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Perception–action development from infants to adults: Perceiving affordances for reaching through openings

Shaziela Ishak [a,*], John M. Franchak [b], Karen E. Adolph [b]

[a] *Psychology, School of Social Science and Human Services, Ramapo College of New Jersey, Mahwah, NJ 07430, USA*
[b] *Department of Psychology, New York University, New York, NY 10003, USA*

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A B S T R A C T

Perceiving possibilities for action—affordances—requires sensitivity, accuracy, and consistency. In the current study, we tested children of different ages (16-month-olds to 7-year-olds) and adults to examine the development of affordance perception for reaching through openings of various sizes. Using a psychophysical procedure, we estimated individual affordance functions to characterize participants' actual ability to fit their hand through openings and individual decision functions to characterize attempts to reach. Decisions were less accurate in younger children (16-month-olds to 5-year-olds); they were more likely to attempt impossible openings and to touch openings prior to refusing, suggesting a slow developmental trend in learning to perceive affordances for fitting through openings. However, analyses of multiple outcome measures revealed that the youngest participants were equally consistent in their decision making as the oldest ones and that every age group showed sensitivity to changes in the environment by scaling their attempts to opening size.

Introduction

Fitting objects—especially body parts—into openings is a ubiquitous behavior. Beginning during the fetal period, children stick their thumbs, fingers, and toes into their mouths. As soon as they can reach, young infants delight in putting their fingers and hands into small crevices. After they can crawl and

* Corresponding author.
E-mail address: sishak@ramapo.edu (S. Ishak).

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walk, infants' locomotor play includes slithering into tight spaces. In fact, infants' fascination with fitting objects into openings sustains an industry of toys such as nesting cups and shape sorters. Infants' propensity for fitting body parts into dangerously small openings has resulted in national safety guidelines for toys and playground equipment (U.S. Consumer Product Safety Commission, 2008). In the current study, we investigated how children of different ages and adults cope with the problem of fitting their hand through openings of different sizes.

Affordances reflect the fit between body and environment

The problem of fitting through openings is a prime example of what Gibson (1979) termed an "affordance"—the match between the body and the environment that makes a particular action possible. Actions can succeed only if they are scaled to the properties of the body and the environment (Fajen, 2005; Franchak & Adolph, in press; Warren, 1984; Warren & Whang, 1987). For example, reaching through an opening is possible only if the hand is smaller than the opening. Even millimeter changes in opening size relative to hand size have drastic effects on whether fitting is possible (Ishak, Adolph, & Lin, 2008). Likewise, changes in the body affect affordances; with growth in hand size or decrease in flexibility, children can no longer fit their hand through the same small openings.

Across the life span, people must perceive affordances to adapt actions to the changing constraints of the body and the environment (Franchak & Adolph, in press). Perceiving affordances can be characterized by sensitivity, accuracy, and consistency. Sensitivity refers to the ability to detect the critical body–environment relations. It is demonstrated by scaling actions or judgments to the changing possibilities for action (e.g., attempting to fit through larger openings more often than smaller openings). Accuracy refers to the match between the actual affordance and participants' decisions. Accuracy is necessary to ensure that selected actions are appropriate given the properties of the body and environment. Errors in action selection, such as trying to fit through openings that are too small, can have dire consequences for safety. Accuracy can be influenced by sensitivity and by differences in response criteria such as how heavily one weights the penalty for error. Finally, affordance perception must be consistent over successive encounters. For example, attempting and refusing to fit through the same opening on successive presentations reflects a lack of consistency.

Development of affordance perception

Adults' perception of affordances for fitting through openings satisfies the demands of sensitivity, accuracy, and consistency. When walking through doorways and under barriers, adults demonstrated sensitivity to affordances by scaling judgments of passable openings to their relevant body dimensions—shoulder width or standing height (Franchak, Celano, & Adolph, 2012; Higuchi et al., 2011; Stefanucci & Geuss, 2010; Wagman & Malek, 2009; Warren & Whang, 1987). When walking though doorways, adults demonstrated accuracy by distinguishing passable openings from impossibly small ones; errors were small and occurred primarily at openings 1 to 2 cm smaller than what was possible to fit through—their threshold opening size (Franchak, van der Zalm, & Adolph, 2010). Moreover, adults' attempts to fit show exquisite consistency (Franchak et al., 2010); adults consistently refused openings that were 2 to 3 cm smaller than their thresholds, and they consistently attempted openings that were 2 to 3 cm larger than their thresholds. Decisions were inconsistent only within a small 4- to 6-cm range around their thresholds. Similarly, when deciding whether to reach through openings of different sizes, adults were sensitive, accurate, and consistent; attempt rates and exploratory behaviors were scaled to opening size, errors were typically less than 1 cm, and decisions were consistent within a 2-cm range around their thresholds (Ishak et al., 2008).

Infants and children must learn to perceive affordances accurately. When they first acquire new skills, infants' decisions about possible and impossible actions are rife with errors, but over weeks of experience practicing their new skills, decisions become increasingly accurate. For example, novice walkers attempted to descend impossibly steep slopes and cliffs (requiring rescue from an experimenter to prevent injury). Over weeks of walking, decisions gradually geared in to infants' actual abilities. Experienced walkers made accurate decisions by refusing to descend or by switching to an alternative sliding or backing position (Adolph, 1997; Kretch & Adolph, 2013a, 2013b).

Although experienced walking infants made accurate decisions in tasks that involved falling, infants of the same age and level of experience produced gross errors in tasks that involved fitting. When walking through openings of different sizes, 17- and 18-month-olds consistently erred by attempting to fit through doorways that were impossibly small, repeatedly wedging their head or body in the openings (Brownell, Zerwas, & Ramani, 2007; Franchak & Adolph, 2012). However, several lines of evidence suggest that infants do, in fact, perceive affordances for fitting through openings. First, infants' errors may be the result of an overly liberal response criterion. In studies where infants' motor decisions were accurate, the penalty was falling (Adolph, 1997; Kretch & Adolph, 2013a, 2013b). In fitting tasks, the penalty for error is entrapment. Thus, infants may have perceived that the opening is too small to fit through but attempted nonetheless because they did not consider the penalty of entrapment to be severe. Although 17-month-olds wedged themselves into doorways, they made accurate decisions when trying to fit their body along ledges of different widths when the penalty for errors was falling rather than entrapment (Franchak & Adolph, 2012).

Second, although infants erred by attempting to fit through impossibly small doorways, they produced other behaviors that were tightly scaled to opening size, demonstrating sensitivity to affordances for fitting. For example, infants turned their shoulders to fit through narrow doorways but walked straight through wider ones (Franchak & Adolph, 2012). When walking through openings varying in overhead clearance, 11- to 15-month-olds modified their locomotor behaviors based on the height of the barrier relative to their own standing height (van der Meer, 1997). Evidence of body scaling suggests that infants, at the very least, are sensitive to how changes in opening size affect possibilities for action. Even 10-month-olds demonstrate a rudimentary ability to scale actions to opening size; they oriented their hand vertically when reaching through vertical openings but not when reaching through horizontal openings (Robinson, McKenzie, & Day, 1996).

It is not surprising that infants commit more errors in fitting tasks compared with adults. But how does perception of affordances for fitting through openings progress from infants' rudimentary body scaling to adult-like accuracy? Despite a wealth of studies on the kinematics of reaching (Berthier, 2011; Hay, 1979; Kuhtz-Buschbeck, Stolze, Jöhnk, Boczek-Funcke, & Illert, 1998; Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002; Smyth, Katamba, & Peacock, 2004) and locomotion (Assaiante, 1998; Assaiante, Woollacott, & Amblard, 2000; Cowie, Atkinson, & Braddick, 2010; Ledebt, Bril, & Breniere, 1998) in children, relatively little is known about children's perception of affordances for fitting. One recent exception demonstrated that 8- to 10-year-olds scaled decisions to turn their shoulders to fit through openings based on opening size (Wilmut & Barnett, 2011).

Most studies of affordance perception (including those with adults) report only accuracy based on error rates; few studies measure consistency and perceptual sensitivity (but see Franchak et al., 2012; Ishak et al., 2008). Although it seems reasonable to expect that accuracy, consistency, and sensitivity in affordance perception improve from infancy to adulthood, no study has explicitly tested these measures across a wide range of ages.

The current study

The primary aim of the current study was to track the development of affordance perception from infancy to adulthood by measuring perceptual sensitivity, accuracy, and consistency. Although a longitudinal design would be ideal for tracking individual developmental trajectories, the goal of our investigation was to bridge the gap between research on infants and research on adults by testing a wide age range. Thus, we used a cross-sectional design to sample affordance perception at six ages: 16 months, 22 months, 34 months, 5 years, 7 years, and 20 years. Our youngest and oldest child age groups were chosen to provide corroborating evidence with existing studies of walking through openings (Brownell et al., 2007; Franchak & Adolph, 2012; Wilmut & Barnett, 2011). We sampled the remaining age groups opportunistically to provide a usefully long developmental description of affordance perception. We chose to study the affordance of fitting the hand through openings to make contact with the extant research with infants (Brownell et al., 2007; Franchak & Adolph, 2012; van der Meer, 1997), children (Wilmut & Barnett, 2011), and adults (Franchak et al., 2010, 2012; Higuchi et al., 2011; Ishak et al., 2008; Warren & Whang, 1987) walking and reaching through openings. To compare performance across such a wide range of ages, we chose a task that each age group could complete without modifications to the procedure; pilot testing showed that infants and children of every age group would perform numerous trials of reaching through openings to grasp a small toy or bite of food without the need for verbal instruction.

In the current study, we used the same adjustable apparatus as in previous work with adults (Ishak et al., 2008) to test participants over dozens of trials with opening sizes varying in 0.20-cm increments. We used a psychophysical procedure to estimate two psychometric functions for each individual. The *affordance function* described the participant's actual ability to fit the hand through openings, and the *decision function* described the participant's attempts to reach. Accuracy was measured for each participant by calculating the discrepancy between the center points of the affordance and decision functions, that is, how much each participant's decisions deviated from his or her actual abilities. Consistency of decisions was derived from the estimated variability of the decision function; small variability indicated that participants responded consistently trial after trial within a small range around their threshold, whereas large variability indicated inconsistent decision making across a large range of openings. Finally, perceptual sensitivity to changing affordances was measured by testing whether children scaled behaviors (e.g., attempts to fit, latency to respond) with respect to opening size.

While fitting their hand through an opening, children can see their hand and the opening simultaneously, allowing direct visual comparison between hand size and opening size. Seeing the hand as it approaches the opening provides a wealth of visual information about how best to maneuver the fingers and thumb to conform to the shape of the opening. However, previous work has shown that infants often employ haptic exploration before making a motor decision (Adolph, 1997). Thus, we scored exploratory touching of the opening to track the use of haptic exploration over the course of development. We expected exploratory touching to decrease in frequency from infancy to childhood as children become more adept at relying on visual information alone. Moreover, testing whether haptic exploration scaled to opening size provided additional evidence regarding children's sensitivity to affordances.

Methods

Participants

We tested 72 children from five non-overlapping age groups: 18 16-month-olds (8 girls and 10 boys, M_{age} = 16.49 months, SD = 0.51), 12 22-month-olds (6 girls and 6 boys, M_{age} = 22.04 months, SD = 0.17), 12 34-month-olds (6 girls and 6 boys, M_{age} = 34.08 months, SD = 0.21), 18 5-year-olds (12 girls and 6 boys, M_{age} = 5.42 years, SD = 0.61), and 12 7-year-olds (6 girls and 6 boys, M_{age} = 7.74 years, SD = 0.31). An additional 7 children (4 16-month-olds, 1 22-month-old, and 2 34-month-olds) were excluded from analyses due to fussiness. All children were healthy and born at term. Children were recruited through commercially available mailing lists and flyers. Families received framed photographs and certificates for their participation.

We also tested 12 college-age adults (8 women and 4 men, M_{age} = 20.96 years, SD = 1.63) as a comparison group. They were recruited from psychology courses and received credit toward course requirements for their participation.

Apparatus

As shown in Fig. 1, to test participants with a wide range of hand sizes, we used a 120-cm wide × 93-cm tall wooden apparatus with an adjustable diamond-shaped opening in the middle (Ishak et al., 2008). Turning a knob adjusted the length of each side of the opening from 0 cm (completely closed) to 40 cm in 0.20-cm increments. When the apparatus was closed, the overlapping segments were still visible so that the apparatus did not look like a blank wall. When the apparatus was open, small targets were placed in the center, behind the opening on the end of a flat wooden stick (91 × 2.54 cm) at a distance that required each participant to insert his or her entire hand through the opening. The target distance was the length of the participant's right hand from the tip of the

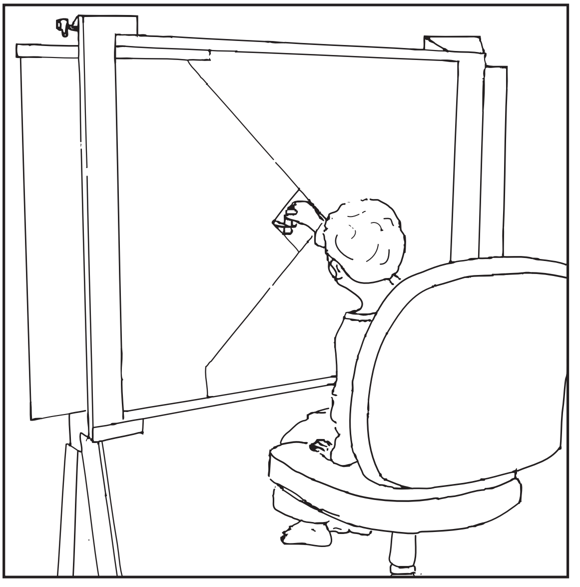

Fig. 1. Adjustable reaching apparatus. Participants sat on a swiveling office chair and reached through openings for targets. Between trials, participants faced away from the apparatus while it was adjusted. Infants sat on their caregiver's lap.

middle finger to the base of the thumb. The target distance remained fixed for the duration of the session. Targets consisted of small toys and snacks that ranged in size from 0.50 to 5 cm in width and were selected for each trial to ensure that they could easily fit through the current opening size.

Video cameras captured four different images that were mixed onto a single video frame and viewed simultaneously for later coding. One camera recorded a zoomed-in view of participants' hand movements during their approach to the opening. A second camera recorded participants' actions on the target side of the opening. A third camera to the left of participants recorded their entire body as they reached. A fourth camera, attached to the apparatus, projected calibration markings to a monitor so that the opening size could be adjusted precisely. The monitor was hidden from participants' view.

Procedure

An experimenter first measured the length of participants' right hand using a ruler and adjusted the wooden stick to the appropriate target distance. Participants then sat on a swiveling office chair 60 cm away from the apparatus with the chair height adjusted so that the center of the opening was at chest level. Younger children sat on their caregiver's lap. The experimenter informed participants that they would be presented with many openings of different sizes—some very small and some very large; if they thought their hand could fit through the opening, they should try, and if they did not think their hand could fit, they did not have to try. Participants faced away from the opening while the experimenter adjusted the size. An assistant collected the targets to ensure that participants' hands were empty for the next trial and showed children puzzles and games to guarantee that they did not peek at the openings. At the start of each trial, the assistant spun participants to face the apparatus and asked, "Do you think you can fit?" or "Can you get it?" to focus their attention on the targets and openings. Participants were not instructed on which hand to use during the session.

Because the youngest infants were preverbal, the experimenter demonstrated the range in opening sizes to all of the participants by encouraging them to reach through the largest 40-cm opening three times and then presented the smallest 0-cm opening once in four warm-up trials. Then, to hone in on the limits of participants' abilities, starting with the 40-cm opening, participants received progressively smaller openings until their hand got stuck. Next, to guarantee that all participants were tested with a range of openings, they were presented with approximately 50 randomly ordered probe trials ranging from 3 cm smaller to 3 cm larger than the opening near their hand size. Participants were presented with a mean of 33.07 (*SD* = 5.46) different-sized openings, some of which differed by 0.20 cm. The number of different opening sizes participants received varied depending on how many increments were needed to estimate their affordance and decision functions. Easy baseline trials between 10 and 40 cm were interspersed throughout the session to maintain participants' interest; younger children tended to receive more baseline trials. Although participants were allotted 10 s to make a decision, trials were relatively fast, lasting a mean of 4.29 s (*SD* = 2.39 s). Participants received a mean of 63.01 trials (*SD* = 5.53), and the number of trials did not differ between age groups. At the end of the session, an experimenter measured the width of participants' hand by placing a caliper at the metacarpophalangeal joints (third knuckle) of the index and pinky fingers while participants rested their hand flat on a table with their fingers together. Most participants completed the session within 20 min.

Data coding

A primary coder used Datavyu (http://www.datavyu.org), a video coding program that allows frame-by-frame identification of the type and timing of events to score participants' responses. As in Ishak et al. (2008), *trial outcome* was scored as a success (touched the target without retracting and reinserting the hand), failure (inserted the hand past the second knuckle of the middle finger but failed to contact the target because the hand was stuck), or refusal to reach (avoided reaching for 10 s or did not insert the hand past the second knuckle of the middle finger). For each refusal, coders scored exploratory *touching* if participants touched the apparatus or poked their fingertips into the opening without attempting to reach. In addition, for each attempt (success and failure trials), coders scored *latency* from when participants faced the apparatus until their fingertips were at the edge of the opening.

A secondary coder independently scored 25% of each participant's trials to ensure interrater reliability. Coders agreed on 87.5% and 96.9% of trials for trial outcome and touching, respectively. The correlation coefficient for latency was $r(826) = .99$, $p < .001$. Disagreements were resolved through discussion.

Affordance and decision function estimation

Based on video coding of trial outcome, we calculated success and attempt rates at each opening size for each participant. Success rates were calculated as the ratio of successful reaches to the number of attempted reaches: $S/(S + F)$, where S is success and F is failure. Attempt rates were calculated as the ratio of attempted reaches to the total number of trials: $(S + F)/(S + F + R)$, where R is refusal. Scaling attempt rates to changes in opening size served as a measure of *sensitivity*. To determine affordance and decision functions for each participant, separate cumulative normal functions were fit to success and attempt rates using maximum likelihood estimation for the μ and σ parameters (Berger, 1985; Wichmann & Hill, 2001) using a customized Matlab routine. The affordance function represents actual possibilities for fitting, whereas the decision function represents participants' perception of whether they could fit (Franchak & Adolph, in press). The μ parameter of the affordance function was used as the affordance threshold (the opening size that permitted successful fits on 50% of attempted trials). The μ parameter of the decision function was used as the estimate of the decision threshold (the opening size that indicated an attempt rate of 50% of all trials). The difference between the affordance and decision functions—decision error—served as a measure of *accuracy*. The σ parameters from each function provided measures of affordance and decision variability across trials for each participant—how *consistently* the participant was able to fit his or her hand through openings and how *consistently* the participant chose to attempt to fit through openings, respectively.

A parametric bootstrap with 10,000 Monte Carlo iterations provided 95% confidence intervals for the μ and σ parameters of each function. Affordance function μ parameters averaged 4.61 ± 0.07 cm, and σ parameters averaged 0.12 ± 0.05 cm. Decision function μ parameters averaged

3.39 ± 0.17 cm, and σ parameters averaged 0.35 ± 0.18 cm. The size of confidence intervals did not differ between age groups.

Results

We analyzed a variety of data to determine whether participants matched their attempts to fit to hand size and affordances. Preliminary analyses showed no gender differences, so data were collapsed across gender for further analyses. Analyses of variance (ANOVAs) with significant effects were followed by post hoc comparisons using Tukey's HSD (honestly significant difference) to control for experiment-wise error rates ($p < .05$).

Hand size, affordance thresholds, and decision thresholds

Some participants could fit their hand through much smaller openings than others. In general, affordance thresholds increased with age (closed symbols in Fig. 2). An ANOVA on affordance thresholds confirmed significant age differences, $F(5,78) = 81.63$, $p < .001$, partial $\eta^2 = .84$. The three youngest age groups (16-, 22-, and 34-month-olds) could squeeze their hand through the smallest openings. The 5-year-olds' affordance thresholds were larger than the 16-month-olds' affordance thresholds but did not differ from those of the 22- and 34-month-olds. The 7-year-olds' affordance thresholds were larger than those of the other children; adults had the largest affordance thresholds. Hand width followed a similar pattern to affordance thresholds and increased with age. Hand width was correlated with affordance thresholds, $r(83) = .91$, $p < .001$, attesting to the reliability of the estimates derived from the psychophysical procedure.

As shown by the open symbols in Fig. 2, decision thresholds also increased with age. An ANOVA on decision thresholds confirmed a significant age effect, $F(5,78) = 54.67$, $p < .001$, partial $\eta^2 = .78$. Post hoc comparisons revealed no differences between decision thresholds for 16-, 22-, and 34-month-olds and 5-year-olds. However, 7-year-olds had larger decision thresholds than the other children; adults had the largest decision thresholds. In addition, significant correlations among hand width, decision thresholds, and affordance thresholds suggest that participants' decisions were related to hand width, $r(83) = .83$, $p < .001$, and affordance thresholds, $r(84) = .90$, $p < .001$.

Although hand size, affordance thresholds, and decision thresholds increased with age, the variability of participants' affordances for fitting the hand through openings did not change. The σ values of individual affordance functions had a mean of 0.13 cm ($SD = 0.15$), indicating that possibilities for manual navigation through the opening shifted sharply from possible to impossible. A nonsignificant ANOVA on the σ parameter of the affordance function revealed that σ values were similar across ages,

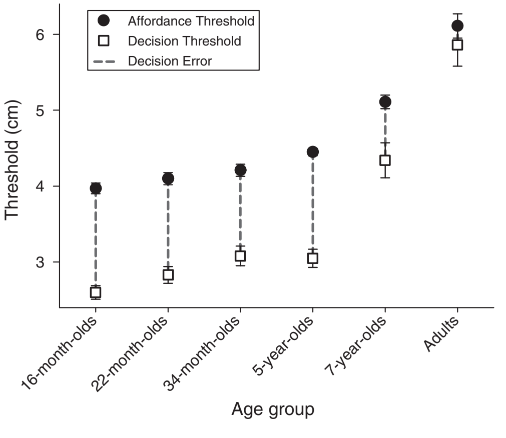

Fig. 2. Mean affordance thresholds (closed circles) and decision thresholds (open squares) for each age group. Dotted line denotes decision error. Error bars indicate standard errors.

$F(5,78) = 1.36$, $p > .05$, partial $\eta^2 = .08$. Success and failure were separated by only a few millimeters in opening size. Because affordance variability did not change with age (and was not proportional to hand size), a difference of 1 cm in opening size was functionally equivalent for infants, children, and adults. Thus, the demands on affordance perception were comparable for the different age groups; adaptive decisions to fit through openings required a high degree of perceptual sensitivity, accuracy, and consistency.

Accuracy and consistency of motor decisions

To determine whether attempts accurately matched affordances, we calculated *decision error* as the absolute difference between attempt and success thresholds (see dashed vertical lines in Fig. 2). An ANOVA on decision error confirmed significant age differences, $F(5,78) = 9.21$, $p < .001$, partial $\eta^2 = .37$. Post hoc comparisons showed smaller decision errors for adults (M = 0.42 cm, SD = 0.64) compared with 16-month-olds (M = 1.35 cm, SD = 0.35), 22-month-olds (M = 1.25 cm, SD = 0.42), 34-month-olds (M = 1.13 cm, SD = 0.26), and 5-year-olds (M = 1.43 cm, SD = 0.49), but they showed no difference compared with 7-year-olds (M = 0.92 cm, SD = 0.48). In addition, 7-year-olds showed only smaller decision errors compared with 5-year-olds; and 5-year-olds did not differ from the younger groups.

We also analyzed the ratio of decision thresholds to affordance thresholds to determine whether relative error differed across age groups. We divided each participant's decision threshold by his or her affordance threshold to obtain a ratio of participants' attempts relative to actual possibilities for action. A decision ratio near 1 indicates that participants attempted openings close to affordances; a decision ratio smaller than 1 indicates that participants attempted openings smaller than their affordance threshold. An ANOVA with age group as the factor on this ratio confirmed significant age differences, $F(5,78) = 15.44$, $p < .001$, partial $\eta^2 = .50$. Post hoc comparisons showed larger ratios for adults (M = 0.96, SD = 0.13) compared with 16-month-olds (M = 0.66, SD = 0.09), 22-month-olds (M = 0.70, SD = 0.09), 34-month-olds (M = 0.73, SD = 0.07), and 5-year-olds (M = 0.68, SD = 0.12), but they showed no difference compared with 7-year-olds (M = 0.84 cm, SD = 0.14). In addition, 7-year-olds' ratios were larger than those of 16-month-olds, 22-month-olds, and 5-year-olds; however, they did not differ from those of 34-month-olds.

The variability of participants' decisions functions provided a measure of response consistency. Paired t tests of σ values from individual affordance and decision functions revealed more variability in participants' decisions to fit compared with their actual affordances, $t(83) = 8.52$, $p < .001$. However, an ANOVA revealed no age difference for decision σ values, $F(5,78) = 0.44$, $p > .05$, partial $\eta^2 = .03$. The σ values of individual decision functions ranged from 0.01 to 2.30 cm (M = 0.49 cm), and values overlapped among age groups. Thus, the youngest participants were just as consistent as the oldest ones.

Sensitivity to opening size

Although participants in all age groups responded consistently from trial to trial, the infants and youngest children made consistently inaccurate decisions. Did inaccurate responses stem from a lack of sensitivity to affordances? If so, infants and children would behave indiscriminately with respect to opening size. However, if infants and children possessed any degree of sensitivity, their behaviors would be systematically scaled to opening size. Therefore, we tested whether participants' attempt rates, haptic exploration, and latency to attempt to reach were scaled to opening size.

Given the range in hand widths, the same absolute opening size that might be possible for one participant could be impossible for another; an infant might be able to fit through an opening that is far too small for an adult. Therefore, we compared participants' behaviors relative to their individual affordance thresholds rather than absolute opening size. We grouped responses into seven opening size increments relative to the affordance threshold at ±3, ±2, ±1, and 0 cm from the affordance threshold. Each increment group spanned 1 cm (e.g., the 0-cm group comprised trials from −0.50 to +0.50 cm around the affordance threshold, the +2-cm group comprised trials from +1.50 to +2.50 around the affordance threshold). Participants contributed a mean of 7.97 trials (SD = 1.00) to each opening size increment. The seven opening sizes divided trials into impossible openings (−3, −2, and −1 cm), uncertain openings (0 cm), and possible openings (+3, +2, and +1 cm). Differential responses for different opening size increments would indicate scaling to affordances.

Attempt rates

As shown in Fig. 3A, participants in every age group scaled attempts to affordances; that is, attempts decreased as the likelihood of fitting decreased. Across age groups, attempt rates were uniformly high—near 1.0—at the +1-, +2-, and +3-cm openings larger than the affordance threshold, and they were uniformly low—near 0—at the −2- and −3-cm openings smaller than the threshold. A 7 (Opening Size) × 6 (Age Group) repeated-measures ANOVA on attempts confirmed main effects for opening size, $F(6,462) = 1080.59$, $p < .001$, partial $\eta^2 = .93$, and age, $F(5,77) = 8.57$, $p < .001$, partial $\eta^2 = .36$, and an opening size by age interaction, $F(30,462) = 8.95$, $p < .001$, partial $\eta^2 = .34$. A significant linear trend, $F(1,77) = 6907.20$, $p < .001$, partial $\eta^2 = .99$, for opening size confirmed that attempts decreased for openings smaller than threshold. Simple main effects of age at each opening size revealed age differences for the −1- and 0-cm openings. Post hoc comparisons showed lower attempt rates for adults compared with all children at 0 cm, lower attempt rates for adults and 7-year-olds compared with 5-year-olds and 16-month-olds at the −1-cm opening, and lower attempt rates for adults compared with 22- and 34-month-olds at the −1-cm increment.

Exploratory touching

We looked for evidence of sensitivity in participants' exploratory touching on trials where they refused to reach. Video coding revealed that participants sometimes poked one or two fingers into

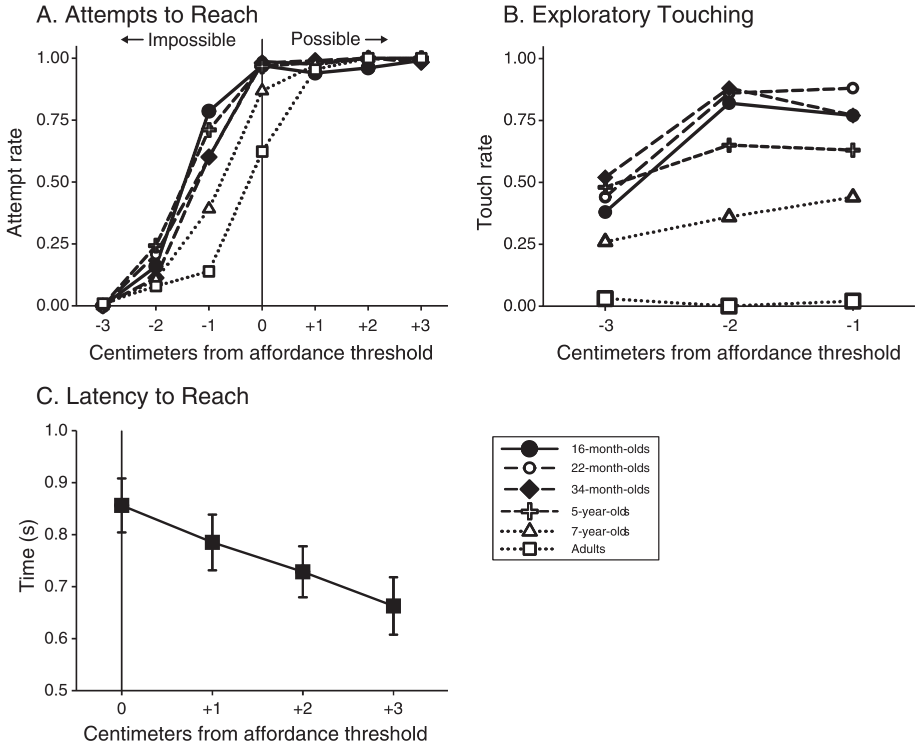

Fig. 3. Average values of participants' attempt rates (A), touching rates (B), and latency (C) for each opening size increment relative to affordance threshold. The solid vertical line at 0 in panels A and C denotes the affordance threshold. Possible openings are represented by positive numbers on the *x* axis, and impossible openings are represented by negative numbers. For panels A and B, age groups are denoted by the legend. In panel C, latency is collapsed by age and error bars indicate standard errors.

openings or outlined openings with their finger prior to withdrawing their hand. Most of these behaviors occurred on openings smaller than the affordance threshold. Therefore, we analyzed touching on refusals at the −3-, −2-, and −1-cm opening sizes to ensure that the most trials were included.

As shown in Fig. 3B, participants touched more often on openings closer to their affordance thresholds. Furthermore, children younger than 7 years were most likely to engage in exploratory touching. A 3 (Opening Size) × 6 (Age Group) repeated-measures ANOVA on touching confirmed main effects for opening size, $F(2,138) = 48.26$, $p < .001$, partial $\eta^2 = .41$, and age, $F(5,69) = 16.37$, $p < .001$, partial $\eta^2 = .54$, and an opening size by age interaction, $F(10,138) = 4.42$, $p < .001$, partial $\eta^2 = .24$. A significant linear trend, $F(1,69) = 51.61$, $p < .001$, partial $\eta^2 = .43$, for opening size confirmed an increase in exploratory touching on openings closer to affordance thresholds. To examine the main effect of age, post hoc comparisons showed lower haptic exploration rates for adults compared with all of the children; 7-year-olds had lower rates than 16-, 22-, and 34-month-olds; and 7-year-olds did not differ from 5-year-olds. We followed up the significant interaction with simple main effects to determine which age groups touched more on openings closer to their affordance thresholds. Separate one-way ANOVAs on touching rates for each age group were significant for 16-, 22-, and 34-month-olds only (all *p*s < .001), and post hoc comparisons revealed that children from these age groups had higher touching rates at the −2- and −1-cm increments compared with the −3-cm increment.

Latency

We analyzed latency on trials where participants attempted to fit their hand through openings and included all 0-, +1-, +2-, and +3-cm opening sizes to include the most trials (adults and 7-year-olds rarely attempted openings less than their affordance thresholds). Although most latencies were brief ($M = 0.84$ s, $SD = 0.28$), Fig. 3C shows that, overall, participants hesitated longer on openings at their affordance thresholds and that latency decreased with increasing opening size. A 4 (Opening Size) × 6 (Age Group) repeated-measures ANOVA on latency confirmed main effects for opening size, $F(3,204) = 6.63$, $p < .001$, partial $\eta^2 = .09$, and age, $F(5,68) = 42.73$, $p < .05$, partial $\eta^2 = .17$. The interaction between opening size and age group was not significant, $F(15,204) = 0.96$, $p > .05$. A significant linear trend, $F(1,68) = 19.59$, $p < .001$, partial $\eta^2 = .22$, and a post hoc analysis on the main effect for opening size confirmed that participants had shorter latencies on openings larger than their affordance thresholds. Post hoc comparisons on the main effect for age showed longer latencies for 16-month-olds compared with 7-year-olds.

Discussion

The current study examined how infants, children, and adults perceive affordances for reaching through openings of different sizes. Fitting through openings is a multi-step process of comparing body parts with opening size, minimizing the relevant body parts, and finally guiding the body through the opening. Accomplishing each component relies on the ability to accurately and consistently make subtle distinctions between the size of the body relative to the opening. In contrast to previous work, we included school-age children to close the gap in affordance research between infants and adults. We designed a task that could be used across age groups, precluding attribution of age-related differences to differences in the task (e.g., Keen, 2003). We used a continuously adjustable apparatus to present participants with a range of small gradations in opening size and a psychophysical procedure to estimate individual affordance and decision functions. From infancy to adulthood, hand size predicted affordances for fitting through openings; infants had smaller hands that could fit through smaller openings, and adults had larger hands that could fit only through larger openings. Analysis of σ values of the affordance function revealed no age differences, suggesting that the demands on affordance perception were equivalent across age groups; a change of just a few millimeters of opening size could shift affordances from possible to impossible for infants as well as for adults.

By measuring what size openings participants decided to reach through, we were able to assess the accuracy, consistency, and sensitivity of affordance perception from infancy to adulthood. Below, we discuss which aspects of affordance perception change over the course of development and which aspects stay the same.

What changes in affordance perception?

Accuracy refers to selecting the correct action—attempting when the opening is possible to fit through and refusing when the opening is impossible. As we expected, accuracy improved with age. Decision errors for infants and young children averaged more than 1 cm; they attempted to reach through openings at ratios of approximately 0.70 of affordance thresholds. In contrast, 7-year-olds and adults matched their decisions more closely to affordance thresholds—0.9 and 0.4 cm, respectively (decision ratios of 0.84 and 0.96 of affordance thresholds). Adults' level of accuracy in the current study is similar to that of adults in previous work (Ishak et al., 2008). Although we expected that the oldest participants would be more accurate, we were surprised that accuracy did not improve from 16 months to 5 years of age; only 7-year-olds showed a significant increase in accuracy compared with the younger children. However, by 16 months of age, most infants have already gained a substantial amount of experience in reaching (nearly 1 year of experience). Younger infants with less reaching experience might be substantially less accurate than the 16-month-olds we tested.

Although young children were less accurate than adults, they still showed evidence of consistency and sensitivity. Adaptive motor decisions need to be consistent over repeated encounters. We measured trial-to-trial variability in participants' decisions and found that every age group attempted and refused with similar consistency. Participants consistently attempted or refused on trial after trial for most opening sizes, with responses varying within a range of approximately ±2 cm surrounding the decision threshold. Similar levels of consistency have been reported in studies of adults walking (Franchak et al., 2010) and reaching (Ishak et al., 2008) through openings, but consistency of responses has not been previously reported in infants and children. However, whereas adults and 7-year-olds were consistently accurate, high consistency in young children meant that they were persistent in their errors as well as in their correct responses.

Sensitivity refers to the ability to detect how changes in the dimensions of the environment affect possibilities for action; scaling behaviors to changing affordances is evidence of sensitivity. Whereas accuracy improved with age, like consistency, sensitivity to affordances did not change from infancy to adulthood: Every age group demonstrated sensitivity by scaling attempt rates, latency, and exploratory touching to opening size. Our results are in line with previous work showing that infants and children scale motor behaviors to changing affordances for walking through openings (Franchak & Adolph, 2012; van der Meer, 1997; Wilmut & Barnett, 2011), descending cliffs (Kretch & Adolph, 2013a, 2013b), and walking down slopes (Adolph, 1997).

Age-related changes in exploratory touching followed the same pattern as accuracy. The youngest participants (16-month-olds) to 5-year-olds typically explored the opening with their hands before refusing, converging with previous work that has documented exploratory touching in infants (Adolph, 1997). However, 7-year-olds and adults rarely touched the opening, suggesting that the older participants relied solely on visual information when making their decisions; they brought their hands up to the opening only after seeing that the opening was sufficiently large. In contrast, the youngest participants used both visual and haptic information while making their decisions. Infants and young children scaled exploratory touching to opening size. They explored more with their hands when the opening was close to threshold and explored less when the opening was impossibly small, suggesting that they relied on visual information to decide whether to engage in manual exploration.

Had we measured only children's accuracy, we would have obtained an incomplete understanding of what develops in affordance perception during childhood. Infants and young children make more errors, and thus are less accurate, compared with 7-year-olds and adults. Young children's errors are not the result of inconsistent decisions; their responses were systematic even when incorrect. They not only consistently attempted to fit through openings that were 1 cm too small but also always attempted larger openings. Moreover, children's errors are not the result of a failure of sensitivity. Even 16-month-old infants detect that changes in opening size affect possibilities for action, and they modify their behaviors accordingly. If infants and young children were consistent in their responses and sensitive to affordances, why did they err more than older children and adults? Moreover, why did accuracy fail to improve from 16 months to 5 years of age? We considered three possible explanations.

Why young children err

The first possibility is that affordance perception does not approach adult-like accuracy until later in childhood. On this account, young children are sensitive to different opening sizes and know that larger openings make the action more likely to succeed, but they do not know exactly where their affordance threshold is amid the range of possible openings. They have some notion of what is possible given that their decision thresholds deviated from affordances by only 1.2 to 1.4 cm; nonetheless, they failed to achieve the same degree of accuracy as adults (0.4 cm). However, other work has shown that infants can perceive some affordances as accurately as adults; for example, 17-month-olds are just as accurate as adults when deciding to walk along ledges of varying widths (Comalli, Franchak, Char, & Adolph, 2013; Franchak & Adolph, 2012). But, it is possible that reaching requires greater precision compared with walking, and children may require more experience to become as expertly calibrated to affordances as adults.

A second explanation for young children's relatively high error rate is that their errors stem from a liberal response criterion. Motor decision making involves an integration of perceiving possibilities for action and evaluating the risks and rewards associated with possible outcomes (Trommershäuser, Maloney, & Landy, 2008). Previous work has shown that infants and adults make riskier (and thus less accurate) decisions when the penalty for errors is entrapment in an opening compared with falling from a precipice (Comalli et al., 2013; Franchak & Adolph, 2012). Similarly, infants discount various penalties for errors in other types of tasks. For example, 14-month-old walking infants respond differentially to bridge width for crossing a precipice but do not respond differentially to the depth of the precipice (Kretch & Adolph, 2013a, 2013b). Despite the fact that falling from a higher bridge (71 cm) has more serious consequences than falling from a lower bridge (17 cm), infants treat the two depth conditions the same. Infants of every age try repeatedly to climb up impossibly steep slopes where the penalty for error is minimal (infants simply end up in a crawling position at the base of the slope), but the same infants consistently refuse to attempt descent where the penalty for error is falling downward (Adolph, 1997). Most likely, the youngest participants in the current study did not consider entrapment of the hand to be a serious penalty. They might have been willing to attempt openings that were slightly smaller than they believed to be possible because getting the hand stuck resulted in only minor discomfort. In accord with this explanation, young children predominantly made errors by attempting openings that were 1 cm too small. If children's errors were solely the result of perceptual inaccuracy, we should have observed errors in both directions—that is, errors by refusing to reach through openings larger than threshold. In addition, infants and children may have been slightly more motivated to retrieve the targets (small toys and snacks) than older participants, which could have led to young children attempting smaller openings (but note that, overall, older children and adults tended to attempt impossible openings as well).

A third possibility is that young children's errors stem from haptic exploration. Infants and young children frequently explored the opening with their hands on trials that resulted in a refusal. If children had already brought their hands up to the opening to explore it, and they did not consider the penalty for error to be high, what would deter them from attempting? Indeed, motor errors—learning by doing—are informative and can provide useful feedback for calibrating affordance perception (Adolph, 1997; Franchak et al., 2010). Moreover, errors resulting from exploratory touching would help to explain why accuracy was similar across the range of 16 months to 5 years of age; children of those ages literally required firsthand experience and touched openings frequently. At 7 years of age, children rarely touched the opening when refusing and were significantly more accurate than the younger children. Thus, the discontinuity in children's errors might not be a discontinuity in affordance perception; rather, it may be a by-product of the changing use of haptic and visual information over development.

A fourth and related explanation is that development of executive function accounts for higher error rates in children under 5 years of age compared with older children. Possibly, children need better inhibitory control to refrain from touching the opening and refuse to attempt fitting through openings that are clearly too small. Aspects of executive function, including inhibition of perseveration, planning, working memory, and task shifting, show substantial improvements after 5 years of age (see

Anderson, 2002, for a review). In fact, between 5 and 8 years of age, children experience the most changes in their ability to inhibit behaviors (Romine & Reynolds, 2005).

In addition, cognitive flexibility and information processing show a significant spurt between 7 and 9 years of age and are not mature until 12 years of age (Anderson, Anderson, Northam, & Taylor, 2000). Changes in executive function are mirrored by neurophysiological developments in the prefrontal cortex (Best, Miller, & Jones, 2009). Moreover, the onset of schooling, typically at 5 years of age, may also play a role in helping these abilities to expand.

These explanations are not mutually exclusive; it is possible that young children are less accurate, more risky, and more prone to attempt because they manually explore openings and have less sophisticated executive functions. However, the current study cannot clearly distinguish among these explanations. Future research should vary the reward structure of the task to disentangle perceptual accuracy from decision factors and to try to equate rewards across age groups. Participants might receive a prize on successful reaches but need to relinquish one on failed attempts, trigger a positive sound on successful reaches but a negative buzzer on failures, or receive social feedback about the accuracy of their decisions. If infants and children consider the penalty for errors to be more severe, they might respond more accurately. Furthermore, testing infants from the onset of reaching to 16 months of age may reveal age-related improvements in accuracy, consistency, and sensitivity as infants gain experience with reaching.

Conclusion and implications for children's safety

Through the use of multiple outcome measures, this investigation provides a more nuanced view of the development of affordance perception compared with past research. Although accuracy improves with age, infants are no less consistent or sensitive to affordances compared with adults. Outside the laboratory, young children's low accuracy has implications for their safety. Young children intentionally wedge their body between two opposing surfaces or between moving parts of equipment (Abbas, Bamberger, & Gebhart, 2004; Doraiswamy, 1999), and accidental entrapment is a leading cause of injury (Tinsworth & McDonald, 2001). Current findings suggest that accidental entrapment injuries may result from children's proclivity for exploring body–environment relations by fitting body parts into tight spaces and their failure to consider entrapment as a severe penalty for errors.

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