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Children's Perception of Gap Affordances: Bicycling Across Traffic-Filled Intersections in an Immersive Virtual Environment

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This study examined gap choices and crossing behavior in children and adults using an immersive, interactive bicycling simulator. Ten- and 12-year-olds and adults rode a bicycle mounted on a stationary trainer through a virtual environment consisting of a street with 6 intersections. Participants faced continuous cross traffic traveling at 25 mph or 35 mph and waited for gaps they judged were adequate for crossing. Children and adults chose the same size temporal gaps, but children left far less time to spare between themselves and the approaching vehicle when they crossed the intersection. Relative to adults, children delayed in getting started and took longer to reach the roadway. Discussion focuses on developmental changes in how children coordinate self movement with object movement.

Bicycle crashes are among the most common causes of severe injuries in childhood (Rivara, 1985). As such, bicycling injuries represent a significant public health problem in the United States. Approximately 500,000 bicycle-related injuries are treated in emergency rooms each year (Baker, Li, Fowler, & Dannenberg 1993). Children between the ages of 5 and 15 represent a particularly vulnerable segment of the population, having the highest rate of injury per million cycling trips (Rivara & Aitken, 1998). Motor vehicles are involved in approximately 33% of all bicycle-related brain injuries and in 90% of all fatalities resulting from bicycle crashes (Acton et al., 1995; Rivara & Aitken, 1998). Notably, Rivara, Thompson, and Thompson (1997) found that wearing a helmet did not protect bicyclists from serious injury when a high-energy impact occurred. They concluded that prevention of serious bicycling injuries cannot be accomplished through helmet use alone but must also include efforts to prevent collisions between bicycles and motor vehicles. A critical first step in developing such programs is understanding why such collisions occur. In this article we focus on how immature cognitive and perceptual skills may put children at risk for car – bicycle collisions. In particular, we examined developmental changes in children's ability to choose adequate traffic gaps when bicycling across traffic-filled intersections in an immersive virtual environment.

Adaptive behavior within the environment depends on perceiving affordances or the fit between the characteristics of the perceiver and the properties of the environment (J. J. Gibson, 1979). Research on the perception of affordances has focused on two broad classes of problems facing all organisms with the capacity for self-produced movement. The first problem is effectively moving the self in relation to stationary objects such as stairs and furniture. In this case, perceivers must scale their actions with respect to static properties of objects and surfaces such as angle, height, and size. Studies with infants, for example, have examined how they traverse surfaces varying in rigidity (Gibson et al., 1987), climb slopes varying in steepness (Adolph, 1995; Adolph, Eppler, & Gibson, 1993), reach for objects at varying locations (McKenzie, Skouteris, Day, Hartman, & Yonas, 1993), and grasp objects varying in size (Newell, Scully, McDonald, & Baillargeon, 1989). Likewise, research with older children has examined how children make judgments about the reachability of objects at varying distances (Plumert, 1995; Plumert & Schwebel, 1997; Schwebel & Plumert, 1999), climbability of stairs of varying heights (McKenzie & Forbes, 1992), and the traversability of barriers of varying heights (Pufall & Dunbar, 1992).

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The second problem is effectively moving the self in relation to moving objects such as balls, cars, and people (see also Cutting, Vishton, & Braren, 1995; Oudejans, Michaels, Bakker, & Dolne, 1996). This problem is much more complex because perceivers must use static (e.g., size and shape) and kinematic (e.g., velocity and acceleration) information about objects to scale their actions appropriately. Not surprising, research on how children and adults perceive the relation between the self and moving objects is far more scarce, particularly with children. One situation in which children and adults must scale their actions in relation to kinematic properties of objects is ball catching (Oudejans, Michaels, Bakker, et al., 1996; Peper, Bootsma, Mestre, & Bakker, 1994; van der Kamp, Savelsbergh, & Smeets, 1997). To catch a fly ball, perceivers must use information about the size, trajectory, and speed of the ball to time their interceptive actions appropriately. Research with infants has shown that even 8-month-old infants are able to manually intercept (i.e., ''catch'') moving objects, provided that the objects are moving along a stable trajectory (i.e., an arc) at a relatively slow speed (Von Hofsten, 1983). Other work has shown that control over the timing of catching is similar in young children and adults under both monocular and binocular viewing conditions, suggesting that children and adults are sensitive to the same information for timing their grasp in one-handed catching (van der Kamp et al., 1997). This suggests that changes over development in ball-catching skill are not driven by differences in the type of information used in catching but by differences in the ability to coordinate motor movements with visual information.

Another situation in which children and adults must scale their actions in relation to dynamic information about objects is crossing roads (Connelly, Conaglen, Parsonson, & Isler, 1998; Demetre et al., 1992; Lee, Young, & McLaughlin, 1984; Pitcairn & Edlmann, 2000; Young & Lee, 1987). To determine whether a gap between two vehicles affords crossing, perceivers must judge the temporal size of the gap in relation to the time it will take them to cross the road. Mathematically, the affordance of a gap is the time available for crossing divided by the time it takes to cross. According to Lee et al. (1984), the temporal size of the gap can be defined as the difference between the time to arrival of the first vehicle with the planned crossing line, $tc(1)$, and the time to arrival of the second vehicle with the planned crossing line, $tc(2)$. Crossing time can be defined as the distance to be traversed, d, divided by the average speed of movement, s. According to this formula, children must accurately judge both the size of the temporal gap and the amount of crossing time. Thus, both overestimation of gap size and underestimation of crossing time can contribute to errors in judging whether a gap is sufficiently large to afford safe crossing.

How good are children at judging whether a gap affords crossing? Although nothing is yet known about road-crossing judgments while bicycling, a handful of studies have addressed children's road-crossing judgments while walking (Connelly et al., 1998; Demetre et al., 1992; Lee et al., 1984; Pitcairn & Edlmann, 2000; Young & Lee, 1987). Lee et al. (1984), for example, devised a road-crossing task in which 5- to 9-year-old children crossed a ''pretend road'' set up parallel to an actual road. Children watched the cars on the actual road and crossed the pretend road when they felt that they could safely reach the other side of the pretend road (i.e., before the oncoming vehicle crossed their line of travel on the real road). Although children were generally cautious, they sometimes accepted gaps that were too short. Had children been crossing the actual road, they would have been hit on approximately 6% of their crossings. In addition, a higher proportion of younger children than older children made such errors. Approximately 75% of the 5-year-olds made at least one road-crossing error, whereas only 58% of 9-year-olds did so. These findings suggest that younger children are more likely than older children to overestimate their ability to walk through traffic gaps.

Connelly et al. (1998) devised another task in which 5- to 12-year-old children stood at a roadside and indicated the last possible moment that they would cross (i.e., made go/no-go judgments). The car speeds were grouped into five categories: 0–31, 32–34, 35–37, 38–40, and 41 mph and over. Overall, 11-year-olds selected safe crossing gap thresholds 92% of the time, whereas 5-year-olds selected safe crossing gap thresholds only 66% of the time. It is notable that children of all ages tended to choose the same distance gap for all car speeds, suggesting that they relied more on distance than on speed when making judgments of crossing gap thresholds. Driving research suggests that adults also tend to rely more on distance than on speed information when making judgments about time to contact (Manser & Hancock, 1996). This creates problems when cars are moving faster than normal for a given roadway and drivers are unable to compensate by increasing their own speed.

These studies of children's road-crossing judgments in the face of real traffic have yielded important findings about developmental differences in children's perception of gap affordances while walking. There are limitations of studies conducted at the roadside, however. First, for obvious safety reasons, none of these studies involved children crossing actual roads. Thus, we are left with an incomplete picture of road-crossing behavior because the relation between gap choice and crossing behavior is largely unknown. Children may choose the same size gaps that adults choose, but those gaps may be inadequate for safe crossing because children take longer to cross the road. Second, as Pitcairn and Edlmann (2000) noted, traffic flow in the real world is highly variable, leading to variation in the kinds of crossing problems children face. Without control over the timing and location of traffic, it is difficult to examine systematically factors hypothesized to play a role in judgments of traffic gaps. For example, not all children in the Connelly et al. (1998) study made judgments about vehicles traveling at each of the five speeds, making it difficult to draw definitive conclusions about the roles of distance and speed in children's crossing gap judgments.

The aim of our investigation was to meet simultaneously the goals of ecological validity and experimental control by studying children's road-crossing behavior in an immersive, interactive virtual environment (see Loomis, Blascovich, & Beall, 1999, for a discussion of immersive virtual environments as a basic research tool in psychology). Specifically, we used a high-fidelity, immersive bicycling simulator to examine the gaps 10- and 12-year-olds and adults accept when bicycling across traffic-filled intersections. Children and adults rode a bicycle mounted on a stationary trainer through a simulated environment consisting of a straight, residential street with six intersections. Their task was to cross all six intersections without getting "hit" by a car. Participants faced cross traffic from their left-hand side and waited for gaps they judged were adequate for crossing. The cross traffic traveled at continuous rates of either 25 mph or 35 mph with varying temporal gaps between vehicles.

Three issues were of particular interest. First, are there age differences in the size of traffic gaps that 10- and 12-year-children and adults accept? We focused on 10- and 12-year-olds for both applied and theoretical reasons (see Schwebel, Plumert, & Pick, 2000, for a discussion of integrating basic and applied research in developmental psychology). With respect to applied issues, bicycle injury rates increase from ages 5 to 9 years and peak between 10 and 14 years. Even when injury rates are adjusted for current amount of bike riding (both time and distance), children in late childhood and early adolescence remain most at risk (Thompson, Thompson, & Rivara, 1990). Thus, examining how children in this age range negotiate traffic-filled intersections is critical for developing targeted intervention programs. With respect to basic research issues, the ability to coordinate self motion with the motions of objects appears to undergo developmental change up until at least 12 years of age (Hoffmann, Payne, & Prescott, 1980; Isaac, 1983; Savelsbergh, Rosengren, van der Kamp, & Verheul, 2003). For example, ball-catching skills continue to improve across middle to late childhood, even under simple circumstances (Savelsbergh et al., 2003). Research on children's gap choices while standing at the roadside or crossing a pretend road suggests that younger children are much more likely than older children to accept gaps that are too small for safe crossing. At present, however, virtually nothing is known about how children coordinate self movement with object movement when self movement is indirect (e.g., bicycling across roads) rather than direct (e.g., walking across roads). Choosing an appropriate gap for bicycling across a traffic-filled road presents an added challenge for children because they must judge the temporal size of the gap in relation to the time it will take them to bicycle across the road. Younger children may have more difficulty than older children and adults with accurately determining how long it will take to start up and bicycle a given distance, particularly from a dead stop.

Second, do children and adults take into account the speed of the oncoming traffic when choosing a gap to cross? According to Connelly et al. (1998), 5- to 12-year-old children tend to rely more on distance than on speed when judging traffic gap thresholds. We examined this issue further by examining whether children and adults chose different temporal gaps when cars were moving at slower (i.e., 25 mph) versus faster (i.e., 35 mph) speeds. If 10- and 12-year-old children (and perhaps adults) have difficulty integrating information about speed and distance, they should choose different size temporal gaps when cars are traveling at different speeds. Finally, how do gap choices relate to crossing behavior? As noted previously, previous studies of children's gap choices while walking do not involve children actually crossing roads. Thus, the precise relation between children's judgments and behavior is unknown. We addressed this issue by examining gap choices and how much time children and adults left to spare (i.e., headway) between themselves and the approaching car when they cleared the path of the car.

Figure 1. Photograph of an adult riding an instrumented bicycle through the virtual environment. (Note that there was no traffic on the street with participants in our experiment.)

Method

Participants

Sixty 10- and 12-year-olds and adults participated. There were 10 males and 10 females in the 10-year-old group (*M* age = 10 years 6 months), 8 males and 12 females in the 12-year-old group (*M* age = 12 years 7 months), and 14 males and 6 females in the adult group (*M* age = 19 years 6 months; 1 adult did not provide her age). Children were recruited from a child research participant database maintained by the Department of Psychology at the University of Iowa. Parents received a letter describing the study followed by a telephone call inviting children to participate. Ninety-two percent of the children were European American, 5% were Hispanic/Latino, and 3% were Asian American. Eight percent of the mothers had completed their high school education, 24% had completed some college education, and 68% had a 4-year-college education or beyond. Adults participated to fulfill research credit for an introductory psychology course. Approximately 92% of the adult participants were European American.

Apparatus and Materials

The study was conducted using a high-fidelity, real-time bicycling simulator (see Figure 1). Participants rode an actual bicycle mounted on a stationary trainer. Seat height adjustments were made for participants so that they could comfortably reach the pedals. The bicycle was instrumented to provide information about steering angle, hand braking, and the speed of the rear wheel's rotation that was used to determine the apparent motion of the bicycle through the virtual environment. The bicycle was positioned in the middle of three 10 ft × 8 ft screens placed at right angles relative to one another, forming a three-walled room. Three Electrohome DLV 1280 projectors were used to rear-project high-resolution, textured graphics onto the screens (1280 × 1024 pixels on each screen), providing participants with 270 degrees of immersive visual imagery. The frame rate varied between 15 and 30 Hz depending on the complexity of the scene and the number of vehicles to be simulated at any given time. The apparent motion through the simulated environment and the motions of vehicles were smooth and visually continuous. The experiment was conducted on an 8-processor SGI Onyx supercomputer with Infinite Reality Graphics. The software foundation was the Hank simulator, a real-time ground vehicle simulation system designed to support complex scenarios (Cremer, Kearney, & Willemsen, 1997; Willemsen, Kearney, & Wang, 2003).

Design and Procedure

The experiment began with a 3- to 5-min warm-up period designed to familiarize participants with the characteristics of the bicycle and the virtual environment. Participants rode the bicycle on a straight, residential street with three intersections. During the warm-up period, there was no traffic on the street with the participant and no cross traffic at any of the intersections. Participants were instructed to stay on the right-hand side of the street and to stop at each intersection. The practice session provided participants with the opportunity to learn how to steer, pedal, and stop the bicycle.

Following the warm-up session, children and adults participated in an approximately 10-min test session in which they crossed six intersections. The test section of the simulated environment was a continuation of the street used during the warm-up period. Each intersection was 12 m wide. The distance between intersections was 138 m. There was no traffic on the street with the participant, but there was continuous cross traffic at each of the six intersections. The cross traffic was restricted to the lane closest to the participant and always approached from the participant's left side. The temporal intervals between the cars were defined as the difference between the time at which the rear of the first vehicle reached the crossing line and the time at which the front of the second vehicle reached the crossing line. The temporal intervals between the cars (1.5, 2, 2.5, 3, 3.5, and 4 s) were blocked into sets of six intervals. The intervals of 1.5, 2.5, and 3.5 s appeared at least once in each set of six intervals (but not more than twice) and the intervals of 2.0, 3.0, and 4.0 s appeared less frequently in each set of intervals.[1] The order of intervals within each set was random. Thus, the gaps participants encountered as they reached each intersection varied randomly across participants. The traffic was continuous, however, making it difficult for participants to determine the beginning or end of each set of gaps. Participants in each age group were randomly assigned to one of two speed order conditions. In the 25 mph first condition, the cars at Intersections 1 through 3 traveled at 25 mph, and the cars at Intersections 4 through 6 traveled at 35 mph. In the 35 mph first condition, the cars at Intersections 1 through 3 traveled at 35 mph, and the cars at Intersections 4 through 6 traveled at 25 mph. Thus, participants completed a total of six road-crossing trials. Participants were instructed to stop at each intersection and to cross when they felt it was okay to cross.

Coding and Scores

Coders viewed computer-generated, two-dimensional replays of the paths of the bicyclist and cross traffic through the simulated environment. The Data Visualizer software also provided the clock times corresponding to the positions of the bicyclist and cross traffic. Five bicyclist behaviors were coded for each intersection. The first was whether the bicyclist came to a complete stop. A complete stop was coded when the bicyclist stopped for 2 s or more at an intersection. The second was the time when the bicyclist stopped (or slowed down). Coders used the time at which the bicyclist came to a stop at an intersection lasting for 2 s or more. If the bicyclist stopped, crept forward, and then stopped again for 2 s or more, coders used the last stopping time. If the bicyclist never came to a complete stop, coders used the time at which the bicyclist began moving at the slowest speed as the stopping time. The third was the time when the bicyclist started moving. If the bicyclist never came to a complete stop, the coders used the time at which the bicyclist began to accelerate from the slowest point. The fourth was the time when the bicyclist entered the roadway. Coders recorded when the front wheel of the bicycle entered the roadway. Finally, the time when the bicyclist cleared the lane of the approaching car was recorded. Coders recorded when the rear wheel of the bike cleared the lane of the approaching car.

Intercoder reliability estimates were calculated for the five bicyclist behaviors. Exact percentage agreement for whether the bicyclist came to complete stop was 90%. Pearson correlations for the time when the bicyclist (a) stopped, (b) started to move, (c) entered the roadway, and (d) cleared the lane of the approaching car were all .999.

The five bicyclist behaviors previously described were used to derive the following scores for each intersection participants crossed.

Stopping. Participants received a score of 1 if they came to a complete stop and a score of 0 if they did not come to a complete stop at an intersection.

Waiting time. Waiting time was the interval between when the bicyclist stopped (or slowed down the most) and started.

Gap choice. Gap choice was the size of the temporal gap participants crossed.

Time left to spare. The time for the approaching car to intersect with the bicyclist's path was calculated at three time points, representing the time left between the bicyclist and the approaching car when (a) the bicyclist started to move, (b) the bicyclist entered the roadway, and (c) the bicyclist cleared the lane of the approaching car.

Start-up time. Start-up time was the length of time participants required to travel the distance between the stopping point (or slowest point) and the edge of the roadway.

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[1] We originally intended to present all six temporal intervals in each set, but a truncation error in the randomization program resulted in temporal intervals that were predominantly 1.5, 2.5, and 3.5 s. Note that 1.5-s gaps were not crossable, 2.5-s gaps were crossable but a little tight, and 3.5-s gaps were easily crossable.

Results

Stopping

Did participants actually come to a complete stop at each intersection? Nearly all participants stopped at the first intersection, but many of them failed to come to a complete stop at subsequent intersections. An Age (3) × Speed Order (2) × Intersection (6) repeated measures analysis of variance (ANOVA) on stopping scores revealed an effect of intersection, $F(5, 270) = 9.50$, $p < .001$. Follow-up tests indicated that stopping scores were significantly higher for Intersection 1 ($M = .97$, $SD = .18$) than for Intersections 3 ($M = .67$, $SD = .48$), 4 ($M = .58$, $SD = .50$), 5 ($M = .63$, $SD = .49$), and 6 ($M = .60$, $SD = .49$), and significantly higher for Intersection 2 ($M = .78$, $SD = .42$) than Intersection 4. No other differences were significant. There was also an Age × Speed Order interaction, $F(2, 54) = 4.67$, $p < .05$. Simple effects tests revealed an effect of speed order for the 10-year-olds, $F(1, 18) = 11.92$, $p < .01$. Ten-year-olds in the 25 mph first condition were less likely to stop at intersections ($M = .55$, $SD = .50$) than were their counterparts in the 35 mph first condition ($M = .88$, $SD = .32$), suggesting that starting out with lower vehicle speeds led younger children to become less vigilant about stopping at intersections. Stopping scores in the 25 mph first ($M = .82$, $SD = .39$) and 35 mph ($M = .75$, $SD = .44$) conditions did not differ for 12-year-olds, $F(1, 18) = .30$, *ns*. Likewise, stopping scores in the 25 mph first ($M = .68$, $SD = .47$) and 35 mph ($M = .55$, $SD = .50$) conditions did not differ for adults, $F(1, 18) = 1.05$, *ns*.

Waiting Time

How long did children and adults wait before crossing intersections? An Age (3) × Speed Order (2) × Intersection (6) repeated measures ANOVA on waiting times revealed a main effect of intersection, $F(5, 270) = 17.27$, $p < .001$, and a significant Speed Order × Intersection interaction, $F(5, 270) = 2.82$, $p < .05$. Simple effects tests revealed a significant effect of intersection for the 25 mph first condition, $F(5, 145) = 14.56$, $p < .001$, and for the 35 mph first condition, $F(5, 145) = 6.12$, $p < .001$. As shown in Figure 2, participants in the 25 mph first condition waited significantly longer at Intersection 1 than at any of the other intersections. Participants in the 35 mph first condition waited longer at Intersection 1 than at Intersections 2, 3, 5, and 6, but not at Intersection 4. Thus, participants in both conditions were more cautious at the first intersection than at subsequent intersections. Moreover, participants in the 35 mph first condition reacted to the change in the behavior of the cross traffic at Intersection 4, whereas participants in the 25 mph first condition did not. Specifically, when the traffic slowed down and the distances between cars decreased, participants in the 35 mph first condition waited nearly as long to cross as they did at the first intersection. Given that the cars were traveling more slowly than before, it seems likely that participants were reacting to the change in distance rather than speed.

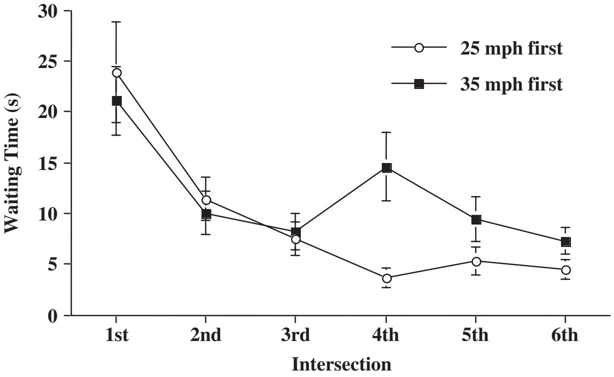

Figure 2. Mean time participants waited before crossing as a function of speed order condition and intersection.

Gap Choice

One of the primary questions of interest was whether the gap sizes that 10- and 12-year-olds and adults chose differed. An Age (3) × Speed Order (2) × Intersection (6) repeated measures ANOVA on gap sizes revealed no effect of age, $F(2, 54) = 1.76$, *ns*. The mean gap sizes chosen by 10-year-olds, 12-year-olds, and adults were 3.5 sec ($SD = .36$), 3.5 sec ($SD = .41$), and 3.6 sec ($SD = .31$), respectively. There was a Speed Order × Intersection interaction, $F(5, 270) = 3.08$, $p < .05$, however. Simple effects tests revealed a significant effect of speed order for Intersection 1, $F(1, 58) = 9.48$, $p < .01$, but not for the other intersections. At Intersection 1, participants in the 35 mph first condition chose significantly larger gaps than did participants in the 25 mph first condition, suggesting that participants were more cautious when the cars were going faster (see Figure 3). Thus, with the exception of the first intersection, gap choices were temporally invariant even though the distances between cars varied with the speed of the cars.

Time Left to Spare

There were no age differences in the size of gaps that children and adults chose to cross. But were

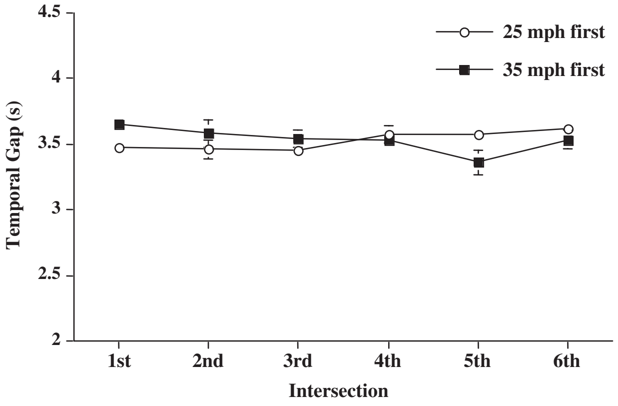

Figure 3. Mean temporal gap chosen as a function of speed order condition and intersection.

there age differences in how much time children and adults left to spare between themselves and the approaching car when they actually crossed the gaps? To answer this question, the time left to spare when the bicyclist cleared the lane of the approaching car was entered into an Age (3) × Speed Order (2) × Intersection (6) repeated measures ANOVA. This analysis revealed a significant effect of age, $F(2, 54) = 18.43$, $p < .001$. Follow-up tests showed that all three age groups differed significantly from one another. Thus, even though children and adults chose the same size gaps, 10-year-olds ($M = 1.13$ s, $SD = .67$) left less time to spare between themselves and the approaching car than did 12-year-olds ($M = 1.49$ s, $SD = .62$), and 12-year-olds left less time to spare than did adults ($M = 1.98$ s, $SD = .46$).

Was the difference in the amount of time children and adults left to spare evident when participants entered the roadway? An Age (3) × Speed Order (2) × Intersection (6) repeated measures ANOVA on time left to spare when the bicyclist entered the roadway yielded significant effects of age, $F(2, 54) = 23.64$, $p < .001$, and intersection, $F(5, 270) = 2.54$, $p < .05$. As with time left to spare when bicyclists cleared the lane of the approaching car, follow-up tests showed that all three age groups differed significantly from one another. The average time left between the bicyclist and the approaching car when the bicyclist entered the roadway was 2.49 s ($SD = .66$), 2.81 s ($SD = .53$), and 3.32 s ($SD = .45$) for 10-year-olds, 12-year-olds, and adults, respectively. Thus, the difference between children and adults emerged between the time when children started off and when they entered the roadway. None of the post hoc tests of the intersection effect reached significance.

One possible reason children left less time to spare between themselves and the approaching vehicle is that they took longer than adults to initiate movement once they had chosen a gap to cross. If this was the case, there should be an age difference in the time between the bicyclist and the approaching car when the bicyclist started moving. To test this possibility, we entered time left to spare when the bicyclist started off into an Age (3) × Speed Order (2) × Intersection (6) repeated measures ANOVA. Although the time left between the bicyclist and the approaching car was less for children than for adults, the effect was not significant, $F(2, 54) = 1.35$, *ns*. When bicyclists started off, the time left between them and the car at the tail of the gap was 5.37 s ($SD = 1.56$), 5.42 s ($SD = 1.24$), and 5.80 s ($SD = 1.45$) for 10-year-olds, 12-year-olds, and adults, respectively.

Another possible reason children left less time to spare between themselves and the approaching vehicle is that children took longer to bicycle from the starting point to the edge of the roadway. Taking significantly longer to reach the roadway would necessarily result in less time between the bicyclist and the approaching car by the time the bicyclist reached the roadway. To test this possibility, we entered start-up times into an Age (3) × Speed Order (2) × Intersection (6) repeated measures ANOVA. Although children took somewhat longer to reach the roadway, there was no effect of age, $F(2, 54) = 1.18$, *ns*. The average time to reach the roadway was 2.88 s ($SD = 1.33$), 2.62 s ($SD = 1.20$), and 2.48 s ($SD = 1.43$) for 10-year-olds, 12-year-olds, and adults, respectively.

Why then did children leave less time between themselves and the approaching car by the time they reached the roadway? Clearly, the answer lies in the additive effects of taking longer to get started and taking longer to reach the roadway. Notice in the preceding analyses of these two factors, children took slightly longer to get started and they took slightly longer to reach the roadway. Taking longer to get started and taking longer to reach the roadway necessarily resulted in less time to spare by the time the bicyclist reached the roadway. Thus, although neither of these two factors varied significantly with age, when summed together they produced significant age differences in the time left to spare between the bicyclist and the approaching car by the time the bicyclist reached the roadway.

Discussion

The results of this investigation clearly show that relative to adults, children's gap choices and road-crossing behavior were mismatched. Children and adults chose the same size gaps and yet children ended up with less time to spare between themselves and the approaching car by the time they even entered the roadway. By the time children actually cleared the path of the oncoming car, the margin for error was very small, particularly for 10-year-olds (1.1 s). How did this mismatch occur? Relative to adults, children delayed slightly in getting started and took somewhat longer to reach the roadway. When concatenated together, these two factors produced pronounced age differences in the time left to spare between the bicyclist and the approaching car by the time participants entered the roadway. This mismatch between children's judgments and their abilities is consistent with a wide array of research on children's perception of affordances (Adolph, 1995, 2000; Adolph et al., 1993; McKenzie & Forbes, 1992; Plumert, 1995; Plumert & Schwebel, 1997; Schwebel & Plumert, 1999) and is consistent with the idea that errors in judging affordances may play an important role in unintentional childhood injuries (Plumert, 1995).

Why did gap affordances differ for children and adults? One possibility is that children had more difficulty judging time to contact or how long it would take the vehicle to reach the crossing line. In other words, children may have thought it would take longer for the approaching vehicle to reach the crossing line than adults thought it would. Research on adults' judgments of time to contact has consistently shown that they underestimate time to contact and that underestimation increases as arrival time increases (Caird & Hancock, 1994; Cavallo & Laurent, 1988; McLeod & Ross, 1983; Schiff & Detwiler, 1979). Although research on children's judgments of time to contact is scarce, the results of one study showed that children under the age of 12 exhibit greater underestimation of time to contact than do adults (Hoffmann et al., 1980). This pattern of findings suggests that children should choose larger gaps than adults. The fact that children and adults in our investigation chose gaps that were virtually identical in size suggests that they did not differ in their perception of the temporal (i.e., time to contact) information. This is consistent with the conclusion that children and adults perceive temporal information similarly in the context of ball catching (van der Kamp et al., 1997). However, further research is needed to determine to what extent perception of time to contact is similar for 10- and 12-year-old children and adults in our task.

A second possible reason the gap affordances of children and adults differed was that children overestimated how quickly they could cross the road. Relative to adults, children had more difficulty in getting the bike started (despite the fact that the bike offered little resistance). Failure to take fully into account the time required to get the bike started would result in more time than anticipated to reach the edge of the roadway and consequently less time available to bicycle across the roadway. This explanation is consistent with other research showing that children often overestimate their physical abilities and that 6-year-olds who overestimate their physical abilities are more at risk for injury (Plumert, 1995; Plumert & Schwebel, 1997; Schwebel & Plumert, 1999). McKenzie and Forbes (1992), for example, found that 9- and 12-year-old boys overestimated the height of the stairs they could climb. Plumert and Schwebel (Plumert, 1995; Plumert & Schwebel, 1997; Schwebel & Bounds, 2003; Schwebel & Plumert, 1999) have consistently shown that 6- and 8-year-olds are especially prone to overestimate their reaching and stepping abilities in ambiguous situations, for example, when objects are just out of reach. Thus, overestimation of how quickly they could get the bike moving may have contributed to why children left less time to spare between themselves and the approaching car.

A third possible reason the gap affordances of children and adults differed is that children had more difficulty coordinating their own movement with that of the traffic. In particular, children took somewhat longer than adults to initiate movement once they had chosen a gap to cross. Given that the cars did not slow down as they approached the intersection, taking longer to initiate movement necessarily resulted in less time available for crossing. The fact that children took longer to initiate movement is consistent with other research using videotaped traffic events showing that one of the biggest differences between adult and child pedestrians is delay before initiation of crossing (Pitcairn & Edlmann, 2000). Unlike adults, child pedestrians often do not begin to initiate crossing until the first of the two vehicles has already passed. This approach to road crossing may actually put children at greater risk for getting hit by a car. Other research has shown that coming to a complete stop before crossing an intersection results in less time to spare between the pedestrian and the approaching car (Oudejans, Michaels, van Doort, & Frissen, 1996). Together, these findings suggest that children have more difficulty than adults in fitting their actions to the environment. This may be particularly problematic in dynamic situations, where children must coordinate their own movement in relation to the movement of objects in the environment.

For both children and adults, gap choices were temporally invariant, meaning that they chose larger distances between cars when the cars were traveling at 35 mph and shorter distances when the cars were traveling at 25 mph. This indicates that children and adults appropriately integrated information about speed and distance in their judgments of gap sizes. We should note, however, that there was some hint in our data that children and adults reacted more to changes in distance than in speed. In particular, participants in the 35 mph first condition reacted to the change in the behavior of the cross traffic at Intersection 4, whereas participants in the 25 mph first condition did not. Specifically, when the traffic slowed down and the distances between cars decreased, participants in the 35 mph first condition waited nearly as long to cross as they did at the first intersection. The most plausible explanation for this finding is that the change in the distances between cars was highly salient, but the change in speed was not. Therefore, participants in the 35 mph first condition waited until they had a better sense of how fast the cars were traveling before attempting to cross. This increased caution on the part of the 35 mph first group makes sense given that shorter distances between the cars would signal unsafe gaps for cars traveling at higher speeds.

The finding that gap choices were temporally invariant is inconsistent with other work suggesting that child pedestrians rely primarily on distance to make crossing threshold judgments (Connelly et al., 1998). However, several differences between the two investigations may have contributed to this inconsistency. First, most children in the Connelly et al. (1998) study were below age 10. Younger children may have more difficulty than older children with integrating speed and distance information to arrive at judgments of time (Piaget, 1946/1970; Siegler & Richards, 1979; Wilkening, 1981). Second, we only tested children's road-crossing judgments for speeds of 25 mph and 35 mph. Children (and adults) may have more difficulty judging speeds that exceed 35 mph and may shift to relying more on distance than on speed for faster moving cars. In fact, Connelly et al. found that safe distance indexes dropped dramatically for car speeds of 35 mph and above, particularly for children under age 10. Third, differences in the tasks themselves may have led to differences in performance. In our experiment, cars were moving at the same continuous rate at a given intersection, making it easier to judge speed. Moreover, participants were free to watch as many cars pass as they liked before crossing the intersection, providing them with more information about the speed of the cars. Finally, choosing a gap that affords safe crossing may be easier than deciding on the last possible moment to initiate safe crossing. Further research is needed to determine the circumstances under which children rely on different sources of information to judge gaps.

A final issue concerns studying behavior in virtual environments. In particular, did children and adults behave in our virtual environment as they do in the real environment? Although virtual environments are an exciting new medium for investigating children's behavior under safe and controlled conditions, the results of such experiments are of questionable value if virtual environments lack ecological validity. First, children and adults did not bicycle recklessly through our virtual environment. In fact, there were only 9 instances out of 360 crossings (2.5%) in which participants were "hit" by a car (all but 1 were 10-year-olds). Second, as one might expect when confronting a novel intersection in the real environment, participants were much more cautious on the first intersection than on subsequent intersections. After the first intersection, children and adults appeared to adopt bicycling habits that are commonly seen in the real environment. Most striking was the high proportion of participants who failed to come to a complete stop at intersections (despite our instructions to stop at each intersection). In fact, 10-year-olds and adults who reported more stopping at intersections in the real environment were more likely to stop at intersections in our virtual environment, $r(19) = .48$, $p < .05$, and $r(20) = .41$, $p = .07$, respectively. Likewise, adults who reported using a bicycle frequently to get around in the real environment were less likely to come to a complete stop at intersections in the virtual environment, $r(20) = -.58$, $p < .01$. This preference for staying in motion (especially among more experienced cyclists) may reflect real-world bicycling experiences. In particular, experienced cyclists may know that it is easier to get up to speed and judge the crossability of gaps when staying in motion. This latter speculation is consistent with the finding that people find it much easier to judge whether a fly ball is catchable if they are allowed to move (as if to catch the ball) before making the judgment (Oudejans, Michaels, Bakker, et al., 1996). Although more direct validation of behavior in virtual environments is needed, the results of this investigation suggest that immersive virtual environments are a promising tool for addressing difficult-to-study problems such as road-crossing behavior.

In conclusion, this investigation adds to a small, but growing number of studies on children's perception of affordances involving kinematic information. The fact that 10- and 12-year-olds and adults chose gaps that were virtually identical and chose gaps that were temporally invariant suggests that they did not differ in their perception of the relevant visual information. However, the fact that children ended up with less time to spare between themselves and the approaching vehicle by the time they reached the edge of the roadway suggests that children had more difficulty than adults in coordinating their own movement with that of the cars. Quite likely, developmental changes in coordinating motor movements with visual information occur as children gain experience with performing particular tasks (Savelsbergh & van der Kamp, 2000). For example, experience with crossing roads may help children develop strategies such as initiating crossing before the first of the two vehicles has completely passed. Further research is needed, however, to clarify the possible mechanisms underlying developmental changes in the perception of affordances involving kinematic information.

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