Development of affordance perception and recalibration in children and adults

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Changes in the body over developmental time (e.g., physical growth) as well as over shorter time-scales (e.g., wearing a backpack or carrying a large object) alter possibilities for motor action. How well can children recalibrate their perception of action possibilities to account for sudden changes to body size? The current study compared younger children (4-7 years), older children (8-11 years), and adults as they decided whether they could squeeze through doorways of varying width. To test for age-related changes in recalibration to modified abilities versus perception of unmodified abilities, half of the participants wore a backpack while making judgments and squeezing through doorways and half did not. Results indicated that judgment accuracy improved with age but that participants had more difficulty when recalibrating to modified abilities. Bias in decision-making also changed with age: Whereas younger children made riskier decisions by attempting to fit through impossibly small doorways, older children were more cautious. Some particularly cautious participants never generated practice feedback by attempting (and failing) to fit through smaller doorways, which prevented them from recalibrating. Taken together with previous literature, the results of the current study suggest that the development of perception for unmodified versus modified ability proceeds at different rates and depends on the particular motor task.

Perceiving affordances means distinguishing which actions are possible given the body's size and capabilities (Gibson, 1979). For example, the affordance for passing through a narrow doorway may be possible for a small child but impossible for a large adult. If perception is *calibrated*—meaning that affordance perception is appropriately scaled to the body's abilities—the child will perceive the doorway as possible to navigate but the adult will not. However, poorly calibrated perception may lead the observer to make a motor error, such as attempting to fit through a doorway that is too small. Understanding affordance perception and its development is relevant to injury prevention in childhood. Accidental injuries are responsible for over 12,000 deaths and nine million emergency room visits each year for children in the United States (Borse et al., 2008). Many injuries resulting from entrapment, falling, and pedestrian/cycling accidents stem from children making motor errors, which may in turn result from poorly-calibrated affordance perception. Indeed, laboratory studies of children's affordance perception suggest early deficits. For example, younger children (3-5 years) make large errors when choosing whether to reach through openings of varying size, but by 7 years children's perception is as well-calibrated as adults' perception (Ishak, Franchak, & Adolph, 2014). Similarly, 4- to 5-year-old children grossly misjudge whether inclined surfaces are possible to stand on (Klevberg & Anderson, 2002), and 6- and 8-year-olds overestimate their abilities to reach, step, and duck under barriers (Plumert, 1995) compared with adults. Critically, motor errors in laboratory tasks predict children's injury rates in everyday life (Plumert, 1995; Plumert & Schwebel, 1997), suggesting that studying the developmental mechanisms of affordance perception through such tasks has direct implications for injury prevention. The goal of the current study is to extend past work by considering not only how children judge their normal, unaltered abilities (as in the examples above), but also how they *recalibrate* their perception to adapt to changing affordances.

Affordances continually change because they depend on the dynamic relation between the body's size/abilities and the environment. Over development, new motor skills as well as physical growth alter the body's abilities. On shorter timescales, carrying or using objects can temporarily modify abilities. For example, wearing a backpack or holding a long rod increases the doorway size needed to pass through (Franchak, 2017; Franchak & Somoano, 2018; Yasuda, Wagman, & Higuchi, 2014) and wearing platform shoes allows actors to sit on higher seats (Mark, 1987). However, sudden

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alterations to affordances adversely affect calibration of perception because actions that were once possible may become impossible (or vice versa). Adults are skilled at recalibrating their affordance perception to reflect changes in the body and abilities provided they can access the right perceptual information (Franchak, 2017; Franchak & Somoano, 2018; Mark, 1987; Mark, Baillet, Craver, Douglas, & Fox, 1990; Stoffregen, Yang, & Bardy, 2005).

Much of the previous work on affordance recalibration has followed Gibson's ecological approach (Gibson, 1979), which conceptualizes perceptual information in a different way from computational approaches. In computational approaches (e.g., Marr, 1982), observers perceive separate, action-neutral metric properties (e.g., the height of the platform shoe, the length of the leg, the height of the seat) and judge whether an action is possible through a computation between those properties. In contrast, the ecological approach posits that observers detect a single action-specific perceptual variable that specifies a given affordance (e.g., seat height as a proportion of eye height for the sitting task). Evidence supports this claim: Mark (1987) demonstrated that observers' perception of affordances for sitting while wearing platform shoes was independent of their perception of the size of the platform shoes. This implies that observers recalibrate by learning something intrinsic about the body's abilities relative to the environment rather than by computing an affordance from constituent properties (see also Thomas, Wagman, Hawkins, Havens, & Riley, 2016). Thus, recalibration is not as simple as "adding" the perceived size of the platform shoe to adjust one's judgment of sitting or the perceived size of a backpack to one's judgment of fitting through doorways. Rather, observers recalibrate to changing affordances through action experience, which reveals relational information about the body and environment (Franchak, 2017; Franchak & Somoano, 2018; Labinger, Monson, & Franchak, 2018; Mark, 1987; Mark et al., 1990; Stoffregen et al., 2005; Yasuda et al., 2014).

Thus, understanding the development of recalibration is critical to understanding the development of affordance perception more generally. However, although numerous studies have investigated children's perception of their unaltered abilities as well as adults' ability to recalibrate, only a handful have tested recalibration in children. In one study, 14-month-old infants were tested as they decided whether to descend a sloping walkway while wearing a lead-weighted or feather-weighted vest (Adolph & Avolio, 2000). The lead-weighted vest compromised infants' balance, making slopes that were normally possible to descend impossible. Infants' decisions were sensitive to changing abilities—they more often walked down a slope of the same steepness while unweighted compared to weighted. But infants failed to fully recalibrate—they still attempted slopes beyond their ability. Another study investigated 11-year-old children's judgments of reaching while adapting to different levels of postural support (Johnson & Wade, 2009). Children updated judgments with respect to changing postural conditions; however, actual affordances were not measured in the altered conditions, rendering it impossible to say how successfully children recalibrated. This limitation was addressed in a study of recalibration to changes in sitting ability when wearing platform shoes: Results suggested that children might have an adult-like ability to recalibrate by 12 years (Chen, Tsai, & Wu, 2014). Notably, children's perception of their altered abilities was as well-calibrated by the end of the study as of their unmodified abilities to sit on seats without wearing the platform shoes, suggesting that children fully recalibrated. However, we lack a comprehensive understanding of children's ability to recalibrate to changing affordances because prior work has studied only three different affordances (slope descent, reaching, and sitting) and has only tested children either in infancy (14 months) or within a narrow age range in middle childhood (11-12 years).

The current study used the task of squeezing through doorways with or without a backpack that modifies body size as a model system for studying recalibration. The advantage of the task is threefold. First, whereas the affordance manipulation used in past work (Chen et al., 2014)—wearing platform shoes—is not something typically encountered in children's everyday life, wearing a backpack is an alteration to body size that children commonly experience and potentially relates to real-life accidental injury. Second, the process of recalibration varies for different affordances (Franchak, 2017), so the doorway squeezing task provides a way to study a different recalibration process compared to what has been investigated in prior work. In the sitting task used by Chen et al. (2014), recalibration is accomplished gradually over time using information generated from movement experience (Mark, 1987). *Practice feedback* from actually sitting on seats—performing the action and observing the results—is not required for recalibration in the sitting task (Mark et al., 1990; Stoffregen et al., 2005). However, practice feedback *is* likely required to recalibrate to altered body size in the doorway squeezing task (Franchak, 2017; Franchak & Adolph, 2014; Franchak & Somoano, 2018; Labinger et al., 2018). In particular, adults' recalibration in the squeezing task depends on receiving both success feedback (i.e., fitting through a sufficiently large doorway) and failure feedback (i.e., attempting to fit through a small doorway and becoming stuck) (Franchak & Somoano, 2018). Whether children can effectively recalibrate using practice feedback is an open question. Prior work shows that the ability to calibrate perception of *unmodified abilities* from practice information does change with age: 8-year-olds' affordance judgments improved following action practice but 6-year-olds' judgments did not (Plumert, 1995). However, children's ability to *recalibrate* their perception using practice information has not been tested. Testing how children recalibrate from different types of information for different affordances is relevant to injury prevention, shedding light on whether interventions that work to foster better calibration for one type of action may or may not translate to another action. Third, studying the squeezing task provides an opportunity to understand how observers *choose* to generate practice feedback. Because the squeezing task depends on participants' decisions to practice, cautious participants who never attempt to fit through small doorways (which would provide failure experience) should be unable to recalibrate successfully.

The latter—how participants choose to generate practice feedback—may depend on age-related changes in risk taking. Adults tend to be overly cautious: A recent study that tested adults in the squeezing task and allowed them to practice as much or as little as they wished found that adults rarely chose to practice; consequently, adults did not recalibrate as fully compared with a condition that forced them to practice over a block of trials (Labinger et al., 2018). Toddlers' risk-taking is at the other extreme: 17-month-olds attempted to wedge themselves into impossibly small doorway trial after trial (Franchak & Adolph, 2012). However, toddlers did not become better calibrated despite repeated practice, suggesting that they do not effectively learn from feedback (see also Joh & Adolph, 2006). Thus, risky infants generate abundant feedback but cannot learn from it, whereas cautious adults can learn from feedback but generate little. Children make riskier decisions compared with adults across a variety of motor tasks (Dekker & Nardini, 2015; Ishak et al., 2014; O'Neal et al., 2018; Plumert, 1995), and more active and undercontrolled temperament predicts individual differences children's risk taking (Plumert & Schwebel, 1997). Thus, compared with adults, children are predicted to more often choose to practice squeezing through impossibly small doorways, which will provide children with feedback necessary for recalibration. However, as previously mentioned, it is unknown whether children can effectively recalibrate from practice. Based on past work (Plumert, 1995), it is unlikely that 6-year-olds would be able to recalibrate from practice information since they were unable to use practice feedback to calibrate their perception of unmodified abilities. Although 8-year-olds were able to use practice information to perceive unmodified abilities, recalibrating to modified abilities may provide too great a challenge.

Thus, the current study asked how effectively younger children (4-7 years), older children (8-11 years), and adults recalibrate using practice feedback in the doorway squeezing task. Younger and older children were compared because past work suggests age-related changes in the ability to perceive unmodified affordances (Ishak et al., 2014; Plumert, 1995) and to learn from practice (Plumert, 1995). Furthermore, differences in riskiness between younger and older children (Dekker & Nardini, 2015; Ishak et al., 2014; O'Neal et al., 2018; Plumert, 1995) might relate to how often children choose to practice. Finally, this age range is important to study because children's affordance judgment errors in the lab are predictive of accidental injury rates in daily life (Plumert, 1995; Plumert & Schwebel, 1997), so understanding how recalibration develops has potential implications for designing interventions to reduce accidental injuries in childhood.

In a block of *decision trials*, participants judged whether they could squeeze through doorways that varied in width. If they judged a doorway to be possible, they attempted to walk through and consequently received practice feedback. *Judgment accuracy* and *judgment bias* were compared between participants in the *unmodified ability* condition (UA), whose bodies were not altered, and participants in the *modified ability* condition (MA), who wore a backpack and thus needed to recalibrate their judgments. Judgment accuracy was measured by the magnitude of error—the degree to which their decisions matched their actual abilities. Judgment bias was determined by measuring both the size *and the direction* of errors—whether participants tended to err by attempting risky, impossible doorways versus avoiding large, possible doorways. Because prior work showed that recalibration in the squeezing task requires experiencing both success and failure feedback (Franchak, 2017; Franchak & Somoano, 2018), the *informativeness* of practice feedback was measured to determine whether participants' decisions to attempt doorways and thus to generate useful feedback predicted their judgment accuracy.

Method

Participants and design

A total of 102 participants in three age groups contributed data to the final sample: 4- to 7-year old younger children (*M* age = 5.5 years, SD = 0.84, *n* = 39, 18 female), 8- to 11-year-old older children (*M* age = 9.5 years, *SD* = 0.84, *n* = 39, 22 female), and college-aged adults (*M* age = 19.9 years, *SD* = 2.2, *n* = 24, 13 female). Six additional children were recruited but were excluded from the final sample for failure to complete both blocks of trials (*n* = 4) or computer issues with recording the data (*n* = 2). Half of the participants from each age group were assigned to either the unmodified ability (UA) condition or the modified ability (MA) condition in a fully between-subjects design, but due to the aforementioned attrition there was a slight imbalance between conditions in the two child age groups: There were 20 younger children in the UA condition compared with 19 in the MA condition, and there were 20 older children in the UA condition compared with 19 in the MA condition.

Families were recruited from local community events and Internet advertisements. Families were compensated $10 for their participation and children received a small toy or book.

Adult participants were recruited through the psychology department subject pool to fulfill a course requirement. Participants (or their caregivers) reported participants' ethnicity as Hispanic (42.3%) or non-Hispanic (52.9%); 3.9% declined to respond. Participants identified their race as White (46.1%), more than one race (21.6%), other (15.7%), Asian (6.8%), Black or African American (3.9%), and American Indian or Alaskan Native (2.9%); 2.9% declined to respond.

Apparatus

An adjustable doorway apparatus was used as in prior work (Franchak, 2017). A free-standing steel frame supported a stationary wall (182 cm tall × 62 cm wide) and an overhead track. A sliding wall (185 cm tall × 100 cm wide) moved along the track (perpendicular to the stationary wall) to create doorways varying in width from 0 to 70 cm. A measurement camera attached to the sliding wall recorded calibration markings that were used by the experimenter to adjust the doorway size in 0.5 cm increments. The sliding wall had a locking mechanism that, while engaged, kept the doorway at a fixed width while the participant squeezed through. A video camera recorded a side view of the participant's approach and passage through the doorway for later coding.

Participants in the modified ability condition wore a backpack on their backs to increase body size and thus alter doorway fitting ability. The backpack (Sunhiker cycling backpack) was selected because it was appropriately sized to fit participants of all three age groups (i.e., a regular-sized backpack when worn by children and a smaller, cycling-style backpack when worn by adults). The backpack measured 35 cm tall × 25 cm wide × 12 cm deep and weighed 1 kg. The backpack was filled with rigid cardboard so that it did not compress while participants squeezed through the doorway.

Procedure

The experiment consisted of a block of 35 decision trials followed by a block of 10 ability trials. Decision trials assessed participants' judgments of whether they were able to squeeze through doorways and provided practice feedback when participants attempted to walk through doorways they deemed possible. Ability trials verified which doorways participants could successfully squeeze through. MA participants put on the backpack at the beginning of the session and wore it during both blocks of trials; UA participants did not wear the backpack. At the end of the session, participants' weight (without the backpack) was recorded with a digital scale. The entire session lasted approximately 45 minutes.

Decision trials. Participants began each decision trial facing away from the doorway at a starting line 320 cm away. Once the experimenter set the doorway to the correct width, an assistant standing near the starting line told the participant to turn around and asked, "Do you think you can squeeze through that doorway without getting stuck?". Participants' yes/no responses were recorded and then later verified from video. If the participant replied "no", the assistant instructed the participant to turn back around to wait for the next trial. If the participant replied "yes", the assistant instructed the participant to try to squeeze through the doorway. The experimenter scored whether the participant successfully squeezed through (touching the sides of the doorway was allowed) or failed by becoming stuck; live coding of success/failure outcomes were later verified from video recordings.

The decision trial block started with two warm-up trials to familiarize participants with the task by presenting a clearly possible doorway (40 cm) followed by a clearly impossible doorway (4 cm). Afterwards, participants completed 33 trials composed of 3 sets of 11 predetermined doorway widths based on age and condition (see below); each set was presented in a randomized order. Doorway widths were selected based on pilot testing and past work (Franchak, 2017) to ensure that each participant was exposed to both possible and impossible doorway widths depending on their body size and whether they wore the backpack. For the UA condition, younger and older children were presented with doorways 6-26 cm in 2-cm increments (i.e., 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, and 26) and adults were presented with doorways 10-30 cm. Doorway sizes in the MA condition were 12-32 cm for younger and older children and 16-36 cm for adults.

Ability trials. For each ability trial, the experimenter set the doorway to a particular size and then the assistant instructed the participant to attempt to fit through, "I want you to try to fit through the doorway even if you don't think you can. If you get stuck it's OK". The experimenter scored whether the participant successfully squeezed through the doorway or failed by becoming stuck; online scores were later verified from video. On the first ability trial, the doorway was set to the median doorway size presented during the decision trial block (for example, a child in the UA condition started with a 16-cm doorway). Each successive trial was determined using a staircase procedure: The doorway size was decreased by 2 cm following a successful attempt and was increased by 1.5 cm following a failed attempt until 10 trials were completed.

Data analysis

The goal of data analysis was to determine the accuracy and bias of decisions by comparing decision data to ability data. As in past work (Franchak, 2017; Franchak & Adolph, 2014), cumulative Gaussian functions were fit to decision data—proportion "yes" responses at each doorway width—and ability data—proportion successful passage at each doorway width (Figure 1). For example, Figure 1 shows that the participant fit through the 28-cm doorway 100% of the time but only responded "yes, I can fit through" to the 28-cm doorway 33.3% of the time (1/3 decision trials). Decision functions used only trials from the decision trial block;

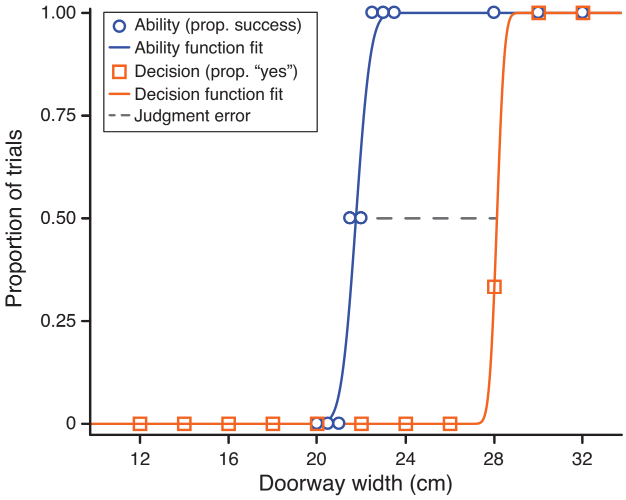

Figure 1. Example of ability and decision function fits to a young child's data in the manipulated ability condition. Blue circles show the rate of successful attempts at each doorway width and orange squares show the rate of "yes" responses at each doorway width. Grey dashed line connecting the ability threshold and decision thresholds (50% point of each function) shows the magnitude of judgment error.

ability functions used "yes" trials from the decision trial block (in which participants attempted to pass through the doorway) in addition to ability trials. Maximum likelihood fits for the threshold of each function were calculated using the Palamedes toolbox (Kingdom & Prins, 2010) in Matlab. Parametric bootstraps with 1000 Monte Carlo iterations determined 95% confidence intervals for threshold parameters.

Decision thresholds reflected the doorway width that participants judged to be possible to fit through 50% of the time. Decision thresholds were fit well for each age group based on relatively small confidence intervals for younger children (M = 18.9 cm ± 1.62), older children (M = 20.6 cm ± 1.54), and adults (M = 24.3 cm ± 1.14). Although confidence intervals appeared to be marginally smaller for adults, confidence interval size did not differ by age group in a one-way ANOVA (p = .09). Ability thresholds indicated the doorway width that participants successfully fit through 50% of the time. Small confidence intervals around ability threshold estimates for younger children (M = 17.6 cm ± 0.58), older children (M = 19.3 cm ± 0.54), and adults (M = 23.8 cm ± 0.40) indicate good fits. Confidence interval size did not differ by age group in a one-way ANOVA (p = .65).

For a small subset of participants, decision functions could not be fit because participants either replied "yes" to every doorway (1 younger child in the UA condition) or "no" to every doorway (1 younger child, 4 older children, and 2 adults in the MA condition). For the participant who said "yes" to every doorway, the decision threshold was set 2 cm smaller than the smallest doorway presented in the decision trial block. For the participants who said "no" to every doorway, decision thresholds were set 2 cm larger than the largest doorways they received in the decision trial block. This approximation assumes that if participants received the next 2-cm increment beyond the tested range that their decisions would have changed. This approximation is conservative and likely underestimates the magnitude of these participants' errors because a change in doorway size much greater than 2 cm might have been required for participants to change their decisions.

Results

Judgment accuracy and bias were calculated based on decision and ability thresholds. Accuracy was indexed by *absolute judgment error*—the magnitude of errors regardless of direction—which was calculated by taking the absolute value of the difference between decision and ability thresholds (i.e., unsigned error). The length of the gray dashed line in Figure 1 shows the absolute judgment error for the example participant. *Constant error* represented bias in participants' judgments and was calculated by subtracting ability thresholds from decision thresholds (i.e., signed error). For the example participant in Figure 1, the constant error was positive, indicating that the participant tended to say "no" to doorways that were possible to fit through (i.e., the child successfully fit through doorways 22-26 cm 100% of the time but said "yes" to do those doorways 0% of the time).

Because absolute errors had a lower bound of 0, they were not distributed normally. Additionally, preliminary analyses revealed significant Levene's tests for violation of homogeneity of variance when testing both absolute and constant errors in ANOVA designs. Thus, non-parametric permutation ANOVAs, t-tests, and regressions were used because they do not require those assumptions (Edgington & Onghena, 2007). Permutation tests were conducted in R using the *ez*, *lmPerm*, and *rcompanion* packages using 1000 Monte Carlo iterations. Effect size estimates (generalized η^2) and F statistics were derived from parametric ANOVAs calculated using the *ez* package. p values in follow-up permutation t-tests were adjusted for multiple comparisons with the Holm-Bonferroni correction.

Ability thresholds

Participants' ability to fit through doorways of varying width depended on body size and, as a result, varied by age group (Figure 2). Affordance thresholds were larger for those participants who wore the backpack compared to those who did not. Table 1 shows participants' weight and ability thresholds by age group and condition. A 3 Age (younger children, older children, adults) × 2 Condition (UA, MA)

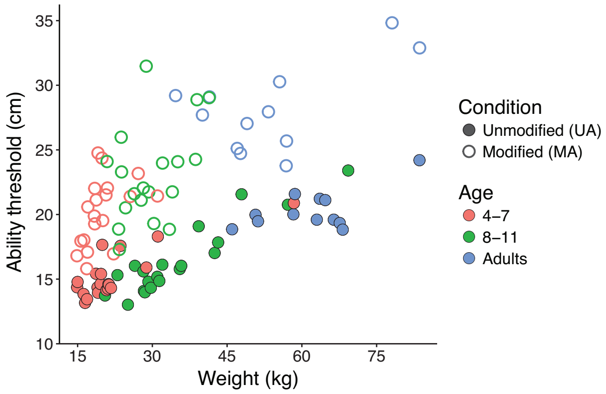

Figure 2. Scatterplot showing the relation between participants' weight (kg) and ability threshold (cm). Closed symbols indicate the unmodified ability (UA) condition and open symbols indicate the modified ability (MA) condition. Symbol color indicates age group.

permutation ANOVA on ability thresholds revealed significant effects of age ($F = 41.33$, $p < .001$, $\eta^2 = .46$) and condition ($F = 131.91$, $p < .001$, $\eta^2 = .58$). Participants' age in years was positively associated with larger ability thresholds in both the unmodified ability condition ($r(50) = .71$, $p < .001$) and the modified ability condition ($r(48) = .75$, $p < .001$).

The association between age and ability thresholds was accounted for by differences in body size. Unsurprisingly, a 3 Age (younger children, older children, adults) × 2 Condition (UA, MA) permutation ANOVA confirmed that participants' body weight differed by age group ($F = 113.90$, $p < .001$, $\eta^2 = .70$) but not by condition ($F = 1.00$, $p = .53$, $\eta^2 = .01$). Participants' age in years was positively associated with body weight in both the unmodified ability condition ($r(50) = .85$, $p < .001$) and the modified ability condition ($r(48) = .89$, $p < .001$). Finally, participants' weight predicted ability thresholds in the unmodified ability condition ($r(50) = .90$, $p < .001$) and modified ability condition ($r(48) = .76$, $p < .001$). A comparison of the ability-weight correlations between the conditions using the Fisher r-to-z transformation revealed that weight was more strongly predictive of unmodified abilities compared with modified abilities ($p = .023$). A weaker relationship between body dimensions and affordances in the modified abilities condition suggests the recalibration task is more difficult compared with judging unmodified abilities.

Judgment accuracy

Figure 3A shows that absolute errors decreased with age for the UA condition but not the MA condition and that errors were larger overall in the MA condition compared to the UA condition. A 3 Age (younger children, older children, adults) × 2 Condition (UA, MA) permutation ANOVA yielded a significant age effect ($F = 5.13$, $p = .012$, $\eta^2 = .10$), a significant condition effect ($F = 11.01$, $p < .001$, $\eta^2 = .10$), and a significant age × condition interaction ($F = 4.00$, $p = .023$, $\eta^2 = .08$). To follow-up on the interaction, pairwise comparisons of error by age were conducted separately for each condition. In the UA condition, permutation t-tests confirmed that errors decreased with age (all groups differed significantly, $ps < .02$): Younger children made larger errors ($M = 4.15$ cm, $SD = 2.65$) compared with older children ($M = 2.01$ cm, $SD = 1.34$), and older children's errors were larger than adults' errors ($M = 1.00$ cm, $SD = 0.65$). In contrast, absolute errors in the MA condition for younger children ($M = 4.11$ cm, $SD = 2.51$), older children ($M = 5.24$ cm, $SD = 3.87$), and adults ($M = 3.03$ cm, $SD = 2.75$) did not significantly differ (permutation t-tests $ps > .29$). A second set of pairwise comparisons tested for condition effects within each age group. Whereas younger children performed similarly regardless of condition ($p = .96$), older children ($p = .006$) and adults ($p = .048$) were less accurate when recalibration was required in the MA condition.

Similar results were found when treating age as a continuous variable instead of comparing means between age groups. For the UA condition, age in years was negatively associated with errors across age groups ($r(50) = -.51$, $p < .001$) as well as when analyzing only the two groups of children ($r(38) = -.49$, $p = .001$). In contrast, there were no significant correlations between age and errors in the MA condition across all three age groups ($r(48) = -.14$, $p = .33$) or when considering only children ($r(36) = -.09$, $p = .57$).

Judgment bias

Figure 3B shows that constant error differed by age and was greater in the MA condition compared with the UA condition. In the UA condition, younger children made riskier decisions by selecting impossibly small doorways ($M = -1.63$ cm, $SD = 4.72$); older children ($M = 0.25$ cm, $SD = 2.45$) and adults ($M = 0.42$ cm, $SD = 1.14$) were relatively unbiased—neither cautious nor risky—with constant errors near 0. In the MA condition, more conservative judgments across age groups meant that younger children were unbiased ($M = 0.27$ cm, $SD = 4.90$) and that older children ($M = 4.38$ cm, $SD = 4.87$) and adults ($M = 1.82$ cm, SD = 3.73) were more cautious and often said "no" to doorways

Table 1

Descriptive statistics (M and SD) for weight (kg) and ability thresholds (cm) by age group and condition.

	Unmodified Ability		Modified Ability	
Age	Weight	Ability thresh.	Weight	Ability thresh.
4-7	22.2 (9.4)	15.3 (1.9)	22.02 (5.7)	20.2 (2.6)
8-11	35.2 (12.0)	16.4 (2.8)	35.5 (8.2)	23.1 (3.7)
Adults	61.8 (10.0)	20.3 (1.5)	68.4 (19.9)	28.2 (3.3)

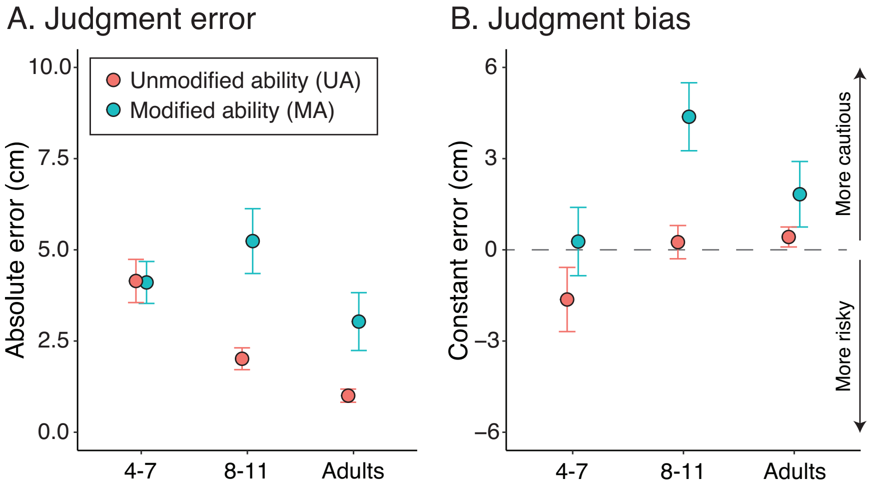

Figure 3. (A) Jugment error (absolute error) and (B) judgment bias (constant error) by age group and condition. Red symbols show the unmodified ability condition (UA) and blue symbols show the modified ability condition (MA). Error bars show ± 1 SE.

that were indeed possible to fit through. A 3 Age (younger children, older children, adults) × 2 Condition (UA, MA) permutation ANOVA confirmed significant main effects of age (F = 5.42, p = .014, η^2 = .10) and condition (F = 9.12, p < .001, η^2 = .09), but the interaction was non-significant (F = 1.10, p = .35, η^2 = .02). The main effect of age was followed up by comparing age groups while collapsing across conditions. Younger children were significantly riskier compared to older children (p = .006); however, no significant differences were found between younger children and adults (p = .19) or between older children and adults (p = .25). Although these results are clear in showing an increase in caution over childhood, they are inconclusive regarding an increase in caution from early childhood through adulthood.

Correlation tests between age and constant errors within each condition found similar results. In the UA condition, age in years was marginally correlated with greater (more conservative) constant errors across age groups ($r(50)$ = .23, p = .09) and within the two child age groups ($r(38)$ = .30, p = .058). For the MA condition, age in years did not predict constant errors across the entire sample ($r(48)$ = .04, p = .79)—as Figure 3B shows, constant errors in the MA condition appeared to increase from younger children to older children and but decrease from older children to adults. Indeed, increasing age did predict more conservative (larger) constant errors when analyzing only children ($r(36)$ = .35, p = .03).

Feedback and judgment accuracy

An *informativeness score* was determined based on participants' self-selected practice experiences during the decision trial block to quantify the quality of feedback. Because prior work showed that both success and failure feedback are required to recalibrate in this task (Franchak & Somoano, 2018), the informativeness score was calculated as the trial number in the decision trial block at which participants had experienced both a successful and failed attempt to fit through the doorway. For example, if a participant said "no" on trials 1-3, said "yes" and succeeded on trial 5, said "no" on trials 6-7, and said "yes" and failed on trial 8, the participant would receive an informativeness score of 8. Smaller informativeness scores indicate that participants experienced both success and failure earlier in the session, and thus had the benefit of informative feedback for a greater portion of the decision trial block. If participants never received informative feedback (i.e., they only experienced success without failure, failure without success, or neither nor failure), they received an informativeness score of 34 (one more than the total number of decision trials, 33). Informativeness scores ranged from 2 (the minimum possible) and 34 (the maximum possible) in each condition. Ten participants in the UA condition and 17 participants in the MA condition received a score of 34, indicating that they received uninformative feedback.

Two multiple linear regression models determined the unique contributions of feedback informativeness and age to absolute error within each of the conditions. For the UA condition, a permutation multiple regression was calculated with age in years and informativeness score as predictors and absolute error as the criterion variable. The unstandardized coefficient for age was significant and negative (b = -0.20, p < .001), suggesting that age predicted smaller errors when controlling for informativeness. However, informativeness did not uniquely predict errors in the UA condition (b = -0.01, p = .623). The full model accounted for 26.6% of the variance in errors scores. For the MA condition, the opposite pattern of results was found. A permutation multiple regres-

Table 2
Absolute error (M and SD) and group size for participants in the informative feedback (IF) and uninformative feedback (UF) groups by age and condition.

Informative Feedback (IF)				Uninformative Feedback (UF)			
Condition	Age	*M (SD)*	*n*	Condition	Age	*M (SD)*	*n*
UA	4-7	4.1 (2.9)	16	UA	4-7	4.1 (1.6)	4
UA	8-11	1.9 (1.3)	18	UA	8-11	2.7 (2.2)	2
UA	Adults	0.8 (0.5)	8	UA	Adults	1.4 (0.6)	4
MA	4-7	3.7 (2.2)	14	MA	4-7	5.4 (3.2)	5
MA	8-11	3.0 (2.0)	11	MA	8-11	8.3 (3.7)	8
MA	Adults	1.5 (1.0)	8	MA	Adults	6.0 (2.7)	4

sion did not find that age significantly predicted errors (b = -0.08, p = .441), but larger (worse) informativeness scores predicted larger (worse) errors when controlling for age (b = 0.11, p = .003). The full model accounted for 21.5% of the variance in error scores.

The regression analyses showed that less informative feedback predicted larger errors in the MA condition. The next analysis explored whether participants who received *any* informative feedback differed with those who *never* received informative feedback during the session. Participants were grouped based on their feedback experiences during the decision trial block. The informative feedback (IF) group contained participants who experienced both success and failure feedback during the decision trial block (informativeness scores < 34), whereas the uninformative feedback (UF) group contained participants who received only success feedback, only failure feedback, or no feedback during the decision trial block (informativeness scores = 34) (Table 2).

Figure 4 and Table 2 show absolute error as a function of age, condition, and feedback type, revealing a striking result: In the MA condition, errors declined with age for IF participants (in contrast to the lack of change observed when analyzing the full sample which included UF participants). Thus, when considering only those participants who received the necessary feedback, the ability to recalibrate did improve with age. A 3 Age × 2 Condition permutation ANOVA was calculated only for participants who received informative feedback (it was not feasible to conduct inferential tests directly comparing IF and UF groups given the low power resulting from a small sample of UF participants). For IF participants, there was a significant effect of age ($F = 10.64, p < .001, \eta^2 = .24$) but no effect of condition or age × condition interaction—as Figure 4 shows, the lines for the UA and MA conditions are superimposed and both decrease with age. Pairwise comparisons between age groups (collapsed across conditions) confirmed that absolute error significantly differed between all three groups (ps < .016).

Visual inspection of Figure 4 reveals that the only group of participants who did not show an age-related decrease in error was participants in the MA condition who received uninformative feedback. This suggests that the lack of an age-related increase in recalibration in the MA condition in the full sample (Figure 3A) was driven by those participants who received uninformative feedback.

Discussion

The current study examined how young children, older children, and adults recalibrate to changing affordances for squeezing through doorways using self-generated practice feedback. Two groups were compared: Participants who judged their original, unmodified affordances and participants who recalibrated to wearing a backpack that modified affordances for fitting through doorways. The current study used a task previously unstudied with children, and the results extended previous work that showed age-related changes in affordance perception (for unmodified abilities) and risk-taking behavior. Furthermore, the current study was novel in revealing age-related changes in children's ability to recalibrate to altered affordances, specifically in their ability to adapt to modified abilities by using practice feedback.

The primary aim of the current study was to determine how effectively children recalibrate to modified affordances using practice information. At first glance, the overall analysis of absolute error appeared to indicate that participants of all ages struggled in the recalibration task: Errors in the MA condition were larger compared to those in the UA condition, indicating that participants were better calibrated when judging their unaltered abilities compared to when they were required to recalibrate. However, previous studies using the doorway squeezing task show that participants' ability to recalibrate depends on informative feedback—experiencing both successful and failed practice attempts (Franchak, 2017; Franchak & Somoano, 2018). Thus, it would be unreasonable to expect that participants exposed to uninformative feedback would recalibrate. Indeed, individual differences in the informativeness of feedback predicted error magnitude in the MA condition: Those participants who generated informative feedback earlier in the session made more accurate judgments than those who did not (informativeness of

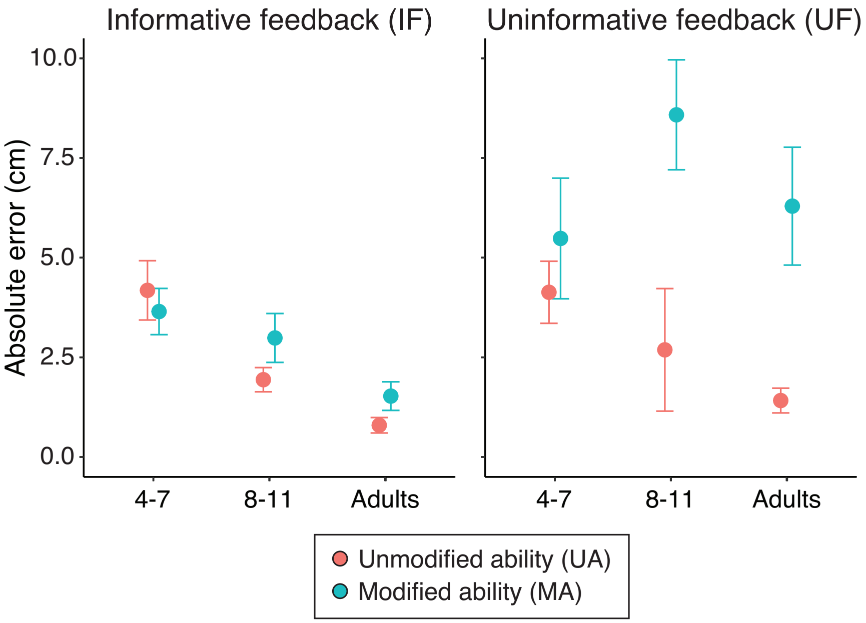

Figure 4. Absolute error by feedback group, age group and condition. Red symbols show the unmodified ability condition (UA) and blue symbols show the modified abilities condition (MA). Error bars show ± 1 SE.

feedback did not matter for participants who judged their familiar, unmodified abilities). Participants who received uninformative feedback made inaccurate judgments in the MA condition regardless of age.

When examining only those participants who were exposed to informative feedback, absolute errors decreased with age in the MA condition and were indistinguishable from errors in the UA condition. Thus, the current study demonstrated that with age children became more effective at using practice feedback to recalibrate. The current findings extends previous research showing age-related changes in using practice information to improve perception of unmodified abilities (Plumert, 1995) by showing a similar age-related trend in the use of practice feedback to recalibrate. However, these findings are inconsistent from the only other study to compare children's perception of both unmodified and modified abilities (Chen et al., 2014). In the sitting task, 12-year-olds showed adult-like perception of both unmodified and modified abilities. However, even the oldest children in the current study (11 years) still lagged behind adults in the squeezing task in both the UA and MA conditions (for those who received informative feedback). The discrepancy between the two studies suggests that recalibration using different types of information (i.e., movement experience in the sitting task, practice feedback in the squeezing task) develops differently.

More generally, this difference in recalibration in the two tasks is consistent with the ecological approach's action-specific account of perception as opposed to an action-neutral account. From a computational perspective, there is no a priori reason to expect a developmental difference in performance in the two tasks if the process of recalibration is rooted in perceiving metric properties such as the size of a platform shoe or backpack. However, the fact that different types of action experiences (general movements versus practice feedback) are needed to recalibrate in the sitting and squeezing tasks supports the claim that recalibration is rooted in detecting relational, action-specific information through movement experience. That children's abilities develop differently in each task lends further support to the action-specific account of perception as opposed to the action-general account. Future research could address this question more directly by testing whether children's perceptual judgments of an object that modifies affordances (platform shoes or backpacks) is related to their perception of affordances, replicating the strategies used in adult studies (Mark, 1987; Thomas et al., 2016).

One limitation of the current study is that participants' access to feedback depended on their own judgments about whether to attempt to fit through doorways. A similar procedure was used in some past studies of affordance perception and recalibration (Adolph & Avolio, 2000; Franchak & Adolph, 2014; Ishak et al., 2014; Labinger et al., 2018), but other work avoided this issue by forcing participants to practice on fixed schedules (Franchak, 2017; Franchak & Somoano, 2018; Yasuda et al., 2014). The benefit of allowing participants to decide whether to attempt doorways is that it improves the construct and ecological validity of the judgment bias measurement—participants actually perform the action and experience the consequences of their decisions. However, the drawback is that some participants never received sufficient feedback to recalibrate, and those participants that did get informative feedback received different amounts. Indeed, the findings indicate that in the MA condition, individual differences in practice informativeness (possibly due to differences in risk-taking) had consequences for judgment errors, but stronger conclusions about the ability to recalibrate could be drawn if all participants received identically-informative feedback. Future research should seek to replicate the current findings when providing children with a fixed practice regimen to control for age-related changes in risk-taking.

In addition to the novel findings regarding the development of recalibration, the results of the current study replicate and extend prior work with respect to the development of affordance perception for unmodified abilities. As in past work (Ishak et al., 2014; Klevberg & Anderson, 2002; O'Neal et al., 2018; Plumert, 1995), children's perception of affordances for their unmodified abilities improved with age. In the unmodified ability condition, younger children (4-7 years) made larger errors compared with the older children (8-11 years), and older children made larger errors compared with adults. Taken together with previous work, findings are mixed regarding the age at which calibration of affordance perception becomes adult-like. Whereas 7-year-olds' judgments about reaching through openings were as accurate as adults' (Ishak et al., 2014), children aged 8-11 in the current study and in Plumert (1995) made larger errors compared with adults in other tasks. Most likely, age-related changes in affordance perception vary according to task; adult-like calibration in one task may not imply adult-like calibration in other tasks. More work is needed to determine what task dimensions constrain children's ability to perceive affordances, such as temperament (Plumert & Schwebel, 1997) and their experience with a task in everyday life.

The current study's findings are consistent with past work showing age-related changes in risk-taking behavior in childhood (Dekker & Nardini, 2015; O'Neal et al., 2018; Plumert, 1995; Plumert & Schwebel, 1997), however, comparisons between children and adults were inconclusive. Across conditions, younger children were more likely to attempt to squeeze through impossibly small doorways compared with older children. Unlike past work that found younger and older children to be equally risky (Dekker & Nardini, 2015), the current study found that older children were more cautious compared to younger children and equally cautious (or possibly more cautious) compared with adults. The declining role of temperament in overestimation might contribute to the age-related changes that were observed (this could not be verified because temperament measures were not collected in the current study). Prior work shows that individual differences in temperament predicted overestimation within younger children (6 years) but not within older children (8 years) (Plumert & Schwebel, 1997), suggesting that older children are better able to inhibit responses when faced with risky motor decisions. Changes in riskiness were most pronounced within the two groups of children. In both the unmodified and modified ability conditions, age was positively correlated with constant error—with age, caution increased. However, the relation between age and cautiousness was weak in the unmodified ability condition, possibly because older children's caution was equal to that of adults. Furthermore, there was no correlation at all in the modified ability condition due to apparent non-linear change in caution: Caution clearly increased from younger to older children but appeared to decrease from older children to adults. A similar non-linear finding in cautiousness was also seen in a study of children and adults pedestrian behavior at a similar age (O'Neal et al., 2018): 12-year-olds were particularly conservative compared with both younger age groups as well as 14-year-olds and adults when selecting which gaps between vehicles were possible to cross. O'Neal and colleagues (2018) suggested that greater caution in 12-year-olds might be due to increased self-assessment concerning their perceptual-motor skill. A similar explanation might apply to the current study: Older children in the modified condition, whose ability to perceive and recalibrate to affordances is somewhat developed but still immature, may have been acutely aware of the deficit in their perception and chose to be exceedingly cautious.

Across ages, participants' bias also differed by condition. Participants judging their unmodified abilities were more risky compared to those who recalibrated to wearing the backpack. Caution when recalibrating could reflect uncertainty or a lack of confidence when adapting to modified abilities. A second possibility is that participants expect the backpack to alter their abilities by a greater degree than it actually did; other work using the squeezing task found that adults made overly cautious judgments while wearing a "pregnancy pack" (Franchak & Adolph, 2014). Although the pregnancy pack extended 15 cm from participants' bodies, because it compressed while participants squeezed through doorways it only increased ability thresholds by 10 cm (relative to ability thresholds without the pack). The degree to which the backpack changed ability thresholds in the current study could not be assessed because ability thresholds without the backpack were not measured for participants in the MA condition. However, the weaker correlation between weight and altered ability thresholds compared with the stronger correlation between weight and unaltered ability thresholds suggests that the backpack's alteration to abilities varied somewhat by participant due to compression.

It is important to acknowledge another way in which the backpack manipulation was unequal across participants: Using the same sized backpack for every participant meant that the change in ability thresholds was proportionally smaller for participants with larger bodies (i.e., adults) whereas the change in ability thresholds was proportionally larger for participants with smaller bodies (i.e., younger children). A potential concern is that the recalibration task might have been easier for adults compared with children because adults' abilities changed by a smaller proportion. No previous work has directly addressed whether an absolute change in affordances (e.g., measured in cm) or proportional change (e.g., scaled to body size) determines the difficulty of a recalibration task. Secondary analysis of prior data from adults recalibrating in the squeezing task (Franchak, 2017) indicates that body size was unrelated to participants' errors when recalibrating to wearing a backpack. In other words, larger participants whose bodies changed by a smaller proportion made judgments that were no more accurate than smaller participants whose bodies changed by a larger proportion. However, this has not been tested across age groups, so the confound cannot be ruled out when considering the age group comparison in the current study. Future work should replicate the current study using a backpack manipulation that is scaled to participants' body dimensions to address this limitation.

Conclusion

In sum, the current study demonstrated that children's affordance perception and recalibration improves with age in the doorway squeezing task when learning from self-generated practice. Taken together with past work (Chen et al., 2014; Ishak et al., 2014; Klevberg & Anderson, 2002; Plumert, 1995), the current findings suggest that affordance perception and recalibration do not develop as a unitary skill, but that children achieve adult-like calibration in different tasks at different ages. This interpretation is consistent with the hypothesis that different action-specific, relational information for perceiving affordances requires different recalibration processes (Franchak, 2017). Learning to perceive some types of affordances, such as those that depend on practice feedback (Franchak & Adolph, 2014; Franchak & Somoano, 2018), might be more difficult than learning affordances that do not depend on practice (Chen et al., 2014; Mark et al., 1990). Although this might depend on experience with different tasks, more general perceptual-motor abilities—such as generating and learning from practice (Labinger et al., 2018; Plumert, 1995)—might also underlie developmental changes. More generally, these results are consistent with the ecological theory of affordance perception (Gibson, 1979) because they emphasize the role of movement experience, such as action practice, in detecting body-environment relations.

The implications for preventing accidental injury in childhood are significant. First, the greater difficulty faced by participants in the modified ability condition across ages suggests that motor errors (and injuries) will be more likely in cases where abilities have been altered and recalibration is needed. Second, the likelihood of an injury-prevention intervention succeeding depends on the specific task and age; young children might not be able to learn as well in a practice-based intervention because they struggle to learn from practice feedback but may learn better in the context of general movement experience. Finally, differences in how affordance perception develops for different motor tasks highlights the need to study a broader range of tasks in future work. Doing so will help identify whether any developing perceptual-motor learning skills have broad effects in shaping affordance perception across different motor tasks. Interventions targeting any such general skills would be more efficient at reducing accidental injuries compared with interventions targeting skills that are only relevant for a narrow set of motor tasks.

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