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

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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 affor-

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 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

$F(5, 78) = 1.36$, $p > .05$, 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, at-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 $ps < .001$), 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.

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 1.31593fib5(the2o230.8234.-1.4335-)]0q2 6371.6(age)-372.1(differ5ands)s-
tently to

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 mea-

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