicating the time in the car path that the child was watching approaching traffic).

Procedure

Children were tested at a laboratory on campus. After the parent and child granted written consent, the parent remained in the waiting area while the child went to the virtual reality (VR) testing room that was adjacent to a room containing a computer that ran the VR pedestrian simulation. Two trained research assistants were involved, with one overseeing the operation of the computer that controlled the VR equipment and instructing the child on the street crossing trials, and the other remaining in the test room and available to assist the child if needed during completion of the trials.

Each child completed two phases. In phase 1 (VR Familiarization), children were introduced to the virtual environment. First, a researcher demonstrated how to cross the street while wearing the headset as the child watched a computer monitor; this included demonstrating what would happen if one were to be hit by a car (i.e., the vehicle disappears just before point of impact and a siren plays). Then the child was

fitted with the VR headset. To ensure the headset was fitted properly and the child could see clearly, a test screen appeared with letters and the child had to correctly identify the letters before he/she was shown the street environment; knob adjustments allowed the child to adjust the headset to improve fit and make the letters clearly visible. Subsequently, the child was positioned to stand on the curb facing a two-way street (i.e., one lane of traffic in each direction); to prevent possible tripping hazards, all curbs were visually presented but the child did not have to step down/up on these. The child was instructed to cross the street and then turn and walk back to the starting sidewalk to a designated stopping point. They proceeded to repeat this process 10 times with no cars appearing. This gave the child time to adjust to the VR environment, experience walking with the headset on, and ask questions before traffic was presented. Previous research has shown that by the end of this phase, children are fully accustomed to the VR equipment ([Kennedy, Stanney, & Dunlap, 2000](#)); pilot data in which we assessed trends in walking speed over trials revealed that walking speed reached asymptote by trial 10 for all age participants.

In phase 2 (test trials), the child was introduced to traffic and had to monitor the traffic flow and cross when they deemed it safe to do so. The trials included variations in the temporal gap between vehicles (i.e., intervehicle gap in seconds), with vehicles traveling at 30, 50, or 70 km/hr; past research reveals that 50 km/hr is a moderate speed and is associated with increased risk of pedestrian injury among children ([Mueller et al., 1990](#); [Roberts et al., 1995](#)). Three intervehicle gap sizes (3, 5, 7 s) were presented randomly, five times at each of the three speeds, resulting in a total of 45 trials. These gap sizes were selected based on pilot testing with children that aimed to identify a range from "difficult" to "easy" crossing conditions. Within each trial, the gap size between vehicles and car speed was constant. As part of [Figure 1](#), the distance for the

Table I. Pedestrian Measures and Definitions

Measure	Definition
Start delay	The time (in seconds) between the rear bumper of the first car in the chosen gap passing the child and the beginning of the child's crossing.
Walking speed	Calculated as distance/time. Walking speed is calculated once every 20th of a second, providing accurate speeds at various locations during the crossing; the distance travelled in 0.05 s is small.
Time left to spare	The time remaining for the approaching car to intersect with the child's path. Calculated as the time left (in seconds) between the child and the approaching car when the child exits the path of the approaching car.
Hit	Whether the participant was hit by a car or not. Determined based on whether the coordinates of the vehicle's front bumper crosses the position coordinates of the participant.
Checking traffic	Extent to which child checks traffic as he/she crosses in front of the approaching car. Calculated as the percentage of time the child is walking within the path of the car and watching traffic (i.e., head turn of at least 65 degrees toward the approaching vehicle).
Temporal gap	The intervehicle gap size measured in seconds rather than distance units. Calculated as the time in seconds from the rear bumper of the first car in the gap passing the participant and the arrival of the front bumper of the second car at the same point.

Figure 1. Intervehicle distance as a function of vehicle speed and temporal gap between vehicles. Note that there are paired conditions for intervehicle distances of 42, 58, and 97, with members within each pair differing in speed and temporal gap despite being the same intervehicle distance.

individual gap $\times$ speed traffic conditions is depicted, so one can see how these parameters are interrelated.

Analytic Approach

Descriptive and parametric statistics were applied to characterize the data and compare the pattern of results across traffic conditions. Several preliminary data checking procedures were applied before analyses were conducted (Howell, 2007). Specifically, we assessed for outliers based on Cook's distance and removed occasional data as appropriate ($\max = 2$ for a given analysis). Variables were examined for violations in normality. Two variables (hits, checking traffic) were skewed and a log transformation was applied (see "Results" section); examination of the residuals confirmed that the transformed data met the normality assumption for ANOVA (see Karazsia & vanDulmen, 2008 for alternative approaches to analyzing count data when violations of assumptions persist). Before reporting within-participant ANOVAs, we assessed for violations of sphericity to determine whether adjustment to the degrees of freedom was warranted, in which case a Greenhouse-Geisser adjustment was used. Effect sizes are reported as partial eta squared. In conducting paired contrasts using t tests, a Bonferroni adjustment for family-wise error rate was applied; the results reported are based on this adjustment.

Results

Understanding our interpretation of the results necessitates awareness of a few key aspects of the traffic conditions presented. For a given temporal gap size, the TTC is exactly the same regardless of vehicle speed. However, for every temporal gap condition, greater speed results in traffic presented at a greater

distance because computationally $\text{speed} = \text{distance} / \text{time}$ (see Figure 1). A main effect of temporal gap, therefore, indicates the observer used distance cues, whereas a main effect of speed could indicate usage of distance or speed cues. To disambiguate the latter, one can selectively compare traffic conditions in which the temporal gap and speed vary, but the distance is essentially the same. If distance cues are primary, then one would expect performance to be similar for these paired conditions, despite differences in temporal gap and vehicle speed. Three such pairings were built into the study for purposes of assessing children's use of distance as a perceptual cue for crossing (see Figure 1): 3/50 (3-s temporal gap at 50 km/hr) vs. 5/30, 3/70 vs. 7/30, and 5/70 and 7/50. Other pairings introduced small (e.g., 5/50 vs. 7/30) to large distance differences (e.g., 3/30 vs. 7/70) along with variation in temporal gap and speed. As will become apparent below, overwhelmingly, the evidence indicates that children use traffic-based *distance cues* in crossing streets. And, doing so gives rise to their experiencing increased risk of injury as a pedestrian in both small and large intervehicle gap conditions.

How Does Start Delay Vary With Traffic Condition?

An ANOVA was conducted on start delay scores with age (2: younger, older) and gender (2: boys, girls) as between-participant factors and gap size (3: 3, 5, 7 s) and speed (3: 30, 50, 70 km/hr) as within-participant factors. Results revealed a main effect of temporal gap size ($F(2, 164) = 83.98, p < .001, \eta_p^2 = 0.51$) and speed ($F(2, 164) = 117.12, p < .001, \eta_p^2 = 0.59$), but no effects involving age or gender were significant. As depicted in the data shown in Table II (top), significant linear trends confirmed increases in start delay with increases in temporal gap size ($F(1, 82) = 121.94, p < .001, \eta_p^2 = 0.60$) and traffic speed ($F(1, 82) = 200.14, p < .000, \eta_p^2 = 0.71$).

That these effects are likely to be due to children's use of distance cues also is suggested by the data. The bottom of Table II shows the mean start delay per traffic condition and gives results for paired-contrasts comparing start delay as a function of magnitude of difference in gap length distance in meters. As can be seen, for the first three paired contrasts in which differences in distance across traffic conditions were negligible, start delay did not significantly vary, $p > .05$. In essence, when the distance is the same, the processing time for TTC is the same, and start delay is the same. However, once the distance difference between traffic conditions reaches 11.03 m, then significant differences in start delay as a function of traffic condition started emerging. In sum, all of these results for start delay suggest that when the car is at a greater distance, children are slower to implement a crossing.

Table II. Descriptive Data Showing Start Delay (in Seconds) as a Function of Intervehicle Gap Size (in Seconds), Speed (km/hr), and Paired-Traffic Contrasts That Depict Different Magnitudes of Difference in Distance Between Individual Traffic Conditions (in m)

Parameter	Condition	Mean (SD)	Difference in distance ^a	<i>t</i> (85) Value
Gap size	3	0.86 (0.19)	–	
	5	1.02 (0.25)	–	
	7	1.12 (0.33)	–	
Speed	30	0.87 (0.21)	–	
	50	1.01 (0.27)	–	
	70	1.14 (0.29)	–	
Contrast ^b	3–50 vs. 5–30	0.86 vs. 0.88	0.04	1.23
	3–70 vs. 7–30	0.99 vs. 0.97	0.03	0.83
	5–70 vs. 7–50	1.16 vs. 1.14	0.17	0.41
	5–50 vs. 7–30	1.03 vs. 0.96	11.03	2.22*
	3–70 vs. 5–30	0.99 vs. 0.88	16.79	4.75**
	3–50 vs. 5–50	0.86 vs. 1.03	27.73	8.50**
	5–70 vs. 7–30	1.16 vs. 0.97	38.95	6.22**
	3–50 vs. 5–70	0.86 vs. 1.16	55.64	11.34**
	3–50 vs. 7–50	0.86 vs. 1.14	55.48	8.63**
	3–30 vs. 7–50	0.75 vs. 1.14	72.17	10.74**
	3–30 vs. 7–70	0.75 vs. 1.27	111.18	12.55**

^aSee Figure 1 for a graphic representation of distances for individual traffic conditions.

^bFor example, 3–50 indicates a 3-s gap presented at 50 km/hr.

* $p < .05$; ** $p < .01$.

How Does Walking Speed Vary With Traffic Condition Once Children Initiate a Crossing?

In the current VR system, even after children initiate a crossing, the traffic is continuing to approach. Therefore, one would expect pedestrians might increase walking speed to be sure they clear the car path and are not hit. Such tight coupling of motor behavior with perceptual information is adaptive for survival (Gibson, 1979). If children perceive cars at a greater distance to pose less risk of injury, then they may show slower walking speeds as they initiate their crossing. To address this question, an ANOVA was conducted on changes in walking speed (i.e., difference in velocity¹ of movement from stepping off the curb to entering the car path) with age (2: younger, older) and gender (2: boys, girls) as between-participant factors and gap size (3: 3, 5, 7 s) and speed (3: 30, 50, 70 km/hr) as within-participant factors. Results revealed main effects of temporal gap size ($F(2, 160) = 17.13$, $p < .001$, $\eta_p^2 = 0.18$) and traffic speed ($F(2, 160) = 17.83$, $p < .001$, $\eta_p^2 = 0.18$), but no effects involving age or gender. As depicted in the data shown in Table III, significant linear trends confirmed greater increase in walking speed when traffic was travelling at lower car speeds and with decreases in temporal gap size, which are both conditions in which cars are at closer distance, $F(1, 80) = 27.89$ and 28.63 , $p < .001$, $\eta_p^2 = 0.26$ and 0.26 , respectively. Thus, for cars at a closer distance, children increased their

walking speed once they initiated their crossing, whereas for cars at a greater distance they did not do so.

That these effects relate to use of distance cues also is evident in Table III (bottom), which shows the results for paired-contrasts comparing increase in walking speed as a function of magnitude of difference in gap length distance. As can be seen, for the first three contrasts in which differences in distance were negligible, the increase in walking speed did not significantly vary with traffic condition, $p > .05$. Thus, once they made their decision and initiated a crossing, whether they increased crossing speed was dependent on vehicle distance. They showed greater crossing speed for cars at closer than farther distances.

How Does TLS Vary With Traffic Condition?

In the current VR system, TLS at the point when the participant exits the oncoming vehicle's path provides the best index of risk of injury because it indicates how close (temporally) the child came to the moving vehicle. For example, 0.5 s TLS indicates greater injury risk than a 1.5 s TLS. An ANOVA was conducted on these data with age (2: younger, older) and gender (2: boys, girls) as between-participant factors and gap size (3: 3, 5, 7 s) and speed (3: 30, 50, 70 km/hr) as within-participant factors. Results revealed main effects of temporal gap size ($F(2, 164) = 7,661.30$, $p < .001$, $\eta_p^2 = 0.99$) and traffic speed ($F(2, 164) = 136.05$, $p < .001$, $\eta_p^2 = 0.62$), but no effects involving age or gender. As shown in Table IV, there was a significant linear trend indicating less TLS (i.e.,

¹ Velocities at specific time points (i.e., leaving curb, entering car path) are possible because the system captures 60 data points per second; they are calculated based on the distance travelled over 0.05 s.

Table III. Descriptive Data Showing Increase in Walking Speed (in m/s) as a Function of Temporal Intervehicle Gap Size (in Seconds), Speed (km/hr), and Paired-Traffic Contrasts That Depict Different Magnitudes of Difference in Distance Between Individual Traffic Conditions (in m)

Parameter	Condition	Mean (SD)	Difference in distance ^a	<i>t</i> (83) Value
Gap size	3	0.19 (0.11)	—	
	5	0.14 (0.08)	—	
	7	0.13 (0.08)	—	
Speed	30	0.18 (0.09)	—	
	50	0.15 (0.07)	—	
	70	0.13 (0.09)	—	
Contrast ^b	3–50 vs. 5–30	0.20 vs. 0.18	0.04	1.59
	3–70 vs. 7–30	0.15 vs. 0.16	0.03	0.86
	5–70 vs. 7–50	0.12 vs. 0.12	0.17	0.37
	5–50 vs. 7–30	0.14 vs. 0.16	11.03	1.76*
	3–70 vs. 5–30	0.15 vs. 0.18	16.79	2.20*
	3–50 vs. 5–50	0.20 vs. 0.14	27.73	3.98**
	5–70 vs. 7–30	0.12 vs. 0.16	38.95	2.31*
	3–50 vs. 5–70	0.20 vs. 0.12	55.64	4.90**
	3–50 vs. 7–50	0.20 vs. 0.12	55.48	5.68**
	3–30 vs. 7–50	0.21 vs. 0.12	72.17	5.38**
	3–30 vs. 7–70	0.21 vs. 0.11	111.18	4.90**

^aSee Figure 1 for a graphic representation of distances for individual traffic conditions.

^bFor example, 3–50 indicates a 3-s gap presented at 50 km/hr.

* $p < .05$; ** $p < .01$.

Table IV. Descriptive Data Showing Time Left to Spare (in Seconds) as a Function of Temporal Intervehicle Gap Size (in Seconds) and Speed (km/hr)

Parameter	Condition	Mean (SD)
Gap size	3	0.74 (0.29)
	5	2.35 (0.38)
	7	4.18 (0.47)
Speed	30	2.60 (0.33)
	50	2.40 (0.39)
	70	2.25 (0.40)

car came closer) for cars travelling at faster speeds (i.e., cars at *farther* distance) ($F(1, 82) = 209.29$, $p < .000$, $\eta_p^2 = 0.78$). This pattern arises because children initiate crossings later (greater start delay) for cars at farther distance, and then they walk more slowly (assuming safety), but this then places them at risk of injury because the vehicles come closer to hitting them as indicated by lower TLS values. In contrast, a significant linear trend for temporal gap size indicates decreasing TLS (greater risk) as intervehicle gaps shorten, $F(1, 82) = 9,879.65$, $p < .001$, $\eta_p^2 = 0.99$. In this case, risk of injury arises based on entering smaller gaps and trying to manage this risk by initiating a crossing quickly (small start delay—see Table II) and increasing walking speed once they start (see Table III). However, this risk management strategy is *not* successful when entering 3-s gaps (see hits below).

How Do Hits Vary With Traffic Condition?

Because the current VR system allows for evasive action, hits are not a frequent occurrence. This created

issues with the normality of the distribution due to zero scores. Therefore, we limited the current analysis to the 3-s temporal gap condition, which is the most risky traffic gap condition and the one that had the fewest 0 scores. Data were log transformed and those stats are reported; however, the nontransformed descriptive statistics are given for ease of interpretation. An ANOVA was conducted on the transformed scores with age (2: younger, older) and gender (2: boys, girls) as between-participant factors and speed (3: 30, 50, 70 km/hr) as a within-participant factor. Results indicated a main effect of speed, $F(2, 162) = 13.80$, $p < .001$, $\eta_p^2 = 0.15$; there were no effects involving age or gender. A significant linear trend revealed that the average number of hits per trial increased as speed (i.e., distance) increased from 30 to 50 to 70 km/hr ($M = 0.01, 0.02, 0.04$, $SD = 0.02, 0.04, 0.05$, respectively), $F(1, 81) = 22.58$, $p < .001$, $\eta_p^2 = 0.22$. In fact, there were 3 $\times$ more hits for cars at 70 km/hr than at 30 km/hr. Thus, consistent with the time to spare findings, using distance as a cue for crossing creates risk because under large gap conditions, children initiate their crossing late and do not adjust their walking speed adequately.

Monitoring Traffic As They Cross

Examining what percentage of the time children watched the traffic (i.e., head turn angle of at least 65 degrees) when they were within the path of travel of the approaching car also provided evidence consistent with the notion that children assumed greater safety with vehicles at greater distances. An ANOVA was conducted on the log-transformed data with age

(2: younger, older) and gender (2: boys, girls) as between-participant factors and gap size (3: 3, 5, 7 s) and speed (3: 30, 50, 70 km/hr) as within-participant factors. Results revealed main effects of temporal gap size ($F(2, 166) = 7.74, p < .001, \eta_p^2 = 0.19$) and traffic speed ($F(2, 166) = 4.37, p < .01, \eta_p^2 = 0.15$). As shown in Table V, significant linear trends confirmed less watching of traffic with *increases* in temporal gap size and with cars travelling at *faster* speeds, which are both conditions in which cars are at farther distance, $F(1, 83) = 5.99$ and $8.30, p < .05, \eta_p^2 = 0.17$ and 0.19 , respectively. In sum, the pattern of their looking data suggests that children recognized there is greater injury risk when vehicles are closer to them and they responded with greater monitoring of traffic as they crossed. In contrast, they seemed to judge there to be less risk of injury with cars at farther distance and monitored traffic less during these crossings.

Discussion

School-age children are at elevated risk of experiencing injury as pedestrians. Addressing this issue, the current study examined how children's street crossing behaviors vary with traffic conditions. The findings reveal that children use certain safety-enhancing strategies when crossing, including checking traffic as they cross in the path of the oncoming vehicle and adjusting walking speed based on traffic conditions. Nonetheless, there are two ways that their behaviors give rise to risk of pedestrian injury, and these vary depending on the size of the intervehicle temporal gap that children cross into.

Considering the findings from all indices of crossing behavior (start delay, walking speed, hits, TLS), the pattern of results suggests that children use predominantly *distance cues* in deciding when to cross (see also Connelly et al., 1998; Simpson, Johnson, & Richardson, 2003). Moreover, consistent with adult perceptual data (Ashmead et al., 2005; Seward et al., 2007), children seem to have greatest difficulty with cars at farther distances (i.e., larger intervehicle gaps); this difficulty presumably occurs because TTC and perception of speed are interdependent and harder to judge for objects at farther distance. This difficulty is reflected in *all* aspects of their crossing behavior and is one way that children experience greater risk of pedestrian injury. Specifically, for more distant cars (i.e., greater intervehicle gaps), children are slower to implement a crossing. They then walk slowly as they cross into the gap, presumably because they assume they are safe, given the car is farther away; adults also have been shown to overestimate safety and assume that they have more time to cross than they do when vehicles are farther away (Seward et al., 2007). Moreover, children fail to check traffic often *as* they cross and when they are in the path of the approaching car. The

Table V. Descriptive Data Showing the Average Percentage of Time Walking Within the Car Path That the Child is Watching Traffic (i.e., Head Turn of at Least 65 Degrees) as a Function of Temporal Intervehicle Gap Size (in Seconds) and Speed (km/hr)

Parameter	Condition	Mean (SD)
Gap size	3	11.60 (18.55)
	5	6.90 (12.98)
	7	5.40 (10.20)
Speed	30	10.00 (21.33)
	50	8.00 (12.98)
	70	6.50 (9.27)

concatenation of these behaviors gives rise to risk of injury for child pedestrians, as evidenced by less time to spare and the car coming dangerously close to the child. Moreover, children were hit significantly more often under *large* distance gaps of the same temporal size.

The second way that risk of injury arises is when children cross in small temporal gaps. Their performance suggests that children recognize they are at elevated risk of injury under small gap conditions: they initiate a crossing more quickly (small start delay—see Table II), increase walking speed more rapidly once they start (see Table III), and check traffic when they are within the car's path of travel for a longer period. When crossing in small gaps, therefore, children's goal seems to be to get across quickly, which is an appropriate and safety-promoting approach. However, their ability to execute this strategy successfully is limited, which again results in the car passing dangerously close to them (i.e., small time-to-spare scores). Limitations in children's ability to effectively coordinate movement velocity to avoid object collisions also has been noted in other testing situations (te Velde, van der Kamp, & Savelsbergh, 2008).

Importantly, the current findings reveal several striking parallels to those obtained in virtual reality studies of children's bicycling in traffic (Plumert, Kearney, & Cremer, 2004; Plumert, Kearney, Cremer, Recker, & Strutt, 2011). First, both studies suggest more similarities than differences between adult and children in the perceptual cues used to judge traffic and determine when to cross. Plumert and colleagues, for example, found children and adults chose the same temporal gaps for biking between cars, suggesting they did not differ in perception of TTC information per se (Plumert et al., 2004, 2011; see also van der Kamp, Savelsbergh, & Smeets, 1997). Placing the current findings with children in the context of past research with adults suggests that across a broad age range, individuals use primarily distance-based cues in deciding when to cross in traffic situations and they have more difficulties doing so when distance gaps between vehicles is large. Second, both studies find that children act in ways that result in cars coming dangerously close to them (TLS score) or even hitting them.

Plumert and colleagues, for example, found that children chose tight gaps (often 3-s gaps) when presented with dense traffic and they entered quickly behind the lead car to try and get through the tight gap. Nonetheless, they were hit on 20% of these trials (Plumert et al., 2011), which is similar to how children performed for the 3-s gap trials in the current study. The pattern of these diverse findings, therefore, suggests that coordinating self-movement with object movement may be a constraint that limits children's ability to safely get across streets, whether doing so by walking or biking. Consistent with this is evidence that developmental improvements in another visual-motor coordination task (i.e., catching a ball) also reflect changes in adapting motor movements based on perceptual information, rather than reflecting differences in the type of perceptual information used or in sensitivity to judge this information per se (e.g., van der Kamp & Savelsbergh, 2000; van der Kamp et al., 1997; von Hofsten, 1983). Across a variety of visual-motor tasks, therefore, the coordination of movement in relation to dynamic (i.e., time varying) perceptual information seems to be the limiting factor that gives rise to children's risk of injury when they cycle or walk in traffic situations.

What constitutes an appropriate and safe temporal gap for crossing a street, therefore, will depend on the child's ability to scale his/her movements in relation to that of the moving vehicle. In naturally occurring fully dynamic traffic situations in which the child must coordinate his/her movement in relation to that of vehicles approaching from different directions and at varying speeds, this can be a particularly difficult task. By extension, anything that affects the child's movement timing and hinders his/her capacity to quickly implement self-movements (e.g., wearing boots and crossing in snow, carrying a backpack) in reaction to changing perceptual information about ongoing vehicle movement, may elevate their risk of injury as a pedestrian. Indeed, Schwebel, Pitts, and Stavrinos (2009) found that wearing a backpack influenced walking speed, time to spare after crossing, and hits/close calls of college students in a VR pedestrian simulation. Similarly, children's tendency to overestimate their physical abilities (Plumert & Schwebel, 1997; Schwebel & Bounds, 2003; Schwebel & Plumert, 1999) could also elevate pedestrian injury risk: children might initiate risk crossings because they erroneously assume that they will be able to implement a walking speed adjustment to avoid being hit.

Limitations and Future Directions for Research

Although this study provides important insights into children's pedestrian behaviors, there are limitations that merit mentioning and considering in planning

future research on this topic. First, this is a fairly homogeneous sample, and extending the research to recruit a more diverse sample is important. For example, urban and suburban youth often have different traffic experiences, and sometimes effects observed with children in suburban settings are not the same as those found for youth living in urban settings (McComas, MacKay, & Pivik, 2002). Future research should more systematically examine the impact of differential traffic experience on children's crossing performance. Second, including adults would provide for direct comparisons that may be informative. Although there were no age or sex differences in any aspect of the results herein, the age range was limited and there may be differences between the performance of children and adults that further inform our understanding of the mechanisms that give rise to pedestrian injury risk during childhood. Including a broader age range (i.e., younger children and adults) in future research, therefore, may reveal age differences not captured in the current study.

Third, varying the traffic conditions that are presented to the children represents an important extension of the current work. For example, including a mix of gap sizes on a given trial would reveal whether children routinely elect to cross in 3-s gap sizes, which they were forced to do in the current study. Also, having kept temporal gap sizes and speeds the same on a given trial may have highlighted distance as a cue to gap size. Therefore, allowing these to vary within trials in future research may yield additional insights into the mechanisms that influence children's performance and that were not evaluated herein. Finally, creating more challenging traffic conditions for children to navigate would provide more direct evidence of the extent to which children's skill in movement timing and coordination of visual-motor information are key determinants of their risk of pedestrian injury. For example, cars that change speed *during* their approach necessitate anticipating the consequences of one's actions, which is important for planning future behavior to ensure safety. Virtually nothing is known about these essential pedestrian skills and if/how they change during childhood. Study of these pedestrian skills is an important direction for future research on the mechanisms that give rise to pedestrian injury risk during childhood.

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