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Changes in children's perception-action tuning over short time scales: Bicycling across traffic-filled intersections in a virtual environment

Jodie M. Plumert *, Joseph K. Kearney, James F. Cremer, Kara M. Recker, Jonathan Strutt

Department of Psychology, University of Iowa, Iowa City, IA 52242, USA

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ABSTRACT

This investigation examined short-term changes in child and adult cyclists' gap decisions and movement timing in response to general and specific road-crossing experiences. Children (10- and 12-year-olds) and adults rode a bicycle through a virtual environment with 12 intersections. Participants faced continuous cross traffic and waited for gaps they judged were adequate for crossing. In the control condition, participants encountered randomly ordered gaps ranging from 1.5 to 5.0 s at all intersections. In the high-density condition, participants encountered high-density intersections sandwiched between sets of control intersections. These high-density intersections were designed to push participants toward taking tighter gaps. Participants in both conditions were more likely to accept 3.5-, 4.0-, 4.5-, and 5.0-s gaps at the last set of intersections than at the first set of intersections, whereas participants in the high-density condition were also more likely to accept very tight 3.0-s gaps at the last intersections than at the first intersections. Moreover, individuals in the high-density condition who waited less and took shorter gaps at the middle intersections were also more likely to take very tight 3.0-s gaps at the last intersections. The 10-year-olds in both conditions had more time to spare when they cleared the path of the oncoming car at the last intersections, whereas the 12-year-olds and adults showed no change in time to spare across intersections. The discussion focuses on linking short-term change in perceptual-motor functioning to longer term perceptual-motor development.

* Corresponding author. Address: Department of Psychology, University of Iowa, 11 SSH East, Iowa City, IA 52242, USA. Fax: +1 319 335 0191.

E-mail address: jodie-plumert@uiowa.edu (J.M. Plumert).

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Introduction

A fundamental problem confronting the developing perceptual-motor system is learning how to bring decisions and actions tightly in line with perceptual information. This ability to fine-tune judgments and actions is important both for learning new perceptual-motor skills and for improving existing ones. Becoming a skilled pedestrian, for example, involves improved use of visual information to guide gap decisions and to time interceptive movements. Clearly, experience plays a critical role in producing these kinds of changes in perception-action tuning. Probably the most important aspect of this experience is repeated practice with performing perceptual-motor skills. But how does practice with performing a skill lead to changes in perception-action tuning over both the short and long term? Contemporary views of perceptual-motor development suggest that short-term learning experiences accumulate to produce long-term developmental changes in the perception-action system (Berthier, Rosenstein, & Barto, 2005; Newell, Liu, & Mayer-Kress, 2001; Thelen & Smith, 1994). An important first step in understanding how these long-term changes occur is examining short-term changes in response to different kinds of experience. Here we examined how child and adult cyclists' gap choices and movement timing changed over a single experimental session in response to general and specific experiences with crossing traffic-filled intersections in a virtual environment.

Experience and perception-action tuning

One way to think about experience is in terms of the *amount* of practice with performing a perceptual-motor skill. In general, more experience should lead to increased skill. This approach is clearly seen in recent work on the development of children's walking skill. Using step counters in toddlers' shoes, Adolph (2005) found that each day toddlers take more than 9000 steps and travel the equivalent of approximately 29 football fields. Another way to think about experience is in terms of the *type* of practice with performing a skill. Open skills such as road crossing and ball catching involve varying one's actions to meet the demands of changing environments (e.g., the speed and distribution of traffic varies from one intersection to the next). In contrast, closed skills such as gymnastics involve performing actions in exactly the same way in an unchanging environment (e.g., doing a handspring on a standard-size balance beam). Because open skills are performed in changing environments, experience with a varied set of situations may lead to better learning, particularly in the long run.

The question of how experience affects the development of the perception-action system has been of long-standing interest to the field (e.g., Adolph, 1997; Gibson, 1988; McGraw, 1935). Past work indicates that extended practice with performing perceptual-motor skills affects *judgments* about possibilities for action. Studies with infants have shown that when a new action system such as crawling or walking becomes available, infants require a period of experience with the new skill to make accurate judgments about possibilities for action. Inexperienced walkers, for example, significantly overestimate the steepness of the slopes they can successfully walk down relative to experienced walkers (Adolph, 1997; Adolph, 2000). Work with older children indicates that practice with performing a skill leads to more accurate judgments (McKenzie & Forbes, 1992; Plumert, 1995). Plumert (1995) found that 8-year-olds were better able to distinguish between tasks that were just beyond and well beyond their ability when given some experience with performing the tasks first regardless of whether the experience involved success or failure. Thus, it appears that experience with learning a new action or with practicing a specific task leads to more finely attuned judgments about the relations between the self and the environment.

Past work also indicates that *actions* themselves become more finely tuned to perceptual information with experience. Work with adults on interception tasks, for example, indicates that movement speed becomes more precisely tuned to visual information over the course of learning (Montagne, Buekers, Camachon, de Rugy, & Laurent, 2003). Longitudinal work on infants' prospective control over grasping also suggests that perception-action linkages become more finely tuned with age and experience (von Hofsten & Fazel-Zandy, 1984; Witherington, 2005). Similar work shows that infants' responsiveness to optic flow becomes more closely tuned to the type of optic flow with increased crawling experience (Higgins, Campos, & Kermoian, 1996).

Despite the well-accepted notion that judgments and actions become more tightly tuned to perceptual information with long-term experience, very little developmental work has directly examined short-term changes in decisions and actions as one is gaining experience with performing a task (for an exception, see Gill, Adolph, & Vereijken, 2009). As noted above, individual infants' ability to discriminate slopes they can successfully traverse from those they cannot successfully traverse improves as they gain experience with walking (e.g., Adolph, 1997; Adolph & Berger, 2006). Likewise, infants' ability to bring their motor movements more tightly in line with perceptual information improves as they gain experience with self-produced locomotion (e.g., Higgins et al., 1996). However, judgments and actions might also change over shorter time scales. In particular, one might also expect to see changes over the time course of a single experimental session as children and adults gain experience with performing a task.

Crossing traffic gaps

One perceptual-motor skill that undergoes change over childhood is road crossing. Nearly all research to date on perception of gap affordances has examined children's road-crossing judgments while walking (Connelly, Conaglen, Parsonson, & Isler, 1998; Demetre et al., 1992; Lee, Young, & McLaughlin, 1984; Pitcairn & Edlmann, 2000; te Velde, van der Kamp, Barela, & Savelsbergh, 2005). Lee and colleagues (1984), for example, devised a road-crossing task in which 5- to 9-year-olds 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 judged that they could safely reach the other side of the pretend road before the oncoming vehicle crossed their line of travel on the real road. Children were generally cautious when crossing the pretend road, but they sometimes accepted gaps that were too short. In addition, younger children were more likely than older children to make road-crossing errors. These findings suggest that younger children are less adept than older children at coordinating visual information and motor movements in the context of crossing traffic gaps.

Recent work on gap acceptance has focused on how child and adult cyclists cross traffic-filled roads in an immersive, interactive virtual environment (Plumert, Kearney, & Cremer, 2004; Plumert, Kearney, & Cremer, 2007). In these studies, children (10- and 12-year-olds) and adults rode a bicycle through a virtual environment consisting of a straight residential street with 6 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 the same size gaps, and yet children ended up with less time to spare when they cleared the path of the car. Thus, by the time children actually cleared the path of the oncoming car, the margin for error was very small, particularly for 10-year-olds.

These results clearly show that the perceptual-motor system is undergoing developmental change even during late childhood, particularly in terms of moving the self in relation to fast-moving objects. This raises an important question: How do gap choices and crossing behavior become more finely tuned with experience? To address this question, it is first important to understand how experience with performing a task leads to change in decisions and actions. One would expect that practice with a task helps to fine-tune the system because individuals directly experience the relation between their motor actions and the perceptual information. This provides useful information about whether the gap choice was correct and the crossing behavior was effective.

Another interesting issue is whether the type of experience matters. In particular, how does experience operating near the limits of the perceptual-motor system affect gap choices and crossing behavior? By practicing at the edge of their ability (e.g., a young pianist playing a challenging etude), novice learners may increase the precision, speed, and/or accuracy of their performance. In addition, the nature of the skill may influence the value of challenging experience. Open skills require individuals to adapt their actions to perform across a wide range of environmental circumstances. An outfielder, for example, must field balls that are traveling at different speeds, distances, and trajectories. Experiences with fielding balls that push the perceptual-motor system near the limit may be especially informative for learning about the boundary between success and failure and for bringing actions more tightly in line with perceptual information. Over time, such experiences should lead to more finely tuned decisions and actions. Road crossing also involves significant variation in environmental circumstances; traffic can differ in speed and density, and roads can vary in width and surface properties. Although pushing road-crossing actions too close to the limit in the real world can have dire consequences, experience with varying safety margins may be informative. Such experience may be particularly useful for instances in which individuals must precisely time their action (e.g., in crossing small gaps).

The current investigation

Our goal was to examine how general and specific experience with performing a perceptual-motor task helps children and adults to bring their decisions and actions more tightly in line with perceptual information. We addressed this issue in the context of bicycling across traffic gaps in a virtual environment. The road-crossing task is a useful model system for studying the development of perception-action tuning because we can look at how both road-crossing decisions (i.e., gap choices) and action (i.e., movement timing) change with age and experience. As with most perception-action skills studied in the laboratory, children and adults bring with them some experience with crossing roads. However, many aspects of this situation are novel and, thus, allow us to use the road-crossing task as a model system for examining change over the course of an experimental session. Moreover, road crossing in a virtual environment allows researchers to study basic questions about perception-action coupling without putting participants at risk for injury.

Children (10- and 12-year-olds) and adults bicycled across 12 intersections with continuous cross traffic coming from their left-hand side. We chose to study 10- and 12-year-olds because previous work has shown that the ability to synchronize self and object movement is undergoing change at least up until 12 years of age (Hoffmann, Payne, & Prescott, 1980; Plumert et al., 2004; Savelsbergh, Rosengren, van der Kamp, & Verheul, 2003). Adults were included as a comparison group. We manipulated traffic density to examine how the experience of operating near the limit of the perceptual-motor system affected later gap choices and movement timing. Based on previous research, we expected children and adults to accept tight gaps when faced with high-density traffic (Adebisi & Sama, 1989; Guth, Ashmead, Long, Wall, & Ponchillia, 2005; Kittleson & Vandehey, 1991). There were two conditions. In the control condition, children and adults encountered randomly ordered gaps ranging from 1.5 to 5.0 s at all intersections. In the high-density condition, children and adults encountered a set of intersections with high-density traffic sandwiched between sets of intersections with randomly ordered gaps ranging from 1.5 to 5.0 s. Thus, the first 4 and last 4 intersections were the same for both groups, but the middle 4 intersections differed. This design allowed us to directly examine the extent to which change in gap choices over the 12 intersections was due to general experience with crossing intersections or to specific experience with high-density traffic.

Our primary interest was in observing how gap choices and crossing behavior changed across the experimental session. We hypothesized that general experience with crossing intersections would be especially informative for learning how to time the movement of the self relative to the movement of the cars. Thus, although we expected to replicate previous results showing that adults had more time to spare than children when clearing the path of the car, we also expected that children would have more time to spare at the later intersections than at the earlier intersections. We also hypothesized that specific experience with crossing tight gaps in high-density traffic would be especially informative for learning about perception-action boundaries. Thus, we expected that children and adults in the high-density condition would show increased willingness to perform "tight fit" actions over the course of the session.

Method

Participants

A total of 72 10-year-olds, 12-year-olds, and adults participated, with 24 participants in each age group. The mean ages of the three age groups were 10 years 11 months (range = 10 years 1 month to

11 years 0 months), 12 years 8 months (range = 12 years 6 months to 12 years 9 months), and 19 years 4 months (range = 18 years 5 months to 21 years 8 months). (No age was reported for 1 12-year-old and 2 adults). There were equal numbers of males and females in each age group. Children were recruited from a child research participant database at a university in the midwestern United States. Parents received a letter describing the study, followed by a telephone call inviting children to participate. Children received $10 for participating. In terms of race, 94% of the children were European American, 2% were African American, and 4% were not classified. In terms of education, 6% of the mothers had completed only a high school education, 26% had some college education, and 68% had completed a 4-year college education or beyond. (Education was not reported by 1 mother.) Adults participated to fulfill research credit for an introductory psychology course. Nearly all of the adult participants were European American.

Apparatus and materials

The study was conducted using a high-fidelity, real-time bicycling simulator (Fig. 1). An actual bicycle mounted on a stationary frame was positioned in the middle of three 10-foot-wide by 8-foot-high 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 $\times$ 1024 pixels on each screen), providing participants with 270° of nonstereoscopic, immersive visual imagery. The viewpoint of the scene was adjusted for each participant's eye height. 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. Four speakers and a subwoofer provided spatialized sound of car engine noise.

The virtual environment was populated with residential buildings, trees, and other roadside features typical of a small town but no people. Participants rode through the town on a 2.25-km-long, two-lane residential roadway with stop signs at the intersections. There were 15 cross streets that intersected the primary roadway at 150-m intervals. All roadways were 12 m wide and at a level grade.

The pedals, handlebars, and right-hand brake on the bicycle all were functional. However, participants were not required to balance the bicycle because the bicycle mount was rigid. The height of the seat was adjustable, so the bicycle could accommodate a wide range of participants. 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. This flywheel was connected to a torque motor, which generated an appropriate dynamic force taking into account rider and bicycle mass and inertia, virtual terrain slope, ground friction, and wind resistance. The underlying software system was a sophisticated real-time

Fig. 1. Photographs of the bicycling simulator. Note that the visual angles in the left panel are correct from the viewpoint of the rider.

ground vehicle simulator that supports complex scenarios involving ambient and programmatically controlled traffic (Cremer, Kearney, & Willemsen, 1997; Willemsen, Kearney, & Wang, 2003).

A Sony Handycam DCR-DVD403 camcorder was positioned on a tripod approximately 3.2 m behind the rider. Videotapes of the participants' ride through the simulation were used to code head turns and veering as they crossed the intersections.

Design and procedure

The experimenter first helped participants to put on a bicycling helmet and adjust the bike seat height. The experimenter then measured participants' eye height while they were seated on the bike. This was followed by 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 3 intersections. During the warm-up period, there was no cross traffic at any of the intersections. Participants were instructed to stay in the right lane and to stop at each intersection. The familiarization session provided participants with the opportunity to learn how to steer, pedal, stop, and start the bicycle.

Following the warm-up session, children and adults participated in an approximately 15-min test session during which they crossed the 12 remaining intersections. There was no traffic on the street with the participants, but there was continuous cross traffic at each of the intersections. The cross traffic was restricted to the lane closest to the participants and always approached from the left side. The temporal gap between the cars was 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. Participants were given the following instructions:

> Your job is to cross every intersection without getting hit by a car. So, when you get to an intersection, you will see a stream of cars coming from your left-hand side. Some of the spaces between the cars will be too small to get across without getting hit, and some will be big enough for you to get across without getting hit. You can wait as long as you need to before going across. Again, I want you to stop at every stop sign. There will be 12 intersections for you to cross.

After giving the instructions and answering any questions, the experimenter minimized any further interaction with the participant to increase the sense of immersion in the virtual environment.

The participants in each age group were randomly assigned to two experimental conditions. In the *control* condition, the participants experienced 12 control intersections. In the *high-density* condition, the participants experienced 4 control intersections, then 4 high-density intersections, and then 4 control intersections. For control intersections, the gaps between the cars (1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 s) were blocked into sets of eight intervals. The order of gaps within each set was random. For high-density intersections, participants encountered approximately 8–10 randomly ordered uncrossable gaps (1.5 and 2.0 s) when they arrived at the intersections. This resulted in a minimum wait of approximately 14–18 s. Participants then experienced alternating sets of 2 same-size crossable gaps and 4 randomly ordered uncrossable gaps (1.5 and 2.0 s). The size of the crossable gaps increased by 0.5 s in each iteration, starting with gaps of 3.0 s.[1] The cars were traveling at 25 or 35 mph on alternating intersections, starting with a 25-mph intersection for half of the participants at each age.

Coding

Automated computer coding

Three bicyclist behaviors were automatically recorded for each intersection: (a) the time when the bicyclist arrived at the intersection, defined as the time the bicyclist was 10 m from the edge of the

[1] This procedure was used to determine the smallest gap participants found acceptable for crossing. If participants were presented with randomly ordered gaps after the set of uncrossable gaps, theoretically they would choose any gap between the minimally acceptable gap and the largest gap available. We attempted to avoid this situation by providing participants with progressively larger temporal gaps separated by smaller uncrossable gaps.

intersection; (b) the time when the rider entered the roadway, defined as the time that the front tire crossed the edge of the intersection; and (c) the time when the rider cleared the path of the approaching car, defined as the time when the rear wheel of the bike cleared the path of the approaching car. The coordinates of both the rider and the leading and trailing cars in the gap were also recorded for each of these time points. This information was used to calculate the number of gaps seen before crossing, the size of the gap the rider crossed, the time between the rider and the lead car in the gap, the time between the rider and the trailing car in the gap, and the time to cross the intersection.

Coding of videotaped records

We also examined videotaped records to provide supplementary information about bicyclists' behavior throughout the session. Due to experimenter error and equipment problems, videotaped records were available for only 68 of the 72 participants. The presence or absence of two bicyclist behaviors was coded for each intersection. The first was whether the bicyclist turned his or her head toward the left to watch the stream of traffic while crossing an intersection. The second was whether the bicyclist veered while crossing an intersection. Cohen's kappa was .70 for head turns and .85 for veering ($n = 12$).

Results

The results are divided into three main sets of analyses: (a) the size of the gaps participants chose to cross, (b) the time to spare when participants cleared the path of the oncoming car, and (c) head turning and veering while crossing the intersection. Unless otherwise noted, the data were analyzed using Age (10 years versus 12 years versus adults) × Condition (control versus high-density) × Intersection Set (first 4 versus middle 4 versus last 4) mixed-model analyses of variance (ANOVAs), with the first two factors as between-participants variables and the last factor as a within-participants variable. Fisher's PLSD (protected least significant difference) tests were used for all pairwise post hoc comparisons.

Gap choices

Mean gap size

The first question of interest was whether participants' gap choices in the two conditions changed across the experimental session. Our first analysis of gap choice focused on the mean gap sizes chosen by the three age groups across the three sets of intersections. As in previous work, there was no effect of age, $F(2, 66) = .26$, *ns.* The mean gap sizes chosen by 10-year-olds, 12-year-olds, and adults were 4.23 s ($SD = 0.63$), 4.20 s ($SD = 0.76$), and 4.25 s ($SD = 0.67$), respectively. However, there were significant effects of condition, $F(1, 66) = 129.34$, $p < .0001$, $\eta_p^2 = .66$, and intersection set, $F(2, 132) = 173.09$, $p < .0001$, $\eta_p^2 = .72$. These effects were subsumed under a significant Condition × Intersection Set interaction, $F(2, 132) = 147.30$, $p < .0001$, $\eta_p^2 = .69$. Simple effects tests revealed a significant effect of intersection for the control condition, $F(2, 66) = 3.03$, $p < .05$, $\eta_p^2 = .08$, and for the high-density condition, $F(2, 66) = 236.83$, $p < .0001$, $\eta_p^2 = .88$. Post hoc tests revealed that participants in the control condition took significantly smaller gaps at both the middle intersections ($M = 4.51$ s, $SD = 0.28$) and last intersections ($M = 4.50$ s, $SD = 0.27$) than at the first intersections ($M = 4.63$ s, $SD = 0.24$). As expected, participants in the high-density condition chose much smaller gaps at the middle intersections ($M = 2.90$ s, $SD = 0.49$) than at either the first intersections ($M = 4.49$ s, $SD = 0.33$) or the last intersections ($M = 4.32$ s, $SD = 0.35$), indicating that our high-density traffic manipulation was successful in pushing participants toward taking tight gaps. In addition, participants took significantly smaller gaps at the last intersections than at the first intersections.

Proportion of gaps accepted

Our second analysis of gap choice focused on the mean proportion of gaps of each size that participants accepted at the three sets of intersections (Fig. 2). In other words, how often did children and adults take gaps of a given size when they saw these gaps? This analysis provided a more sensitive measure of the minimal gap size participants were willing to accept.

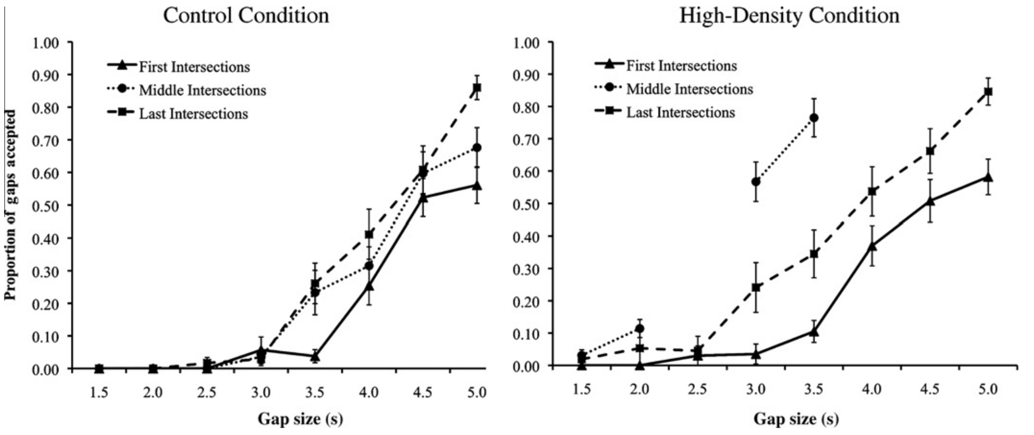

Fig. 2. Mean proportions of gaps accepted in the control condition (left panel) and in the high-density condition (right panel) by gap size and intersection set. (For the high-density condition, there is no data point for 2.5-s gaps for the middle 4 intersections because participants did not see any 2.5-s gaps. There are no data points for 4.0-, 4.5-, and 5.0-s gaps for the middle intersections because virtually no participants waited for gaps of these sizes before crossing.)

To determine whether our high-density traffic manipulation led participants to take smaller gaps, we examined condition differences in the proportion of 3- and 3.5-s gaps accepted at the middle set of intersections. As expected, separate one-way ANOVAs revealed a significant difference between the high-density and control conditions for 3.0-s gaps, $F(1, 59) = 43.92$, $p < .001$, $\eta_p^2 = .43$, and for 3.5-s gaps, $F(1, 46) = 24.74$, $p < .001$, $\eta_p^2 = .35$. (Larger gap sizes were not analyzed because very few participants in the high-density condition took gaps larger than 3.5 s at the middle intersections.) Participants in the high-density condition accepted a higher proportion of each of these gaps sizes than participants in the control condition. Thus, participants in the high-density condition shifted their gap acceptance criterion when they needed to wait for many gaps to pass before a minimally acceptable gap appeared.

We were particularly interested in whether the mean proportion of gaps of each size that participants accepted changed from the first 4 intersections to the last 4 intersections for the two conditions. We entered the mean proportion of 3.0-, 3.5-, 4.0-, 4.5-, and 5.0-s gaps that participants accepted at the first and last sets of intersections into separate Condition (high-density versus control) × Intersection Set (first versus last) mixed-model ANOVAs.[2] (Age was not a factor because preliminary analyses revealed no effects relating to age for any gap size.) As shown in Fig. 2, there was a significant effect of intersection set for 3.5-s gaps, $F(1, 53) = 18.67$, $p < .001$, $\eta_p^2 = .26$, for 4.0-s gaps, $F(1, 53) = 6.32$, $p < .05$, $\eta_p^2 = .11$, for 4.5-s gaps, $F(1, 60) = 3.99$, $p = .05$, $\eta_p^2 = .06$, and for 5.0-s gaps, $F(1, 60) = 45.53$, $p < .001$, $\eta_p^2 = .43$. In all cases, participants in both conditions accepted a greater proportion of gaps at the last intersections than at the first intersections, indicating an influence of general experience with road crossing on gaps of these sizes. However, the analysis of the 3.0-s gaps revealed a significant Condition × Intersection Set interaction, $F(1, 51) = 4.95$, $p < .05$, $\eta_p^2 = .09$. Simple effects tests showed a significant effect of condition for the last set of intersections, $F(1, 51) = 8.42$, $p < .01$, $\eta_p^2 = .14$, but not for the first set of intersections, $F(1, 51) = .07$, *ns*. Thus, both groups nearly always rejected 3.0-s gaps at the first set of intersections, but the high-density group was significantly more likely than the control group to take these very tight gaps at the last set of intersections.

To further explore how experiences with high-density traffic at the middle set of intersections affected gap choices at the last set of intersections, we looked at the relationships between wait length and gap choices at the middle intersections and the proportion of very tight 3.0-s gaps taken at the last

[2] Note that the number of participants included in analyses involving the proportion of gaps taken varies depending on how many participants saw at least one gap of a given size during a particular set of intersections.

intersections. Our measure of waiting was the number of gaps participants saw between the time they arrived at the intersection and the time they started to cross the intersection. For participants in the control condition, the correlation between the number of gaps seen at the middle intersections and the proportion of 3.0-s gaps taken at the last intersections was nonsignificant, $r(29) = -.02$, *ns*. Likewise, the correlation between the mean gap size at the middle intersections and the proportion of 3.0-s gaps taken at the last intersections was nonsignificant, $r(29) = .10$, *ns*. For participants in the high-density condition, however, there was a strong negative correlation between the number of gaps seen at the middle intersections and the proportion of 3.0-s gaps taken at the last intersections, $r(27) = -.55$, $p < .01$, and between the mean gap size at the middle intersections and the proportion of 3.0-s gaps taken at the last intersections, $r(27) = -.64$, $p < .001$. The number of gaps seen and the mean gap size at the middle intersections were highly correlated, $r(27) = .94$, $p < .0001$. (This is a reflection of the fact that only short gaps were available at the beginning of the gap sequence.) These findings indicate that, when confronted with high-density traffic, individuals who waited less and accepted tighter gaps were also more likely to take very tight gaps at the subsequent set of intersections even though bigger gaps were readily available.

Time to spare

Hits

We examined the number of times participants were “hit” by cars to provide information about instances in which participants failed the road-crossing task. On average, 10-year-olds, 12-year-olds, and adults were hit 4.2% (*SD* = 11.1), 4.9% (*SD* = 15.5), and .3% (*SD* = 2.9) of the time, respectively. Given the extremely low number of times adults were hit, we analyzed the data from only the 10- and 12-year-olds. Significant effects of condition, $F(1, 44) = 12.16$, $p < .01$, $\eta_p^2 = .22$, and intersection set, $F(2, 88) = 8.41$, $p < .001$, $\eta_p^2 = .16$, were subsumed under a significant Condition × Intersection Set interaction, $F(2, 88) = 11.68$, $p < .0001$, $\eta_p^2 = .21$. Simple effects tests revealed a significant effect of condition for the middle intersections, $F(1, 44) = 15.10$, $p < .001$, $\eta_p^2 = .26$, but not for the first intersections, $F(1, 44) = 0.22$, *ns*, or for the last intersections, $F(1, 44) = 0.00$, *ns*. Children in the high-density condition were much more likely to be hit at the middle intersections (*M* = 20%, *SD* = 25) than children in the control condition (*M* = 0%).

Mean time to spare

Our second major question of interest was whether the time to spare between the bicyclist and the approaching car changed across the three sets of intersections. Time to spare was defined as the time for the approaching car to intersect with the bicyclist’s path at the point when the bicyclist’s back wheel cleared the lane of the approaching car. Significant effects of condition, $F(1, 66) = 11.18$, $p < .01$, $\eta_p^2 = .14$, and intersection set, $F(2, 132) = 80.55$, $p < .0001$, $\eta_p^2 = .55$, were subsumed under a significant Condition × Intersection Set interaction, $F(2, 132) = 84.39$, $p < .0001$, $\eta_p^2 = .56$. Simple effects tests revealed a significant effect of intersection set for the high-density condition, $F(2, 70) = 137.57$, $p < .0001$, $\eta_p^2 = .80$, but not for the control condition, $F(2, 70) = 2.14$, *ns*. As shown in Fig. 3, participants in the high-density condition had far less time to spare at the middle intersections than at either the first or last intersections. This is consistent with the fact that they took much smaller gaps at the middle intersections. However, they also had significantly more time to spare at the last intersections than at the first intersections. Participants in the control condition also followed this trend, particularly in terms of the difference between the first and last sets of intersections.

As in previous work, there was also a significant effect of age, $F(2, 66) = 17.29$, $p < .0001$, $\eta_p^2 = .34$, indicating that 10-year-olds (*M* = 1.40 s, *SD* = 0.66) and 12-year-olds (*M* = 1.70 s, *SD* = 0.75) had less time to spare than adults (*M* = 2.09 s, *SD* = 0.62). There was also a significant Age × Intersection Set interaction, $F(4, 132) = 3.56$, $p < .01$, $\eta_p^2 = .10$. Simple effects tests revealed a significant effect of intersection set for all three ages, all $Fs(2, 46) > 11.47$, $p < .0001$, η_p^2s = .33, .33, and .43 for 10-year-olds, 12-year-olds, and adults, respectively. As shown in Fig. 4, year-olds and adults had significantly less time to spare at the middle intersections than at the first or last intersections. Although 10-year-olds also had less time to spare at the middle intersections than at the last intersections, the difference between the first and middle intersections did not reach significance. In addition, 10-year-olds had significantly

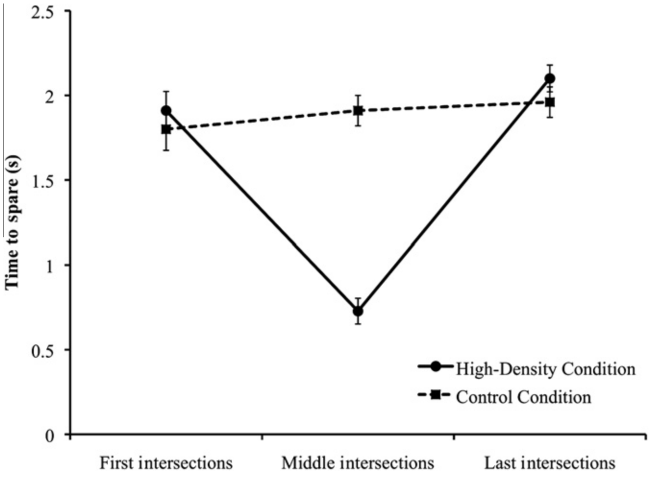

Fig. 3. Mean times to spare when clearing the path of the oncoming car by condition and intersection set.

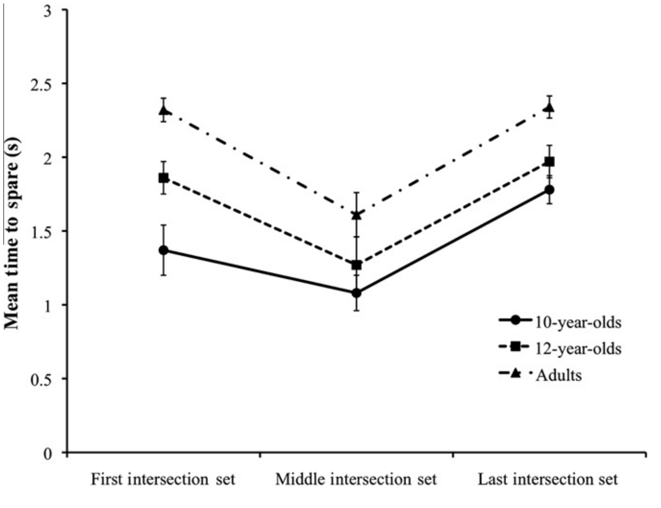

Fig. 4. Mean times to spare when clearing the path of the oncoming car by age and intersection set.

less time to spare at the first intersections than at the last intersections. This finding suggests that 10-year-olds' timing of their movement relative to that of the cars became more finely tuned over the course of the session. However, 12-year-olds and adults exhibited no significant change in time to spare from the first intersections to the last intersections.

What accounts for changes in time to spare across the session?

There are two primary factors that could account for why the younger children had more time to spare at the last set of intersections than at the first set of intersections. The first is how children timed their movement relative to the lead car in the gap, and the second is how quickly they crossed the roadway. We examine these two factors in turn below.

Timing movement relative to the lead car in the gap. To maximize time relative to the trailing car in the gap (i.e., time to spare), the rider should minimize the time relative to the lead car in the gap. Hence, the rider should cut in as close behind the lead car as possible. We examined whether there were changes across the session in how children and adults timed their movement relative to the lead car by looking at how much time there was between the rider and the lead car when the rider entered the intersection (i.e., the time since the lead car of the gap passed the rider). There were main effects of age, $F(2, 66) = 25.22$, $p < .0001$, $\eta_p^2 = .43$, and intersection set, $F(2, 132) = 32.45$, $p < .0001$, $\eta_p^2 = .33$. Post hoc tests revealed that all three age groups differed significantly from one another. The mean times for 10-year-olds, 12-year-olds, and adults were 1.40 s ($SD = 0.59$), 1.06 s ($SD = 0.43$), and 0.67 s ($SD = 0.35$), respectively. Post hoc tests of the intersection effect indicated that all groups left more time relative to the lead car at the first intersections ($M = 1.25$ s, $SD = 0.57$) than at either the middle intersections ($M = 0.93$ s, $SD = 0.52$) or the last intersections ($M = 0.96$ s, $SD = 0.52$). The middle and last intersections did not differ. There was also a significant effect of condition, $F(1, 66) = 14.90$, $p < .001$, $\eta_p^2 = .18$, that was subsumed under a significant Condition × Intersection Set interaction, $F(2, 132) = 4.40$, $p < .05$, $\eta_p^2 = .06$. As shown in Fig. 5, this interaction appears to be due to the fact that there was a small (albeit significant) difference across conditions in the amount of time participants left between themselves and the lead car at the first intersections, $F(2, 66) = 4.01$, $p < .05$, $\eta_p^2 = .06$, but there was a large difference across conditions at the middle intersections, $F(2, 66) = 27.29$, $p < .0001$, $\eta_p^2 = .29$, and at last intersections, $F(2, 66) = 9.06$, $p < .01$, $\eta_p^2 = .12$. The large difference between the two groups at the middle set of intersections indicates that taking short gaps put pressure on riders to time their movements more precisely relative to the lead car in the gap. Interestingly, this large difference was also apparent at the last set of intersections, where participants in the high-density condition were continuing to take some very tight gaps.

Time to cross the roadway. Riders can also maximize time to spare by taking less time to cross the roadway. We examined whether there were changes across the session in crossing time by looking at how much time it took participants to cover the distance from the point they entered the roadway to the point they cleared the path of the oncoming car. There was a significant effect of intersection, $F(2, 132) = 6.52$, $p < .01$, $\eta_p^2 = .09$, and a significant Age × Intersection Set interaction, $F(4, 132) = 4.46$, $p < .01$, $\eta_p^2 = .12$. Simple effects tests revealed a significant effect of intersection set for 10-year-olds, $F(2, 46) = 9.76$, $p < .001$, $\eta_p^2 = .30$, and for adults, $F(2, 46) = 3.45$, $p < .05$, $\eta_p^2 = .13$, but not for 12-year-olds, $F(2, 46) = 0.75$, *ns*. As shown in Fig. 6, year-olds' crossing time was significantly slower at the first intersections than at the middle and last intersections. The middle and last sets of intersections did not differ. Adults crossed significantly faster at the last intersections than at the middle intersections but not at the first intersections. The first and middle sets of intersections did not differ. Crossing times of 12-year-olds were virtually unchanged from the first, to the middle, to the last intersections.

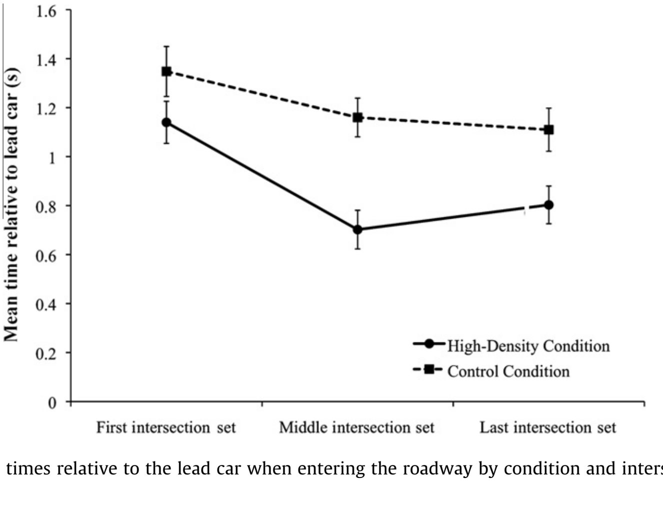

Fig. 5. Mean times relative to the lead car when entering the roadway by condition and intersection set.

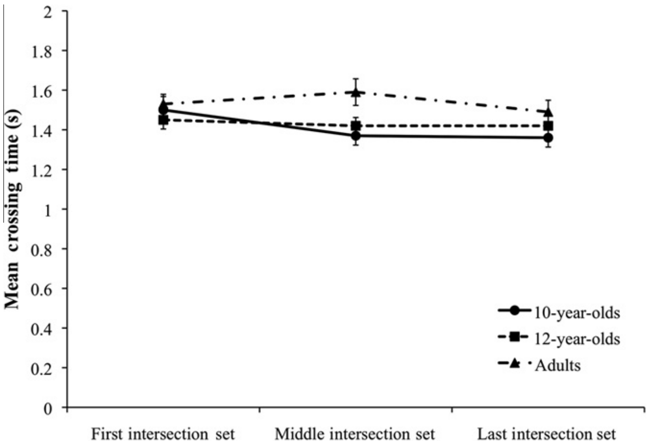

Fig. 6. Mean crossing times by age and intersection set.

Head turning and veering

We analyzed head turning and veering from the available video records to provide supplementary information about participants' behaviors as they crossed the intersections. Analyses of veering indicated that there were significant age differences in the proportion of intersections at which participants veered, $F(2, 62) = 9.48$, $p < .001$, $\eta_p^2 = .23$, with 10-year-olds ($M = .28$, $SD = .33$) veering significantly more than 12-year-olds ($M = .14$, $SD = .22$) and adults ($M = .04$, $SD = .11$), but there was no significant difference between 12-year-olds and adults. In addition, there was a decline in veering across the three sets of intersections, $F(2, 124) = 8.84$, $p < .001$, $\eta_p^2 = .12$, with significantly more veering at the first intersections ($M = .20$, $SD = .29$) and middle intersections ($M = .18$, $SD = .28$) than at the last intersections ($M = .08$, $SD = .18$). There was also an Intersection Set × Condition interaction, $F(2, 124) = 5.35$, $p < .01$, $\eta_p^2 = .08$. This was the result of more veering by participants in the high-density condition ($M = .26$, $SD = .32$) than in the control condition ($M = .10$, $SD = .20$) at the middle intersections, $F(2, 62) = 6.76$, $p < .05$, $\eta_p^2 = .10$. The high-density and control conditions did not differ at the first intersections ($M = .24$, $SD = .32$ versus $M = .16$, $SD = .25$), $F(2, 62) = 1.38$, *ns*, or at the last intersections ($M = .06$, $SD = .16$ versus $M = .10$, $SD = .20$), $F\ (2, 62) = .93$, *ns.* The higher level of veering in the high-density condition at the middle intersections is likely due to the fact that they were attempting to cross tight gaps at a high speed.

We also analyzed head turns to provide information about whether participants watched the oncoming traffic while they crossed the intersection. Head turns while crossing the intersection occurred on a high proportion of trials ($M = .75$, $SD = .32$). There was also some tendency for head turns to decrease across the three sets of intersections, $F(2, 124) = 2.91$, $p = .058$. Follow-up tests showed that there were significantly more head turns at the first intersections ($M = .78$, $SD = .29$) and middle intersections ($M = .77$, $SD = .31$) than at the third intersections ($M = .70$, $SD = .35$). The first and middle sets of intersections did not differ significantly.

Discussion

The results of this investigation clearly reveal changes in gap choices and movement timing over the course of the session. Children and adults chose smaller gaps to cross at the last set of intersections than at the first set of intersections. More specifically, participants in both conditions were more likely to accept gaps of 3.5, 4.0, 4.5, and 5.0 s at the last intersections than at the first intersections. The tendency to take smaller gaps at the last set of intersections was also influenced by the type of previous experience. At the group level, participants who experienced high-density traffic prior to the last intersections also accepted more tight 3.0-s gaps at the last intersections than at the first intersections. At the individual level, participants who took smaller gaps and waited for less time when confronted with high-density traffic were also more likely to take very tight 3.0-s gaps at the last set of intersections. We also found general changes in movement timing over the course of the session, particularly for the youngest children. The 10-year-olds in both conditions had significantly more time to spare between themselves and the oncoming car at the last 4 intersections than at the first 4 intersections. This is noteworthy given the fact that they were also accepting smaller gaps at the last intersections than at the first intersections.

The fact that children and adults in the control condition accepted smaller gaps at the last intersections than at the first intersections indicates that gap acceptance shifted in response to general experience with crossing roads in our virtual environment. This is likely a reflection of the learning that occurred from crossing intersections. More specific, crossing the intersections provided children and adults with feedback about how their gap choices related to crossing outcomes, particularly with respect to the time to spare between themselves and the oncoming car. Our coding of the videotaped records indicates that head turns toward the left as participants rode through the intersections were very frequent for all age groups. Although we cannot tell exactly where participants were looking, head turns appear to reflect exploratory activity aimed at gathering feedback about time to spare. Participants likely used feedback about time to spare gained at the early intersections to inform their gap decisions and refine their movements at the later intersections.

The finding that children and adults in the high-density condition were more likely than participants in the control condition to accept very tight 3.0-s gaps at the last intersections shows that gap acceptance also shifted in response to specific experience with high-density traffic. Clearly, participants in the high-density condition took much tighter gaps at the middle intersections than participants in the control condition. We also observed that within the high-density condition, individuals who took smaller gaps and waited for less time at the middle intersections were also more likely to take very tight 3.0-s gaps at the last intersections.

What might account for these findings? One possibility is that participants became more skilled. The experience of taking very small gaps in the high-density intersections may have honed both their judgments and actions. In particular, participants in the high-density condition not only learned that very tight gaps were indeed crossable but also learned how to coordinate their motor actions with the available visual information more effectively by initiating their motion more quickly after the lead car in the gap passed them. Indeed, at both the middle and last sets of intersections, children and adults in the high-density condition cut in closer behind the lead car than their counterparts in the control condition. Hence, a more tightly tuned perception-action system may have contributed to a greater willingness to take very tight gaps at the last set of intersections even when larger ones were readily available.

Another possible explanation is that participants became more risky in response to high-density traffic. That is, the experience of crossing high-density traffic may have increased their willingness to take greater risks, perhaps due to heightened arousal or impatience. In fact, individuals who were more willing to take smaller gaps and wait for less time in high-density traffic were also more willing to take very tight 3.0-s gaps at the last set of intersections. This suggests that experiencing high-density traffic may have made risky individuals become even more risky. Note, however, that the two explanations offered above are not necessarily mutually exclusive; a highly tuned perception-action system coupled with a willingness to engage in risky behavior may have created the right conditions for some children and adults to accept very tight gaps.

We also observed general changes in movement timing across the session, particularly for 10-year-olds. At the first 4 intersections, 10-year-olds in both conditions had relatively little time to spare when they cleared the path of the car. By the last 4 intersections, they had increased their time to spare by an average of 25% (0.44 s). However, 12-year-olds (5%) and adults (1%) exhibited minimal change in time to spare across the session. This raises the question of why these effects were more pronounced for 10-year-olds than for 12-year-olds. Although both 10- and 12-year-olds were less skillful than adults, 10-year-olds were more transitional than 12-year-olds with respect to this road-crossing task. As a consequence, they had more room for improvement. A second question these results raise is what accounts for improvements in the younger children's time to spare. At a specific level, these improvements were due to changes in how children timed their movement relative to the lead car and how fast they crossed the intersection. At the later intersections, younger children crossed intersections at a higher speed and cut in closer behind the lead car. Both of these factors contributed to a greater safety margin at the last intersections than at the first intersections.

How might these specific improvements fit into a more general framework for thinking about perceptual-motor change either in the short term or in the long term? One general factor that seems to play an important role in perceptual-motor change is gaining better control over motor actions (Adolph & Berger, 2006). In our case, this involves learning to better control the bicycle. One indication of control over the bicycle is speed. In general, better control over the bicycle makes it possible to ride at a higher speed. As noted above, 10-year-olds showed significant changes in their crossing speed across the session. Another indication of control over the bicycle is steering. Younger children's problems with steering at the beginning of the session were especially apparent while they were crossing intersections. As noted above, participants typically watched the traffic on their left while crossing the intersection. This often led to veering toward the right as younger children rode through the intersection, requiring a noticeable subsequent correction in steering. The 10-year-olds veered significantly more than the 12-year-olds and adults. In addition, although all age groups showed a decline in veering across the session, 10-year-olds exhibited a large (45%) and significant decline in veering from the first set of intersections to the last set of intersections. Quite likely, better control over the bike made it easier for 10-year-olds to bring their crossing movements tightly in line with the visual information. Hence, they cut in more closely behind the lead car in the gap, leaving them with a greater safety margin relative to the trailing car in the gap at the end of the session than at the beginning of the session.

Another general factor that seems to play an important role in producing change in perceptual-motor functioning is learning to better anticipate consequences of actions. Von Hofsten (2007) argued that a major hallmark of perceptual-motor development is the ability to anticipate what is going to happen next and to use this information to guide behavior. In our case, timing of movement relative to the lead car in the gap requires prospective control over movement. That is, to effectively cut in behind the lead car with minimal clearance, individuals need to anticipate exactly when to begin moving. In situations such as our virtual road-crossing task, experience in crossing small gaps gives children valuable practice in learning how to precisely time their motions with respect to the approach of the lead vehicle in the gap. Improvements in the ability to synchronize self-motion with the motion of the traffic may have led to better prospective control over the timing of their movement later in the session.

A general question this investigation raises is what significance these changes across the course of an experimental session have for our understanding of perceptual-motor development. To begin, it is important to point out that we replicated previous findings showing significant age differences between children and adults in time to spare (Chihak et al., in press; Plumert et al., 2004). In the current investigation, there were significant age differences in time to spare between children and adults at every set of intersections. This clearly shows that perception-action coupling continues to undergo change even during late childhood and early adolescence. Thus, although infants show early precocity in timing their interceptive movements in catching tasks (von Hofsten, 1980), the ability to move the self in relation to other moving objects undergoes a long and protracted development (see also te Velde et al., 2005). A large part of this development appears to be increased skill in movement timing.

The changes we observed in 10-year-olds' movement timing across the session provide a hint about how changes in movement timing across development might occur. As others have proposed, short-term changes in perception-action tuning accumulate to produce longer term changes in perception-action coupling (Berthier et al., 2005; Thelen & Smith, 1994). When children are transitional with respect to a perceptual-motor skill such as the 10-year-olds here, they exhibit short-term gains in perception-action tuning each time they practice a skill. Although these short-term gains dissipate to some extent between bouts of practice, small changes in perception-action coupling persist. The next time children encounter a similar task, these small changes in perception-action coupling affect how they experience that task. For example, if we brought back the 10-year-olds to do the same task 3 weeks later, they may be better able to control the bicycle and anticipate upcoming events. As a result, they would be able to further refine their movement timing. Over time, these kinds of small changes stemming from experiences with road crossing lead to long-lasting changes in road-crossing skill.

On a final note, the results of this investigation raise interesting questions about the relationship between risk taking and skill development. Becoming better at performing a skill involves aspiring to do things that are beyond one's current level of ability (Bjorklund & Green, 1992; Plumert, 1995). Attempting to do something beyond one's current level of ability often involves some measure of risk taking. A baseball player learning how to slide into a base or a figure skater learning how to do a triple axel, for example, will engage in some risk taking as the athlete acquires the new skill. The dilemma is to take risks that lead to increases in skill but not risks that lead to disastrous consequences. Further research is needed to better understand how children negotiate the balance between risk taking and skill development.

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