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How Children and Adults Learn to Intercept Moving Gaps

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Abstract

We used an immersive virtual environment to examine how children and adults learn to intercept moving gaps and whether children and adults benefit from variability of practice. Ten- and 12-year-old children and adults attempted to bicycle between two moving vehicle-size blocks without stopping. In Experiment 1, block motions were timed such that if participants maintained a constant speed, they would intercept the gap between the blocks. By the last set of intersections, adults learned to maintain a constant speed throughout the approach to the intersection and 12-year-old exhibited less variability in time-to-spare when they intercepted the blocks. Ten-year-olds exhibited no significant change across intersection sets. In Experiment 2, block motions during the first eight intersections were timed such that participants had to either speed up or slow down on all intersections, or had to speed up on half and slow down on half of the intersections. On the last four intersections, all groups encountered a novel block timing in which no adjustment in speed was necessary to intercept the blocks. Adults performed well regardless of whether they experienced consistent or variable block timings. Ten-year-olds in the variable condition performed better on slow-down trials than their peers in the slow-down condition, but worse on speed-up trials than their peers in the speed-up condition. Discussion focuses on possible developmental changes in reliance on perceptually-available and remembered information in complex perception-action tasks.

A critical component of refining any perceptual-motor skill is learning how to bring motor actions more tightly in line with perceptual information. Skill in perception-action tuning is essential for performing temporally-sensitive tasks, and becomes critical when the tasks in question have potentially severe consequences for failure. One such high-stakes task is crossing through busy traffic as a pedestrian or bicyclist. A sizeable body of literature has shown that children and young adolescents are not as proficient as adults at road crossing (Lee, Young, & McLaughlin, 1984; Young & Lee, 1987; Plumert et al., 2004; te Velde et

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al., 2005). This performance deficit is borne out in pedestrian and bicyclist injury data, in which children are overrepresented relative to adults (National Highway Traffic Safety Administration, 2009). A number of studies have indicated that children's problems with road-crossing may be due to immature perceptual-motor skills, and in particular children's ability to coordinate their movement with the movement of other objects in the environment (te Velde et al., 2005; Chihak et al., 2010). However, we know little about how perceptual-motor tuning in movement synchronization tasks improves as children gain experience with performing such tasks.

Contemporary views of perceptual-motor development suggest that short-term learning experiences produce long-term developmental changes in the perception-action system (Newell, Liu, & Mayer-Kress, 2001; Thelen & Smith, 1994). It seems likely, then, that exploring differences in how adults and children learn to perform tasks over a relatively short interval will provide insight into the mechanisms by which short-term changes in perception-action tuning links to long-term development. The objectives of the current study were to explore how short-term learning in a gap interception task varies between child and adult bicyclists, and to determine whether children and adults benefit from variability of practice while performing this task.

Synchronizing Self and Object Movement

Road crossing requires the successful completion of two perceptual-motor tasks. Roadway users must first identify a gap in traffic that affords safe crossing. This involves user assessments of how long they will take to cross the lane of traffic and how long vehicles will take to reach their crossing path (i.e., time-to-arrival). A gap affords crossing if the individual's (projected) crossing time is less than the temporal size of the gap (Lee et al., 1984). Once an acceptable gap has been identified, users must then coordinate their movement through the gap with the movement of traffic so as to avoid a collision with a vehicle. This involves cutting in closely behind the lead vehicle in the gap, while crossing as quickly as possible. To effectively cut in behind the lead car with minimal clearance, roadway users need to exert prospective control over movement by anticipating exactly when to begin moving.

Previous studies by Plumert, Kearney, and Cremer (2004) and Plumert, Kearney, Cremer, Recker, and Strutt, (2011) explored how children (10- and 12-year-olds) and adults cross roadways by having them ride a bicycle through a virtual environment consisting of a straight residential street with multiple intersections. Participants faced cross traffic from their left-hand side and waited for gaps they judged were adequate for crossing. The results clearly showed that, relative to adults, children's gap choices and road-crossing behavior were less finely tuned. Children and adults chose to cross through the same size gaps, yet children ended up with less time to spare when they cleared the path of the car. For 10-year-olds in particular, this resulted in a very narrow safety margin. Further analyses revealed that children delayed their entry into the roadway relative to the lead vehicle in the gap (as compared to adults). This resulted in less time to spare when children cleared the path of the approaching car. These differences in how children and adults time movement suggest that immature perceptual-motor skills may play a role in putting children at greater risk for car-bicycle collisions.

A follow-up study by Chihak et al. (2010) modified this road-crossing task to examine movement synchronization in children and adults by providing a single target gap through which riders were to cross without stopping. The target gap in the cross-traffic was timed to arrive at the intersection such that riders would either need to speed up or slow down in order to successfully intercept the gap. Although children and adults appeared to be using similar strategies for intercepting a moving gap without stopping, children were much more variable on their approach to the intersection, and made significant speed overcorrections as they approached. Interestingly, the incidence and magnitude of children's speed overcorrections were significantly greater on trials where the rider was required to slow down than to speed up in order to intercept the gap. More specifically, children slowed down far more than was necessary as they approached the intersection, which then required them to accelerate sharply in order to intercept the gap. The net effect of children's imprecise movement timing was a significantly smaller safety margin than was seen in adults. In all, child bicyclists appeared to be less skilled at synchronizing their movement with the movement of other objects.

Children's difficulty with coordinating self- and object-movement is not limited to road crossing, and has been observed across a number of interceptive tasks. For example, te Velde, van der Kamp, and Savelsbergh (2008) found that younger children (5- to 7-year-olds) were less successful than older children (10- to 12-year-olds) and adults when performing a small-scale interception task that involved moving a doll across a small-scale "roadway" in between two approaching model cars. In another study, Chohan, Verheul, Van Kampen, Wind, and Savelsbergh (2008) had 5- to 7-year-olds, 10- to 12-year-olds, and adults walk to intercept a moving target in the real world. As in the Chihak et al. (2010) study, children's performance suggested that while they were trying to use a strategy similar to that of adults when intercepting the target, their performance was significantly more variable due to less precise movement timing.

Learning to Synchronize Self and Object Movement

Numerous studies have shown that adults exhibit a tightening of their interception skills with practice, even over relatively short time periods (Buekers et al., 1999; Montagne et al., 2003; Camachon et al., 2007). For example, using a highly-constrained interception task in a virtual environment, Montagne et al. (2003) found that adult performance became less variable and more structured over the course of the experimental session. Other work 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 arc at a relatively slow speed (von Hofsten, 1983). However, little work has been devoted to investigating how children become more proficient at performing interceptive tasks involving translation of the actor through the environment. In particular, what changes in timing skills are occurring as children become better at performing a movement synchronization task, and are these changes different from what is observed in adults?

Some indication of how children might be learning to coordinate movement can be drawn from previous work looking at short-term changes in children's road-crossing performance. Plumert et al. (2011) explored how movement timing changed in both child (10- and 12-year-olds) and adult cyclists while crossing 12 intersections during the course of a single experimental session. Ten-year-olds in particular benefitted from experience with the road-crossing task, as they showed improved timing of their movement relative to the lead car in the gap across the trials (i.e., cutting in closer behind the lead car when they entered the intersection). As a result, they also improved their safety margins during the later trials. These types of gains in movement timing over short-term timescales may help produce the developmental changes seen over longer-term timescales.

One question left unanswered is how variability of practice impacts children's perceptual-motor learning in interception tasks. Previous work indicates that when individuals perform a task over a range of conditions (e.g., throwing balls of varying weights) their overall performance for that entire class of movements (ball throwing) will increase more rapidly than if they perform the task the same number of times under consistent conditions (e.g., throwing balls of the same weight). This phenomenon has been documented over a broad range of perceptual and motor tasks such as ball throwing, airplane guidance, and even discrimination of speech sounds (Schmidt, 1975; Shea & Wulf, 2005; Rost & McMurray, 2009.) For example, recent work by Huet et al. (2011) manipulated elements of the visual scene that could be used to guide a landing task in a flight simulator. In the variable practice condition, adult participants encountered different values of these visual variables on different trials. Participants in the constant practice condition experienced the same number of trials, but the visual variables were held constant. Adults who received variable practice performed better in the absence of feedback, and were better at adapting to a novel landing scenario than participants who had experienced constant practice. While considerable work has been done exploring the benefits of variable practice for children when performing simple motor tasks (e.g. Clifton, 1985; Smoll & DenOtter, 1976; Wulf, 1991), the effects of variable practice when coordinating a complex movement synchronization task like road crossing have yet to be explored.

The Current Investigation

The objective of the current investigation was to identify differences in how children and adults learn to perform a gap interception task in a single experimental session. Ten- and 12-year-old children and adults rode a bicycling simulator through a series of intersections in an immersive, interactive virtual environment. The participants’ task at each intersection was to pass without stopping through a gap between two fast-moving objects (i.e., rectangular blocks the size of a typical car that moved at 35 miles per hour). In Experiment 1, we were interested to see whether repeated performance on a task in which no speed adjustment was required would produce differential learning effects for adults and children over the course of the experimental session. Therefore, the blocks at all of the intersections were triggered to begin moving such that if the rider made no adjustments in speed, he or she would pass directly through the middle of the target gap. We were particularly interested in whether children would exhibit overcorrections in their approach (i.e., slowing down far more than is necessary), and whether the variability and magnitude of overcorrections in children changed over the course of the session.

In Experiment 2, we wanted to determine how practice with consistent versus variable trial types affected the rate at which children and adults improved their performance on the interception task and adapted to a novel block timing. To address this question, the block timings were adjusted such that on the first eight trials participants needed to adjust their speed in order to successfully intercept the gap. Participants were either required to speed up on all of these trials, slow down on all of these trials, or to speed up on some trials and slow down on other trials. During the last four intersections, participants in all conditions experienced a block timing they had not previously encountered in which no speed adjustment was necessary (the same timing as in the first experiment). We expected that children in the variable-trials condition would demonstrate more rapid perception-action tuning during the first eight trials, and would be quicker to adapt to the novel block timing during the last four trials than those who had seen only speed-up or only slow-down trials.

EXPERIMENT 1

Method

Participants—Fifty 10- and 12-year-olds and adults participated. There were 7 males and 7 females in the 10-year old group (*M* = 10 years, 7 months; range = 10;4 to 10;10), 10 males and 6 females in the 12-year old group (*M* = 12 years, 9 months; range = 12;4 to 12;11), and 10 males and 10 females in the adult group (*M* = 19 years, 2 months, range =

18;3 to 24;3). Six additional 10-year-olds were excluded because they failed to follow instructions throughout the experimental session (two participants) or there was a mechanical problem with the simulator that made the data unanalyzable (four participants). Ninety-seven percent of the children were Caucasian, and 3% chose not to identify their race or ethnicity. The children were recruited from a child research participant registry maintained by the Department of Psychology at a Midwestern university, and were paid $10 for their participation. Adult participants were recruited from an introductory level psychology course, and received course credit for their participation.

Apparatus and Materials—The study was conducted using a high fidelity, real-time bicycling simulator (Plumert et al., 2004; 2011; http://www.cs.uiowa.edu/~hank/). A bicycle mounted on a stationary frame was positioned in the middle of three 10 ft wide × 8 ft high screens placed at right angles relative to one another. Three Projection Design F1+ projectors rear-projected high-resolution graphics onto the screens, providing participants with 270 degrees of immersive visual imagery. The viewpoint of the scene was adjusted for each participant's eye height. The virtual environment was populated with residential buildings and roadside features typical of a small town. Participants rode through the town on a 2.25 km-long, two-lane roadway. There were 15 cross streets which intersected the primary roadway at 150 m intervals. All roadways were 12 m wide, and at a level grade. There was no ambient traffic on the roadway with the participant, and the intersections did not have stop signs or other traffic control devices.

The pedals, handlebars, and right hand brake on the bicycle were all functional, but participants were not required to balance the bicycle because the bicycle mount was rigid. The bicycle was instrumented to record the steering angle of the front wheel and the speed of the rear wheel. These two measures were combined with virtual terrain information to render the graphics corresponding to the bicyclist's real-time trajectory through the virtual environment. The rear wheel was mated to a friction-drive flywheel and torque motor which generated an appropriate dynamic force taking into account rider and bicycle mass and inertia, ground friction, and other physical factors.

The computing platform for the simulation environment was a network of six PCs. The underlying software system was a sophisticated real-time ground vehicle simulator developed in-house by the co-investigators (Cremer, Kearney, & Willemsen, 1997; Willemsen, Kearney, & Wang, 2003).

Design and Procedure—The experimenter first helped participants put on a bicycling helmet and adjust the bike seat height. The experimenter told participants that they would be riding through a virtual neighborhood, and instructed them to ride as though they were riding in a similar, real-world neighborhood.

The experiment began with a brief warm-up session designed to familiarize participants with the characteristics of the bicycle and the virtual environment. The familiarization session provided participants with the opportunity to learn how to start, stop, and steer the bicycle. During the familiarization session, participants rode for two blocks without any other moving objects on the roadway or on the cross streets. Participants were instructed to notify the experimenter if they experienced any simulator sickness.

Following the warm-up session, children and adults participated in an approximately 10-minute test session in which they crossed 12 test intersections. At each test intersection, there was a series of 14 blocks placed in the near lane of the cross-street on the participant's left-hand side. The front of the lead block was positioned 173 m from the intersection. The blocks were 7.8 m long, 2 m wide, and 2 m high—roughly the size of a typical sedan.

Abstract colored blocks were used in lieu of actual vehicle models to avoid concerns about encouraging children to ride through tight gaps in real world traffic. The sequence of blocks consisted of nine yellow blocks, two red blocks, and then three yellow blocks. The target gap was defined by the red blocks.

As the cyclists approached the intersection, the blocks started to move and traveled towards the intersection at 15.646 m/s (35 mph). The red blocks were spaced 3.5 s (55 m) apart. All of the other blocks were spaced 0.5 s (7.8 m) apart. This meant that once the blocks were triggered, the participants were able to observe moving blocks for 20 s before the target gap arrived at the intersection (i.e., the crossing line), and for another 3.5 s before the gap closed. The participants' task was to safely pass through the 3.5 s target gap without stopping.

We used an adaptive scenario approach (Grechkin & Kearney, 2011) in which the timing of the trigger was based on an estimate of each participant's time-to-arrival at that intersection. The blocks were timed to begin moving so that if participants maintained a constant speed, they would arrive at the intersection in the center of the target gap (i.e., 1.75 s after the gap opened). On a given trial, the simulation continuously calculated the participant's likely time-to-arrival, assuming the participant maintained their average speed as measured using a trailing 2-s window. In pilot testing this window was shown to afford the best balance between stability and responsiveness to changes in participant speed. Post-hoc assessment showed that the overall distribution of initial projected arrival times (i.e., when the blocks began moving) was centered on the middle of the gap.

If a participant did not successfully intercept the gap the trial was categorized as a "collision." Of the 600 total trials there were only three trials that resulted in a collision (all children). On one trial, the participant missed the gap by more than 1.75 s (half the size of the gap) and the data from that trial were excluded from all analyses.

The first intersection served as a practice intersection for the interception task. After the practice intersection, participants rode through six test intersections after which participants were given a two-minute rest period. After the break, participants rode through an empty intersection (with no moving blocks) before riding through the next set of six test intersections. The participant was then debriefed about the experiment and thanked for their participation.

Results

As in previous work (Chihak et al., 2010), we analyzed two aspects of the bicyclists' interception performance. The first was participants' performance along the approach to the intersection. For each trial, we computed each participant's instantaneous projected time-to-spare on the approach as a function of the time remaining to participant's actual arrival at the intersection. Projected time to spare was computed as the projected time the participant would pass through the gap (assuming they traveled at constant speed) minus the time the front of the trailing block in the gap would cross the line of travel of the participant. This measure provided information about how participants were guiding their movement relative to the motion of the target gap during the approach. The second aspect of interception performance was the participant's actual time-to-spare at the point of interception between the midpoint of the bike and the center of the path of the moving blocks. This measure provides information about the participant's overall success at intercepting the gap and indicates how close a participant came to a collision with a block. All post-hoc analyses used Fisher's PLSD with an alpha of .05 unless otherwise reported. Where noted, violations of sphericity were corrected using the appropriate Greenhouse-Geisser estimate of sphericity to calculate degrees of freedom. Due to the complexity of our multivariate ANOVAs, in the interest of parsimony only significant effects and interactions are reported here.

Projected Time-to-Spare on the Approach—Our previous work has indicated that while children and adults appear to be using similar strategies to guide their approach to the intersection, children are much more volatile in their performance and more likely to make overcorrections than adults, particularly for slow-down trials. As movement timing improves, we expect to see a reduction in the magnitude of these overcorrections. To evaluate participants' stability on approach to the intersection, we calculated their instantaneous projected time-to-spare relative to the target gap (Chihak et al., 2010; Montagne et al. 2003). To compute the projected time-to-spare we first calculated the participants' projected time-to-arrival (TTA_p) at the point of interception for each time step along the approach by dividing the participant's current distance from the point of interception (D_p) by the participant's current speed (V_p).

$$TTA_p=\frac{D_p}{V_p}$$

The point of interception was the intersection of the rider's actual crossing path and the middle of path traced by the blocks. For each individual and trial, the speed data were segmented into 1-s intervals, counting backward from the point at which the participant arrived at the interception point. The mean speed in each of these intervals was calculated. This procedure was similar to the "binning" procedure used by Chardenon et al. (2005) to reduce noise in their data. The projected time-to-arrival was then subtracted from the time-to-arrival of the front of the trailing block in the target gap (TTA_b). The difference between these two times-to-arrival gives the projected time-to-spare (i.e., how many seconds ahead of the rear block the participant would arrive at the intersection if the participant were to maintain a constant speed for the remainder of the approach.)

$$\text{Projected Time}-\text{to}-\text{Spare (s)}=(TTA_b-TTA_p)$$

This instantaneous projected time-to-spare was calculated for each trial between the time at which the blocks began moving and the time the participant arrived at the intersection – roughly a 20-s interval.

There were three independent variables in the analyses of projected time-to-spare. The first variable (participant age) was a between-subjects variable, while the second and third variables (intersection set and segment) were within-subjects variables. For each participant we calculated the average values for all measures for the first four intersections, the middle four intersections, and the last four intersections. Calculating the mean performance for each intersection set allowed us to assess any changes with learning that occurred across the experimental session. To analyze how the projected time-to-spare changed during the approach to the intersection, the mean projected time-to-spare data for each participant was divided into five 4-second segments, starting from the moment of interception and working backwards. We chose this interval because it provided for reasonably fine-grained analyses of changes occurring during the approach to the intersection.

The mean projected time-to-spare profiles for each age group and intersection set can be seen in Figure 1[1]. Adults and 12-year-olds had very similar patterns of behavior on the approach, with relatively small adjustments in projected position relative to the gap. Ten-

[1]Error bars on all figures represent one standard error above and below the mean.

year-olds, however, demonstrated a different pattern of behavior on approach, slowing down considerably (shifting their mean relative position in the gap outside of the target gap entirely) then accelerating when they came within 4–6 seconds of intercepting the gap. The magnitude of 10-year-olds' adjustments diminished across intersection sets.

The projected-time-to spare data were entered into a full-factorial mixed design ANOVA with Age (10 years, 12 years, adults) as the between-subjects variable, and Intersection Set (first, second, third) and Segment (1–5) as the within-subjects variables. There was a significant main effect of age, F (2, 47) = 12.37, $p < .001$, $\eta_p^2 = 0.34$. Post-hoc tests indicated that over the entire approach, 10-year-olds (M = 0.5 s, SD = 1.13) were projected to have significantly less time-to-spare than 12-year-olds (M = 0.99 s, SD = .67) or adults (M = 1.36 s, SD = .58). The difference between 12-year-olds and adults was significant as well.

The analysis also showed a significant effect of segment, F (2.38, 112.21)[2] = 21.99, $p < .001$, $\eta_p^2 = 0.32$. While approaching the intersection participants progressively decreased their projected time-to-spare, shifting their projected point of interception in the gap towards the rear of the gap as they moved toward the intersection, and then increased their projected time-to-spare in the final segment (in the last 5 s of the approach.)

There was also a significant Age x Segment x Intersection Set interaction, F (16, 376) = 2.27, p = .04, $\eta_p^2 = 0.09$. Simple effects tests showed a significant Intersection Set x Segment interaction for adults, F (3.4, 64.6) = 2.89, $p < 0.05$, $\eta_p^2 = 0.13$, but not for 10-year-olds, F (1.9, 24.3) = 1.69, p = .21, or 12-year-olds, F (3.8, 57.5) = 1.99, p = .11[3]. Further analyses showed that this interaction was driven by changes across intersection sets in adults' behavior in Segment 4, F (2, 38) = 5.85, $p < .01$, $\eta_p^2 = 0.24$. As shown in Figure 1, in the first two intersection sets, the adults initially accelerated, moving their projected position of arrival in the gap forward in Segment 4 (M = 1.76 s, SD = .75; M = 1.75 s, SD = .59, respectively) relative to their position in Segment 5 (when the blocks began moving). In the third intersection set adults did not make this (unnecessary) adjustment, instead maintaining a stable position relative to the arrival of the gap (M = 1.34 s, SD = .33).

Time-to-Spare at the Point of Interception—Time-to-spare was defined as the temporal difference between the time at which the bicyclist reached the interception point and the time at which the rear block of the target gap arrived at the interception point. Larger values of time-to-spare are usually preferable as they indicate that participants had a greater safety margin in which to correct for any miscalculations in timing their crossing. However, if a participant's time-to-spare with respect to the rear block of the gap on a given trial is too large, the participant risks colliding with the lead block. We also calculated the standard deviation of each participant's mean time-to-spare. The variability of the time-to-spare measure provides an indicator of the consistency with which participants were able to perform the interception task.

Mean time-to-spare: Mean time-to-spare scores for the first, second, and third intersection sets were entered into an Age x Intersection Set mixed design ANOVA. This analysis revealed a significant main effect of age, F (2, 47) = 4.63, $p < .05$, $\eta_p^2 = 0.17$, indicating that 10-year-olds (M = 1.7 s, SD = .55) and 12-year-olds (M = 1.7 s, SD = .38) had significantly less time-to-spare than adults (M = 2.0 s, SD = .39). The 10- and 12-year-olds did not differ from each other. There were no significant interactions.

[2] $\varepsilon = 0.60$

[3] ε = 0.23, 0.48, and 0.43 for 10-year-olds, 12-year-olds, and adults, respectively.

Variability of time-to-spare: The mean variability of the time-to-spare scores across the three intersection sets can be seen in Figure 2. These scores were entered into an Age x Intersection Set mixed design ANOVA which revealed a significant main effect of age, F (2, 47) = 3.00, p = .05, η_p^2 = 0.11. Ten-year-olds (M = .38, SD = .18) and 12-year-olds (M = .38, SD = .30) were significantly more variable in their performance than adults (M = .27, SD = .14).

There was also a significant Age x Intersection Set interaction, F (4, 94) = 3.96, p < .05, η_p^2 = 0.14. Simple effects tests revealed a significant effect of intersection set for 12-year-olds, F (2, 30) = 4.61, p < .05, η_p^2 = 0.24, but not for 10-year-olds, F (2, 26) = 1.14, p = .34, or adults, F (2, 38) = 1.54, p = .23. The 12-year-olds had significantly less variability in the final intersection set (M = .25, SD = .15) than in the first (M = .40, SD = .25) or second set (M = .49, SD = .41).

Discussion

The results suggest that two different learning effects were occurring during the experimental session. First, at the level of perception-action tuning, the reduction in the variability of the 12-year-olds' performance at the final intersection set suggests that they were fine-tuning their ability to coordinate their own movement with the optically-specified movement of the target gap. Ten-year-olds did not show this same reduction in variability, indicating that even by the end of the experimental session they had not achieved the same level of perception-action tuning as the 12-year-olds. Second, on a strategic level, the fact that adults initially responded to the movement of the blocks by accelerating, only to correct for this adjustment by the final set of intersections, suggests that adults had figured out that the gap could be successfully intercepted without any adjustment in speed.

Interestingly, we observed neither a significant improvement in time-to-spare nor a reduction in the variability of the 10-year-olds over the course of the experimental session. Taken with the fact that 12-year-olds did show improvement in variability of time-to-spare, this suggests that repeated practice with a block timing that required no adjustment in speed may not provide sufficient information for 10-year-olds to be able to fine-tune their movement coordination. To determine whether variability of practice would benefit 10-year-olds where consistent practice had not, we designed a second experiment in which the timing of the movement of the target gap would necessitate an adjustment in the rider's speed. Two groups of riders experienced a consistent block timing, requiring them to either speed up or slow down on every trial, while a third group of riders received variable block timing where either acceleration or deceleration would be necessary. Here, we focused on 10-year-olds with adults as a comparison group.

EXPERIMENT 2

Method

Participants—Ninety-five 10-year-olds and adults participated. There were 24 males and 22 females in the 10-year-old group (M = 10 years, 7 months; range = 10;4 to 10;11), and 20 males and 29 females in the adult group (M = 21 years, 7 months, range = 18;2 to 32;11). Ninety-two percent of children were Caucasian, 4% were African American, 2% were multiracial, and 2% did not identify their race or ethnicity. The children and adults were recruited in the same manner as in Experiment 1.

Design and Procedure—Participants crossed 12 test intersections, divided into learning trials (the first two intersection sets) and transfer trials (the last intersection set). The same apparatus and experimental procedure was used as in Experiment 1, with the exception of the timing of the blocks. Relative to the position of the rider, the point at which the blocks began moving at the first two intersection sets (i.e., the first eight intersections) was manipulated to create one of three between-subjects experimental conditions. In the *speed-up* condition, the blocks at the first two intersection sets were timed to begin moving such that if the participant maintained a constant speed they would arrive at the intersection 0.5 s after the target gap had closed. In this condition, riders would have to speed up in order to successfully cross through the gap. In the *slow-down* condition, the blocks at the first two intersection sets were timed to begin moving such that if the participant maintained a constant speed they would arrive at the intersection 0.5 s before the target gap had opened. In this condition, riders would have to slow down in order to successfully cross through the gap. For participants in the *variable* condition, half of the trials were slowdown trials and half were speed-up trials. The presentation of the learning trials in this condition was randomized within intersection sets to ensure that participants experienced two of each type of trial within each of the first two intersection sets. For all conditions, the timing of the blocks at the last four intersections (i.e., transfer trials) was the same as in Experiment 1, such that participants maintaining a constant speed would arrive in the center of the target gap.

Post-hoc assessment showed that the overall distributions of the initial projected arrival times (i.e., when the blocks began moving) were appropriate for the trial type, indicating that our computational approach for creating adaptive experimental scenarios (i.e., where key events in the simulation are timed to the movement of the individual participants) was successful (Kearney & Grechkin, 2011). Out of 1,188 trials, there were 88 instances (69 for children and 19 for adults) in which the timing of the trigger resulted in initial projected arrival times that were wrong for the intended trial type (e.g., an intended speed-up or slow-down trial that required no speed adjustment). The data from these trials were excluded from all analyses. Of the 48 collisions recorded (13 for adults), the participant missed the gap by more than 1.75 s on 12 occasions (3 for adults). The data from these 12 trials were subsequently excluded from all analyses leaving a total of 1,088 viable trials.

Results

In the second experiment we were interested in examining two different learning effects. First, we wanted to know how experiencing either consistent block timing (all speed-up or slowdown trials) or variable block timing (experiencing both trial types) would affect learning over the course of the first two intersection sets. Second, we wanted to know how experiencing either consistent or variable trial types affected participants' ability to adjust to a novel block timing (constant speed trials) in the last intersection set. To this end, we performed two separate sets of analyses for mean and variable projected and actual time-to-spare. The measures in this experiment were calculated the same way as in Experiment 1 unless otherwise noted.

Learning across the First Two Intersection Sets—To analyze how experiencing consistent versus variable block timing affected learning, we compared riders' performance between the first two intersection sets. Separate analyses were conducted for speed-up and slow-down trials. For the analyses of slow-down trials, we compared the performance of the participants in the slow-down condition to the performance of the participants in the variable condition on their slow-down trials. For the analyses of speed-up trials, we compared the performance of the participants in the speed-up condition to the performance of the participants in the variable condition on their speed-up trials. This meant that the mean performance within an intersection set for participants in the consistent timing conditions was based on four observations, while the mean performance for participants in the variable timing condition was based on two observations. This disparity was unavoidable given that we wanted to keep the overall amount of experience the same across all conditions (i.e., experience with intercepting the blocks at a total of eight intersections).

Projected Time-to-Spare During the Approach

Mean projected time-to-spare for slow-down trials: The mean projected time-to-spare data for slow-down trials for each age and condition were plotted in two graphs –one for each intersection set – and can be seen in Figure 3. The mean approach profiles for each group show an appropriate slowing down followed by an acceleration through the intersection, although in the first intersection set the scale of the initial slowing down was much higher for 10-year-olds in both the slow-down and variable conditions (who slowed down considerably more than was necessary) than for adults. By the second intersection set, the initial slowing down remained high for children in the slow-down condition, whereas children in the variable condition looked much more like the adults.

We first analyzed the projected time-to-spare data for slow-down trials in a full-factorial Age (10 years, adults) x Condition (slow-down, variable) x Intersection Set (first, second) x Segment (1–5) mixed design ANOVA. This analysis yielded significant effects of age, F (1,58) = 19.87, $p < 0.01$, $\eta_p^2 = 0.26$, intersection set, F (1,58) = 7.10, $p = 0.01$, $\eta_p^2 = 0.11$, and segment, F (2.18, 126.47)[4] = 121.84, $p < 0.01$, $\eta_p^2 = 0.67$. Overall, adults had greater projected time-to-spare (M = 2.4 s, SD = 1.1) than children (M = 1.2 s, SD = 2.4). There were also significant 2-way interactions of age and intersection set, F (1, 58) = 10.73, $p <$ 0.01, $\eta_p^2 = 0.16$, and age and segment, F (4, 232) = 8.78, $p < 0.01$, $\eta_p^2 = 0.13$. These effects were subsumed under a significant Age x Intersection Set x Segment interaction, F (4, 232) = 3.34, $p = 0.01$. Simple effects tests revealed a significant Age x Segment interaction for intersection set 1, F (2.28, 136.8)[5] = 8.10, $p < 0.01$, $\eta_p^2 = 0.12$ and for intersection set 2, F (2.01, 120.69)[6] = 4.63, $p = 0.01$, $\eta_p^2 = 0.07$. At both intersection sets, there was no difference in performance for children and adults in segment 5, however adults outperformed children in all the remaining segments.

To test how experiencing consistent or variable trial types affected the approach behavior of 10-year-olds and adults across the first eight trials, we also conducted a series of planned comparisons examining whether there was an effect of intersection set for 10-year-olds and adults in the variable and slow-down conditions. If variable practice produced accelerated perception-action tuning, then we should expect to see a reduction in the magnitude of overcorrections on approach between the first two intersection sets for children in the variable condition but not for children in the slow-down condition. We found that 10-year-olds in the variable condition had significantly greater projected time-to-spare during the second than during the first intersection set, F (4, 60) = 4.61, $p < .05$, $\eta_p^2 = 0.24$. This pattern of learning was not observed for children who only experienced slow-down trials, F (4, 60) = .60, $p = .66$, nor for adults who experienced variable, F (4, 68) = .72, $p = .58$, or only slow-down trials, F (4, 56) = .45, $p = .77$. As can be seen in Figure 3, children in the variable condition performed more like adults in the second intersection set while children who only saw slow-down trials continued to make overcorrections on approach.

Mean projected time-to-spare for speed-up trials: Figure 4 shows projected time-to-spare profiles for speed-up trials. While the adults and 10-year-olds in the speed-up condition appear to be speeding up appropriately in both intersection sets, 10-year-olds in the variable

[4] $\varepsilon = 0.55$.
[5] $\varepsilon = 0.57$.
[6] $\varepsilon = 0.50$.

condition appear to be initially slowing down in the first intersection set, and responding more appropriately within the second intersection set.

We first analyzed the projected time-to-spare data for speed-up trials in a full-factorial Age (10 years, adults) x Condition (speed-up, variable) x Intersection Set (first, second) x Segment (1–5) mixed design ANOVA. This analysis yielded significant effects of age, F (1, 60) = 12.63, $p < 0.01$, $\eta_p^2 = 0.17$ and segment, F (2.54, 172.58) [7] = 59.37, $p < 0.01$. Overall, adults maintained greater average projected time-to-spare over the entirety of the approach (M = 0.3 s, SD = 0.9) than children (M = −.36, SD = 1.28). There were also significant 2-way interactions of condition and segment, F (4, 240) = 3.92, $p < 0.01$, $\eta_p^2 = 0.06$, and age and segment, F (4, 240) = 8.06, $p < 0.01$, $\eta_p^2 = 0.12$, and a 3-way interaction of age, intersection set, and segment, F (4, 240) = 4.45, $p < 0.01$, $\eta_p^2 = 0.07$. Simple effects tests of the Condition x Segment interaction revealed that participants in the variable condition did not accelerate as quickly as participants in the speed-up condition, particularly during the middle segments in the approach.

Simple effects tests of the Age x Intersection Set x Segment interaction revealed an Age x Segment interaction for the first intersection set, F (4, 240) = 10.33, $p < 0.01$, $\eta_p^2 = 0.15$, but not for the second intersection set, F (4, 240) = 1.80, p = .13. Further analyses of performance during the first set of intersections revealed a significant effect of age for segments 1, 2, 3, and 4, F*’s* (1, 62) > 5.8, p*’s* < 0.05, but not for segment 5, F (1, 62) < 3.48, p = .07. This indicates that overall adults began responding to the need to speed up much faster than children in intersection set 1, but by intersection set 2 the children started responding at about the same rate (though not as effectively) as the adults.

To test whether experiencing consistent or variable trial-types affected the approach behavior of 10-year-olds and adults, we also conducted a series of planned comparisons examining whether there was an effect of intersection set for 10-year-olds and adults in the variable and speed-up conditions. We found that 10-year-olds in the variable condition had greater projected time-to-spare during the second than during the first intersection set, F (4, 56) = 2.44, p = .057, $\eta_p^2 = 0.15$, while those who only experienced speed-up trials did not show such a trend, F (4, 64) = .83, p = .51. Likewise, there was no significant difference in projected time-to-spare between the first and second intersection sets for adults who experienced variable, F (4, 64) = 2.40, p = .09, $\eta_p^2 = 0.13$, or only speed-up trials, F (4, 60) = .44, p = .78. As shown in Figure 4, children in the variable condition initially slowed down much more than necessary in the first intersection set, with some improvement occurring during the second intersection set.

Time-to-Spare at the Point of Interception—For each participant, mean actual time-to-spare scores were calculated for each of the first two intersection sets. These scores for the slow-down trials were then entered into an Age x Condition x Intersection Set mixed design ANOVA. The analysis revealed significant main effects of age, F (1, 57) = 18.93, $p < .001$, $\eta_p^2 = 0.25$, and intersection set, F (1, 57) = 8.6, $p < .01$, $\eta_p^2 = 0.13$. Post-hoc analyses indicated that 10-year-olds (M = 1.82, SD = .71) overall had significantly less time-to-spare than adults (M = 2.40, SD = .44). These effects were subsumed by a significant Age x Intersection Set interaction, F (1, 57) = 17.61, $p < .001$, $\eta_p^2 = 0.24$. Ten-year-olds had significantly less time-to-spare in intersection set one (M = 1.6 s, SD = .78) than in set two (M = 2.0 s, SD = .58), whereas adults exhibited no change in time to spare from the first (M = 2.4 s, SD = .48) to the second (M = 2.4 s, SD = .40) intersection set. There was also a significant main effect of condition, F (1, 57) = 6.26, $p < .05$, $\eta_p^2 = 0.1$, indicating that

[7] $\varepsilon = 0.64$.

overall participants who only experienced slow-down trials (M = 1.96 s, SD = .44) had less time-to-spare than participants in the variable condition (M = 2.31 s, SD = .61).

The mean actual time-to-spare scores for the speed-up trials were also entered into an Age x Intersection Set x Condition ANOVA. This analysis revealed that overall 10-year-olds (M = 1.5 s, SD = .65) had significantly less time-to-spare than adults (M = 1.6 s, SD = .74), F (1, 59) = 4.62, $p < .05$, $\eta_p^2 = 0.07$. There were no other significant results.

Transfer during the Last Intersection Set—We compared the mean performance of participants in all three conditions on the last four trials to analyze how consistent versus variable block timing affected riders' ability to adjust to a novel block timing. Because every participant experienced the same block timing at the last four intersections the mean performance for all participants was based on four observations.

Projected time-to-spare during the approach: Figure 5 shows the mean projected time-to-spare profiles for the last four intersections for both 10-year-olds and adults in each condition. The projected time-to-spare data for the last four intersections were entered into a mixed model ANOVA with age (10-year-olds, adults) and condition (speed up, slow down, variable) as the between-subjects variables, and segment (1–5) as the within-subjects variable. There were significant main effects of age, F (1, 89) = 10.73, $p < .01$, $\eta_p^2 = 0.11$, and segment, F (1.76, 156.77)[8] = 08.27, $p < .01$, $\eta_p^2 = 0.17$. These effects were subsumed by a significant Age x Segment interaction, F (4, 376) = 7.23, $p < .01$, $\eta_p^2 = 0.08$. Post-hoc analyses indicated that overall adults had greater projected time to spare on the approach than the children and further, adults slowed down in segment 2 considerably less than the children did. However, we saw no effect of condition or interactions involving condition, suggesting that the previous experience did not influence approach profiles when participants encountered a block timing that required no adjustment in speed.

Time-to-spare at the point of interception: An Age x Condition ANOVA on mean actual time-to-spare scores revealed that 10-year-olds (M = 1.8 s, SD = .63) had significantly less time-to-spare than adults (M = 2.1 s, SD = .34), F (1, 89) = 12.15, $p < .01$, $\eta_p^2 = 0.12$. There was no significant effect of condition, F (2, 89) = 2.23, p = .11, nor was there a significant interaction. Thus, time-to-spare did not differ significantly for either children or adults depending on their previous experience with the block timings.

Discussion

The results of this experiment demonstrate two key findings. First, the analysis of participants' mean projected time-to-spare while on the approach showed that the effects of variable practice on slow-down and speed-up trials were asymmetric for 10-year-olds. On slowdown trials, children in the variable condition exhibited less overcorrection in the second intersection set than did children in the slow-down condition. In fact, by the second intersection set the mean approach profile of children in the variable condition closely resembled that of the adults. In contrast, adults did not show significant changes in approach behavior in the first two intersection sets. On the speed-up trials, children who experienced variable block timing actually performed worse than children in the speed-up condition. They (incorrectly) slowed down as the blocks started moving during the first intersection set, although they partially corrected for this behavior by the second set of intersections. Children in the speed-up condition (as well as adults in both conditions) began speeding up as the blocks started moving, and did not exhibit this slowing behavior. The reasons for this asymmetry will be addressed in the General Discussion.

[8] $\varepsilon = 0.44$.

Second, whether a participant had experienced consistent or variable block timings had no effect on their ability to adapt to the novel block timing presented during the last four intersections. This finding suggests that there may be limitations on the benefits that variability of practice can provide over a short time frame, and will be further discussed in the General Discussion.

GENERAL DISCUSSION

The experiments reported here revealed that there are differences in the way children and adults learn to intercept moving gaps based on their experiences with variable vs. consistent block timing and with variable or consistent practice. When no adjustment in speed was necessary to intercept the moving gap (Experiment 1), only adults showed significant improvement across the session, likely due to large differences in variability of performance across adults and children in this task. When an adjustment in speed was needed to intercept the moving gap (Experiment 2), children's performance was influenced by whether they experienced consistent or variable practice. In particular, children in the variable condition performed better than children in the slow-down condition for slow-down trials, but worse than children in the speed-up condition for speed-up trials. Adults performed the task effectively regardless of whether they experienced consistent or variable practice. The implications of these findings are discussed in more detail below.

Learning When No Adjustment Is Necessary

The first experiment confirms previous findings (e.g., Chohan et al., 2008; Plumert et al., 2005; te Velde et al., 2008) that children are not as proficient as adults when performing dynamic movement coordination tasks. Along with the disparity in overall safety margins between age groups, different patterns of learning were observed within each age group. Even though no adjustment in speed was necessary, 10-year-olds erroneously slowed down when the blocks began moving. By the final set of intersections the magnitude of this adjustment was diminished, albeit not significantly so due to the high level of variability in this age group. Interestingly, although both 10- and 12-year-olds had less time-to-spare than adults, 12-year-olds demonstrated an improvement in variability of time-to-spare such that by the last intersection set their performance did not differ from that of the adults. This suggests that there may be significant developmental differences between 10- to 12-year-old children's perception-action tuning over a relatively short time scale. One specific area of development could be the children's ability to determine the speed of the moving blocks. Manning et al. (2012) found that by the age of 11, children's processing of speed information for fast-moving stimuli was on par with that of adults. If 10-year-olds were underestimating the speed of the blocks, then they may have slowed down more than necessary on approach to the intersection, only to find that they needed to accelerate sharply when they reached the intersection.

Another possibility is that children were slowing down as they got closer to the intersection because they were attempting to maximize the "window of adjustment" proposed by Chihak et al. (2010). Intercepting a fast-moving gap at a high speed requires precise timing of movement. Slowing down upon nearing the intersection is useful for balancing the competing constraints of intercepting the gap at the right time while maintaining control over the bicycle. Other work has shown changes in 10-year-olds speed and steering over the course of an experimental session (Plumert et al., 2011), suggesting that difficulty with maintaining control over the bicycle may lead 10-year-olds to slow down as they reach the intersection rather than attempting to intercept the gap at a high speed. Although we saw some change in 10-year-olds slowing down behavior across the session, this change was not statistically significant. We would expect more change if 10-year-olds came in for multiple sessions, allowing them to gain more practice with the task and controlling the bicycle.

Unlike the children, adults demonstrated more fine-tuned learning over the course of the experiment. By the final intersection set, adults had stopped (unnecessarily) accelerating when the blocks began moving, instead maintaining a relatively constant speed on their approach to the intersection. This pattern of control is consistent with adoption of a higher-order control strategy, such as the constant-bearing angle strategy. Numerous studies have shown that, when intercepting moving objects, people attempt to maintain a constant bearing angle with the target object (Montagne et al., 2003; Camachon et al., 2007; Chohan et al., 2008). This strategy ensures successful interception and only requires a single optically-specified invariant (the instantaneous visual angle between the object and the individual's direction of motion) to guide the interceptive action. That adult cyclists were behaving in accordance with the constant-bearing-angle strategy during the final set of intersections suggests that this strategy may not be immediately apparent and that a period of training is required to identify the usefulness of the bearing angle as an invariant to guide action. Interestingly, adult cyclists in the Chihak et al. (2010) study, who were required to make an adjustment in their speed in order to successfully intercept the target gap, did not appear to be using this strategy even though it would have led to a successful outcome. This suggests that the ability to identify and use optical invariants for guiding movement may be more difficult when an adjustment in speed is necessary.

Learning When a Consistent vs. Variable Adjustment Is Necessary

In the second experiment, where a speed adjustment was necessary in order to successfully intercept the target gap, adults again performed better than the 10-year-olds both in terms of stability on the approach to the intersection as well as overall safety margins at the point of interception. Additionally, different patterns of learning (demonstrated by improvement in performance over intersections) were observed in adults and 10-year-olds. Adults in both the consistent and variable practice conditions demonstrated relatively stable performance over the course of the experimental session regardless of whether a given trial required acceleration or deceleration. However, children who experienced variable practice demonstrated a different pattern of change over the course of the session than those who experienced consistent trial types. On slow-down trials, their approach behavior on the second set of intersections more closely resembled that of the adults than that of the children in the slow-down condition. However, for speed-up trials these same children initially performed considerably worse on the approach to the intersection than both adults and their peers in the speed-up condition. While they demonstrated some improvement in the second intersection set, their approach behavior did not resemble that of adults as closely as did that of children in the consistent condition.

How might we explain this pattern of findings? The fact that adults performed well regardless of whether they needed to speed up or slow down indicates that they zeroed in on the perceptual information that was most relevant to the task. An extensive body of literature has shown that adults are quite good at using perceptually-available information to guide their movement through space (Montagne et al., 2004 for summary; Fajen & Warren, 2004, 2007). Further, a number of studies have provided evidence that certain locomotor tasks might be optimally performed by guiding one's actions so as to maintain a certain perceptual invariant at a target level (Lee, 1976; Yilmaz & Warren, 1995; Chapman, 1968). For example, Fajen and Warren (2004) found that, when pursuing a moving target, people move in such a way so that the retinally-defined heading angle between their direction of motion and the target remains constant. As mentioned earlier, other work has shown that adults are adept at using a constant bearing angle to guide their interceptive actions in simple situations (Lenoir, Musch, Janssens, Thiery, & Uyttenhove, 1999; Lenoir, Musch, Thiery, & Savelsbergh, 2002).

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Relative to children, adults have considerably more experience identifying the perceptual variables that are most relevant to completion of various motor tasks. When faced with a complex perceptual-motor task like intercepting a moving gap, children may have more difficulty than adults at precisely zeroing in on which perceptual invariants are relevant to optimal task performance. As a result, children may be more dependent on information gleaned from previous experience. Ten-year-olds' performance in the variable condition suggests that they were relying on a mix of available perceptual information and learned movement patterns. On slow-down trials, they slowed down far less than children in the slow-down condition, particularly on the second set of intersections. On the speed-up trials, they sped up less than did children in the speed-up condition. Thus, they appeared to use a "split-the-difference" approach whereby they averaged their previous experience with the two trial types. This was beneficial in the slow-down trials, but detrimental in the speed-up trials. The fact that children in the two consistent timing conditions (speed up and slow down) showed very little change across the session suggests that they also were learning at least in part to repeat a particular movement pattern (i.e., speed up or slow down).

These findings suggest that children may learn to coordinate perception and action on a more coarse-grained level before a more fine-grained level. Thus, their experience with intercepting the blocks apparently taught them something about *what* adjustment was needed (e.g., "I need to slow down to get through the blocks") but not precisely *how* to make the adjustment. Adults, on the other hand, quickly learned that adjustments in speed were necessary and were able to bring their motor actions tightly in line with the perceptual information to modulate their approach to the intersection and to successfully intercept the blocks.

Contrary to other research, we did not find that variable experience helped children adapt more readily to a novel block timing in the final four intersections. One possible reason for the lack of difference between the consistent and variable experience conditions is that eight intersections of practice were too few to reveal differences between conditions. Most studies that have examined the role of variable and consistent practice have involved many more practice trials. Due to the nature of the bicycling simulator task, it was not feasible to have participants ride for more than 12 blocks without experiencing significant physical fatigue. Another possible reason for the lack of differences is that the "novel" block timing only differed from the speed-up and slow-down trials by 1.75 seconds. The closeness of all three block timings may have made it difficult to see differences based on previous experience. Future work may find an effect of previous experience with more extreme differences in block timing (e.g., going from all speed-up to slow-down trials or vice versa).

In closing, the results of this investigation add to our understanding of how short-term experience influences perception-action tuning in children and adults. These results also underscore the importance of practice with coordinating self and object movement, particularly in situations that have real-world consequences such as crossing busy intersections. Further work is needed to better understand how experience leads to enhanced perception-action tuning across late childhood and early adolescence.

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Highlights

- We used a virtual environment to examine how cyclists learn to intercept moving gaps.
- We asked if children and adults benefit from variability of practice for this task.
- Child cyclists show more overcorrections in speed and cross less safely than adults.
- When no speed adjustment is needed, child cyclists do not learn as quickly as adults.
- When speed adjustment is needed, variability of practice affects children's learning.

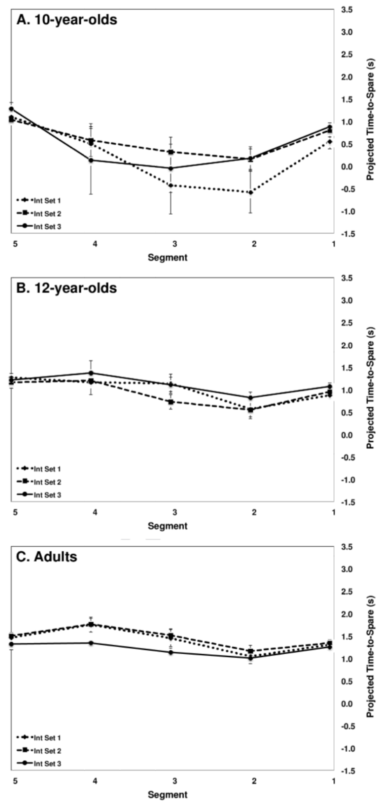

Figure 1.
Mean Projected Time-To-Spare across Segments by Age and Intersection Set.

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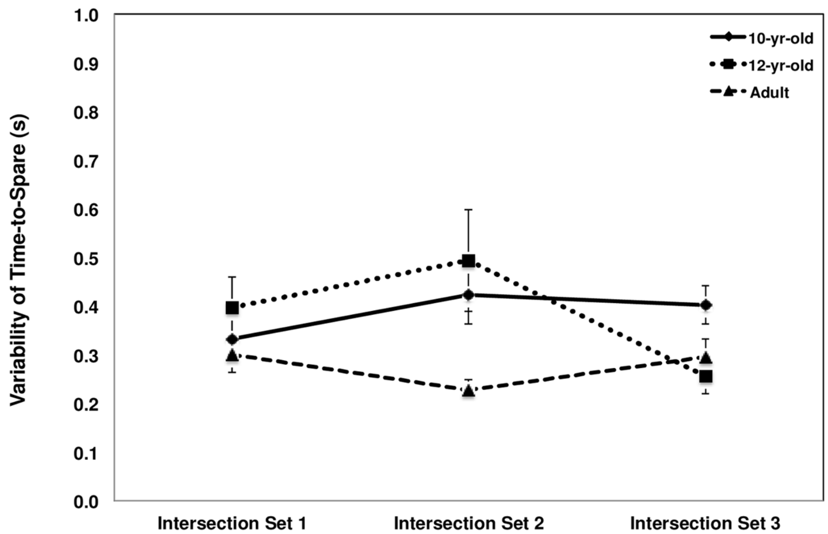

Figure 2.
Mean Variability of Time-to-Spare by Age and Intersection Set.

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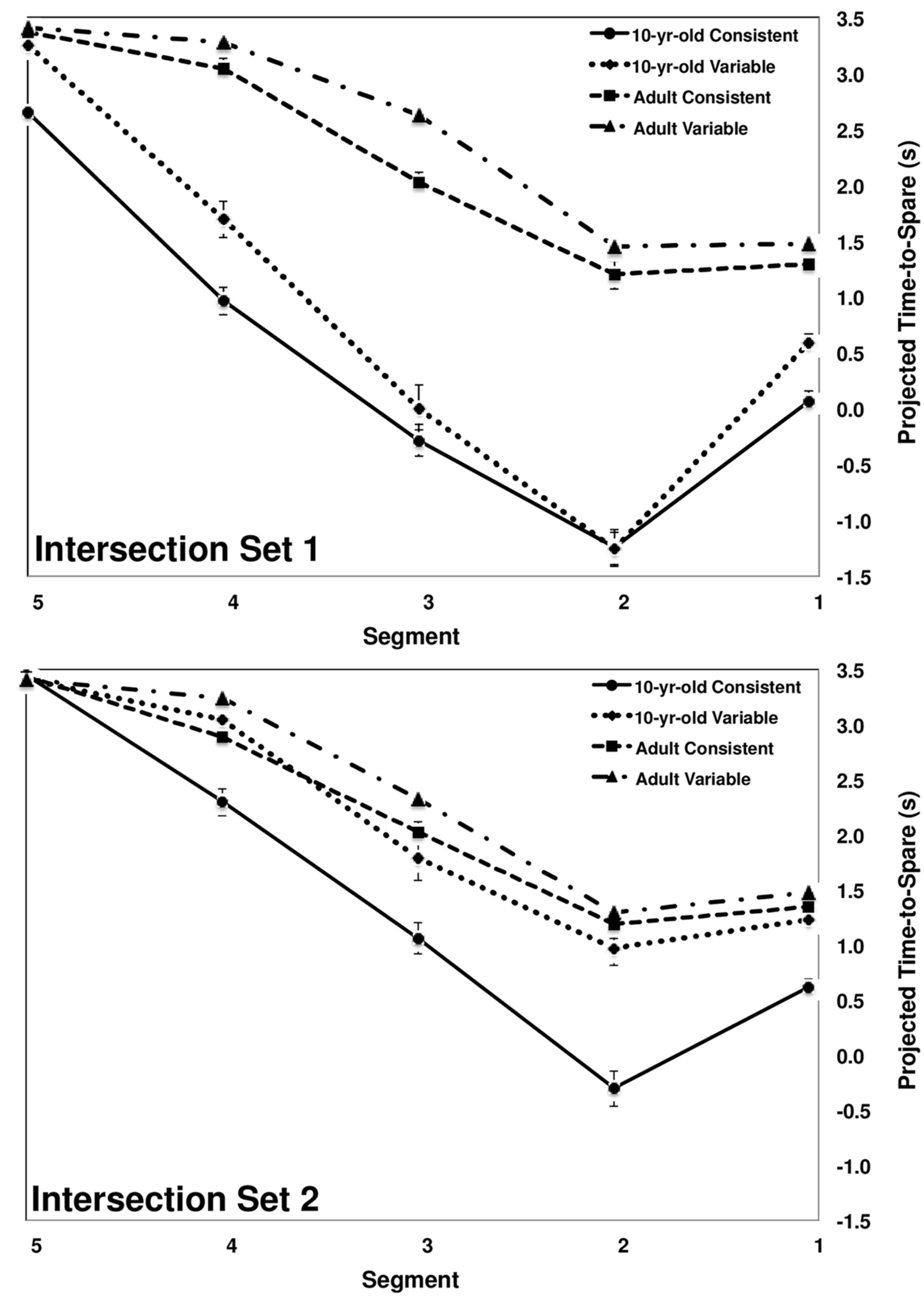

Figure 3.
Mean Projected Time-to-Spare across Segments for Slow-Down Trials by Age, Condition, and Intersection Set.

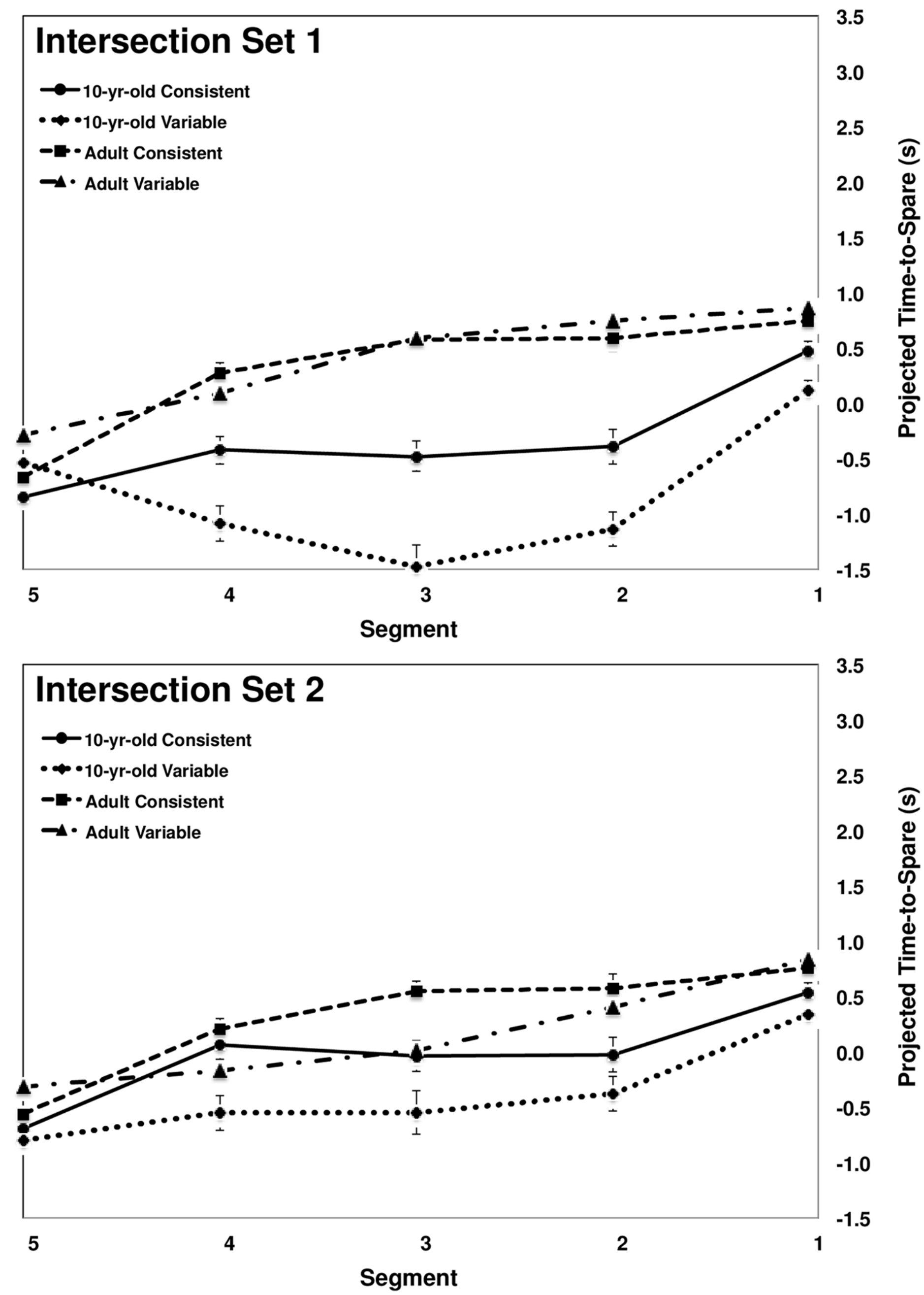

Figure 4.

Mean Projected Time-to-Spare across Segments for Speed-Up Trials by Age, Condition, and Intersection Set.

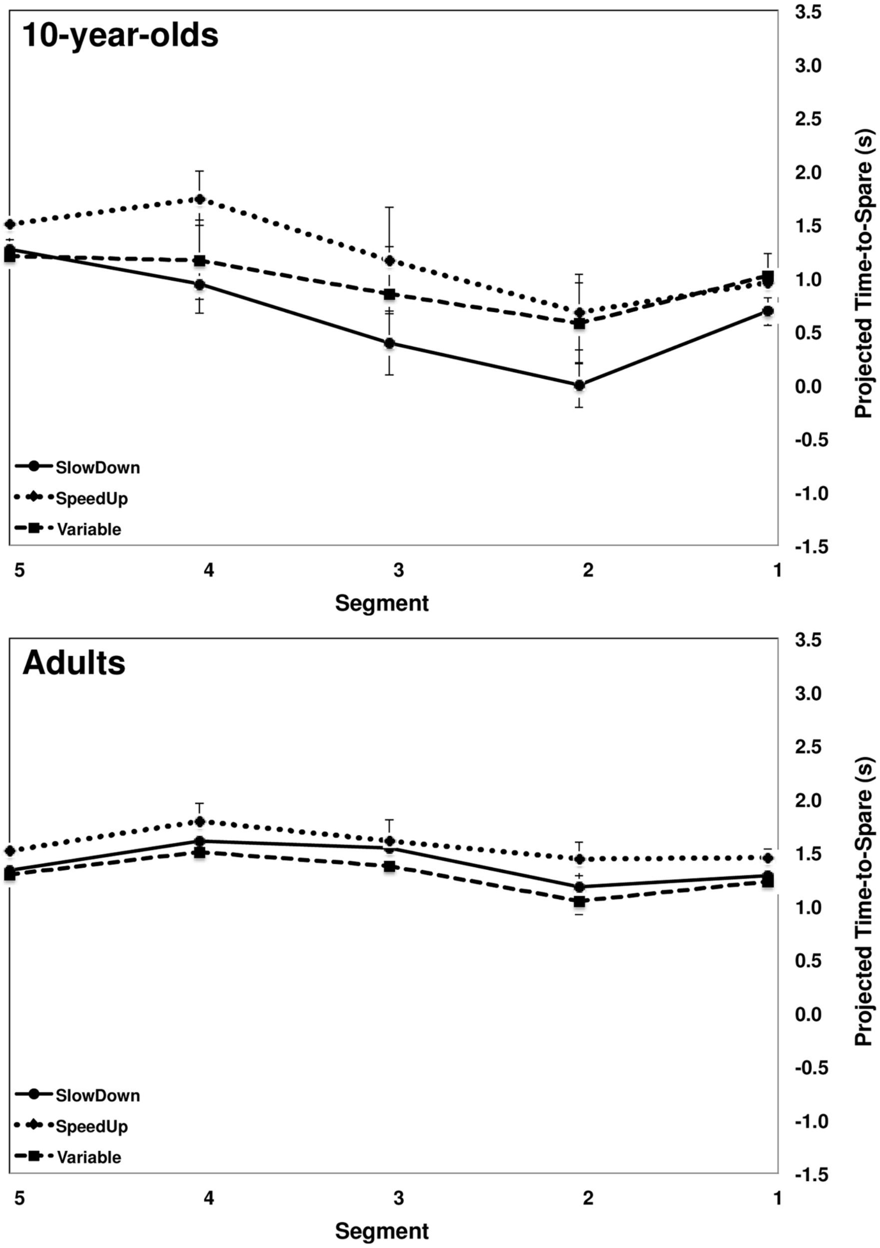

Figure 5.
Mean Projected Time-to-Spare across Segments for Transfer Intersections by Age and Condition.