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Learning the Designed Actions of Everyday Objects

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Abstract

How do young children learn to use everyday artifacts—doorknobs, zippers, and so on—in the ways they were designed to be used? Although the designed actions of such objects seem obvious to adults, little is known about how young children learn the “hidden affordances” of everyday objects. We encouraged 115 11- to 37-month-old children to open two types of containers: circular jars with *twist-off* lids (Experiment 1) and rectangular Tupperware-style containers with *pull-off* lids (Experiment 2). We varied container size to examine effects of the body-environment fit on display of the designed action and successful implementation of the designed action. Results showed a developmental progression from non-designed actions to performance of the designed twisting or pulling actions to successful implementation of the designed action. Non-designed actions decreased with age as performance of the designed action increased. Successful implementation lagged behind performance of the designed action. That is, even after children appeared to know what to do, they were still unsuccessful in opening the container. Why? For twist-offs, very large lids were difficult to manipulate, and younger children often twisted to the right, or in both directions, and did not persist in consecutive turns to the left. Larger pull-off containers required new strategies to stabilize the base, such as holding the container against the tabletop or the chest. Findings provide insights into the body-environment factors that facilitate children’s learning and implementation of the hidden affordances inherent in everyday artifacts.

Keywords

manual action; manual exploration; affordances; perceptual-motor development; problem solving; cultural artifacts

Action and Design

Possibilities for action—what J. J. Gibson (1979) termed “affordances”—depend on the relation, or fit, between the biodynamic characteristics of the body and physical features of

the environment. Affordances are objective body-environment relations. That is, actions are possible or not, regardless of whether affordances are perceived or used (Franchak & Adolph, 2014). However, affordances must be perceived to select and modify actions adaptively (E. J. Gibson & Pick, 2000).

Historically, researchers have focused on young children's perception of affordances for actions such as walking and reaching, where perceptual information for the body-environment fit is readily apparent. Perceptual information specifies whether it is possible to crawl down a steep slope (Adolph, 1997), walk over a narrow bridge (Kretch & Adolph, 2013), grasp a tilted rod (Lockman, Ashmead, & Bushnell, 1984; von Hofsten & Fazel-Zandy, 1984), or reach for a distant object (Adolph, 2000). Even without prior experience navigating slopes or bridges, grasping particular rods, or leaning forward to retrieve a distant toy, experienced crawling, walking, reaching, and sitting infants detect such overt affordances with impressive, adult-like accuracy (Adolph & Robinson, 2015).

But many activities of daily living involve more than just basic actions. As design guru, Don Norman (1988) points out, an adult's daily life is filled with artifacts (>20 thousand everyday things!). And each requires a particular, designed action: pulling a zipper, twisting a faucet knob, unlatching a lunchbox, and unsticking the plastic on a piece of individually wrapped cheese (Bix, de la Fuente, Sunder, & Lockhart, 2009; Norman, 1988). Although artifacts offer affordances for many basic actions (banging, shaking, and rotating a jar; grasping, pulling, and fingering a doorknob), typically only one *designed* action is relevant for the use intended by the designer. Moreover, many designed actions are not readily specified by visual or haptic information (Norman, 1999, 2013). The required, designed action is "hidden" and the user must discover it (Albrechtsen, Andersen, Bodker, & Pejtersen, 2001; Gaver, 1991; Hartson, 2003). Closures (on containers, clothing, cabinets, doors, etc.) are prime examples of "hidden affordances." Typically, the goal is known (open jar or door), but how to accomplish the goal is not. Even infants can easily perceive that a doorknob is the right size for grasping and an open door permits passage (Franchak & Adolph, 2012; Schum, Jovanovic, & Schwarzer, 2011). But infants must discover that the designed action to open the door entails twisting the doorknob while pushing or pulling.

The problem is even more complicated because designed actions are often arbitrary (twist left, not right, to open a screwtop lid) and the information to specify them is often ambiguous. As Norman (1988, 2013) bemoaned, doors should not require an "instruction manual" to push or to pull. Yet many do (we often push rather than pull, and vice versa). Sometimes the information for a designed action is so buried that users do not recognize how to implement it. Think of struggling to work the temperature controls for a shower in an unfamiliar hotel room: Did it entail pushing or turning? Which part in which direction? As engineers and designers know, users optimally should be able to encounter an unfamiliar object and use it effortlessly on the first try (Norman, 1988). But such is not the case for most artifacts. Moreover, even when users know which designed action to use on an artifact, each unique exemplar requires subtle modifications for successful implementation—such as using a pincer grasp to twist a toothpaste cap but palmar grasp to twist a pickle jar, or applying the appropriate force to pull open tight versus loose Tupperware lids.

Discovering the Designed Actions of Artifacts

Despite the prevalence of artifacts in everyday activities, researchers know little about when and how children discover their designed actions. Adults' know-how for many everyday hidden affordances is so implicit that the designed action is automatic (Bix, de la Fuente, Sunder, et al., 2009; Norman, 1988). But such actions cannot be readily apparent to a neophyte. Without tutelage or instructions, the hidden affordance must be discovered (Hartson, 2003).

Out of all the possible exploratory actions, how does a neophyte hone in on the right one? Trial-and-error learning is most likely when the designed action becomes obvious during the course of spontaneous exploration. For example, infants' common exploratory actions (banging, shaking, rotating, and pulling) are likely to reveal the designed action of shaking a rattle. Social information, such as watching an adult model or older sibling perform the designed action may also highlight the hidden affordance. However, common exploratory actions or social feedback alone are unlikely to reveal the specific designed action of left-twisting a screw-top lid or twisting a doorknob while pushing the door open. Moreover, mechanical constraints can present barriers to discovering the designed action. If a jar lid is too tight to twist or a door is too heavy to push, how can learners discover that twisting or pushing are the designed actions? If discovery of the designed action lags far behind exploration in real time, how do neophytes recognize that they are "getting warmer" by searching in the right part of the problem space?

Implementing the Designed Action of Artifacts: The Body-Environment Fit

Although designed actions on everyday artifacts look easy, often they are not. Discovery is only the first step. Many designed actions require precise biomechanical adjustments of body and artifact. For example, zipping a coat requires the application of force in the direction opposite to the stopper (holding down the stopper while pulling the slider tab). Turning a key requires an awkward hand position at the beginning or end of rotation. Opening the plastic seal on a yogurt tin requires a tight pincer grip on the edge of the seal while stabilizing the base with the other hand. Such everyday examples demonstrate the confluence of know-how and body-environment factors that contribute to successful implementation of a designed action. Thus, knowing the designed action does not guarantee successful implementation.

The problems inherent in discovery and implementation of designed actions may explain why 7-to 18-month-olds detect overt affordances for reaching, grasping, and locomotion with adult-like precision, but older children (24+ months) cannot perform self-care and other activities of daily living for which designed actions are critical (Hayase et al., 2004; Teaford, 2010). By kindergarten, designed actions on artifacts are central to function at home and school. Children need to operate the closures on their pants, coats, and shoes so they can toilet themselves and get ready for recess and naps. They need to cope with the closures on containers to unlock their lunchbox and open the lids and seals on the food items inside. Inventories such as the Hawaii Early Learning Profile (Teaford, 2010) focus on ages when

children display various skills (e.g., skill #6.169: “Opens container and removes food” at 4.4–5.4 years of age) rather than *how children learn the particular motor actions* required.

Current Studies

In two experiments, we charted age-related changes in learning the designed actions for opening everyday artifacts—jars with *twist-off* lids (Experiment 1) and Tupperware-style containers with *pull-off* lids (Experiment 2)—both made of transparent plastic. We put small snacks inside the containers to motivate children (11–37 months of age) to open them. The age range spans infancy, when children perceive and use affordances for basic manual and locomotor actions, to preschool, when self-care becomes important.

For both experiments, we hypothesized a three-step developmental progression, starting with primarily non-designed actions at the youngest ages (e.g., rotating and banging the containers), then occasional displays of designed actions at intermediate ages (twisting or pulling the appropriate lid), and finally successful implementation of the designed action at the oldest ages (by left-twisting the jar lid the required number of revolutions, and by stabilizing the base of the Tupperware while pulling the lid). Thus, we expected that even when young children engage in the designed action, they would still be unsuccessful. Consequently, they would continue to display non-designed actions. In contrast, older children’s performance of the designed action would likely result in success. Therefore, they should hone in on the designed action and rarely display non-designed actions.

We manipulated container size to examine the manual adjustments required to successfully implement the designed action. Given the expected difficulties imposed by large container sizes, we predicted a greater discrepancy between display of the designed action and successful implementation with containers larger than children’s hands.

Experiment 1: Twist-Off Lids

In Experiment 1, we encouraged children to open clear, plastic, jars with twist-off lids. Twist-off lids serve as an ideal model for studying how children learn about hidden affordances for several reasons. First, an important aspect of the designed action is arbitrary, in this case, direction specific: Lids must be twisted to the left to open (“leftie-loosie, rightie-tighty”). Second, implementation has interesting biomechanical demands. Children can rotate their wrists long before 12 months of age, so the twisting action is potentially in children’s repertoire (Soska & Adolph, 2014). However, the designed action must be repeated. Children must persist at twisting, lifting and repositioning their hand as the lid moves along each thread. Moreover, the designed action requires bimanual coordination. One hand must stabilize the base while the other hand twists the lid. Finally, in many cultures, twist-off lids pervade activities of daily living—twisting the lid of a water bottle or baby bottle, twisting the lid of a body lotion or diaper cream, and so on. Thus, twist-offs have ecological validity and relevance.

Method

Participants

Experiment 1 was the first of its kind, so with no apriori knowledge about when children would succeed at opening twist-off lids, we sampled across a broad age range. We tested 63 children (38 boys, 25 girls) between 11 and 37 months of age (Figure 1A). Data from 11 additional children (12 to 24 months) were excluded due to experimenter error such as presenting the wrong container sizes or video failure ($n = 4$) or because children did not complete $> 25\%$ of the trials ($n = 7$). Fussy children were distributed across age. We asked the first 33 mothers whether their children had prior experience opening twist-off lids; however, mothers' reports were unrelated to children's age or success in the task so we concluded that this was not a behavior that caregivers note reliably.

Our original plan was to test infants from approximately 12 to 36 months of age in 6-month intervals. However, pilot data suggested interesting developments between 18 and 24 months, so we added children around 21 months of age. All children were healthy and born at term. Parents reported children's race as white (67%), Asian (11%), multi-race (17%), or chose not to respond (5%); 88% were non-Hispanic, 10% were Hispanic, and 2% chose not to respond.

At the end of the session, we measured palm size in 43 children (shown by striped bars in Figure 1) by pressing their hands against a transparent grid and photographing it from the bottom. Palm width ranged from 4.5 cm to 6.0 cm ($M = 5.3$ cm) and was correlated with children's age, $r(41) = .63, p < .001$. We did not attempt to measure hand size in the first 20 children we tested. The study protocol was approved by the New York University Institutional Review Board.

Designed Action of Twist-Offs

We presented children with 14 twist-off jars, all requiring a leftward twisting action to open the lid. The jars were commercially available and made of lightweight plastic, with opaque lids and transparent bodies so that small snacks inside ("goldfish" crackers, Cheerios, or Rice Chex) were clearly visible. To ensure that the lids required the same amount of force to open across children, we aligned each lid to marks on the container body before each trial. As shown in Figure 2, we tested four lid diameters: 4 containers with $M = 3.5$ -cm lid diameters; 4 containers with $M = 5.5$ -cm lid diameters; 4 containers with $M = 7.3$ -cm lid diameters; and 2 containers with $M = 9.3$ -cm lid diameters. Because of the variation in children's palm size, we normalized container size relative to children's palm size. We considered containers < 1 – 3 cm relative to children's palm size as small (requiring children to curl their fingers around the lid), containers within ± 1 cm as palm-sized, containers > 1 – 3 cm as hand-sized (requiring children to bend their fingertips around the lid), and containers > 3 – 5 cm as large (requiring children to stretch their fingers to encompass the lid). We assigned children without a palm size measure the average palm size of their corresponding age.

We used a transparent sugar bowl with an inverted cover (7 cm diameter) as an easy "baseline" container to teach children the game of opening containers and to maintain their

motivation to open the containers across repeated trials. Children could easily remove the cover by gripping the lid to retrieve small snacks inside.

Procedure

Younger children sat in a highchair with a tray and 30- and 36-month-olds sat at a child-sized table. The experimenter sat across from children, and mothers sat to children's left side, so children could easily see them (Figure 2, top right corner). To acclimate children to the task, the experimenter first presented the sugar bowl and encouraged children to retrieve the snack inside by saying, "Open it! Can you open it? Do you want the cracker?" Children opened the sugar bowl at least twice before test trials began. Containers of different sizes were presented in random order, in two blocks of 14 jars each, with the rule that two jars with the same lid diameter were not presented consecutively. The experimenter presented containers in different orientations in random order: lid facing up, lid facing down, lid facing sideways to the left or right, lid facing the child, and lid facing away from the child.

Trials began when the experimenter placed the container on the highchair tray or table. On each trial, the experimenter provided encouragement ("Open it! Get the cracker"), but did not tell children how to open it. The experimenter also instructed caregivers not to provide specific instructions if children asked them for help, and not to accept the jar if children tried to hand it to them. Trials lasted until children opened the lid, threw the jar to the floor, or after 30 seconds had elapsed, whichever occurred first. Pilot data showed that children became fussy with longer trial lengths. The experimenter presented the sugar bowl at the beginning to get children in the game of opening, after every trial that did not end in successful opening, and as often as needed between trials when children fussed. The experimenter presented a minimum of one block of 14 twist-off trials ($M = 24.6$) and $M = 12.3$ sugar-bowl trials, and ended the session after two blocks of twist-off trials (28 trials) or sooner if the child refused to continue in the task. Analyses included only 11–13 twist-off trials for 4 children (12–21 months) who willingly completed at least one trial block because the experimenter inadvertently left the lids partially open on a few trials (1.4% of trials).

Cameras on each side of the child recorded children's hands and face, a side camera captured a view of the caregiver, and a third camera behind the child recorded the experimenter. The three camera views were mixed online onto a single video frame for ease of later coding. Sessions lasted approximately 30 minutes. Videos and data files are openly shared in the Databrary video repository (databrary.org).

Data Coding

A primary coder scored videos of each session using Datavyu software (www.datavyu.org) that allows frame-by-frame identification of user-defined events. The coder determined for each trial when participants displayed the *designed twisting action*—any rotational movement of the palm or fingers that caused the lid to rotate. Additionally, coders scored the presence of six *non-designed actions*: *pulling* the lid with the fingers; *rotating* the whole container to view a different side; *banging* the container against the table; *shaking* the container; *hitting* the container with the hand; and *mouth*ing any part of the container.

Children could display the designed action and multiple non-designed actions during each trial.

Coders scored each trial as *successful* if the child opened the lid using the designed action, a *refusal* if the child dropped or threw the container onto the floor, or a *time-out* if the child did not open the container within 30s. *Latency* to open the container was the time interval between the moment when the experimenter let go of the container and children opened the lid. If children did not open the lid, success latency was 30s (the maximum trial length). Trials in which children refused were excluded from analyses of success latency.

A primary coder scored 100% of the data and a second coder independently scored at least 25% of each child's data for inter-rater reliability. The coders agreed on > 98.9% of the categorical behaviors, $Kappas > .90$, $ps < .001$. Correlation coefficients for latency and number of twists were $r_s > .97$, $ps < .001$. Disagreements were resolved through discussion.

Results and Discussion

Across the entire session, children opened the sugar-bowl on $M = 99.2\%$ of the trials, with no difference across age, $r(61) = .21$, $p = .105$. Thus, children were engaged in the task of opening throughout the entire session, and any behaviors during the test trials other than successful opening were due to properties of the test containers and not disinterest in the task. Sugar-bowl trials were excluded from subsequent analyses.

Our primary analyses focused on the display of *non-designed* and *designed* actions, *latency* to open the lid, and *normalized twist direction* [(n° of left twists – n° of right twists) / total n° of twists]. We used Pearson correlations to characterize the relation of each measure with age. We used Generalized Estimating Equations (GEEs) to analyze the main effects of age and normalized container size for each measure. Age was entered as a covariate and normalized container size was entered as a within-subjects variable. We used GEEs instead of linear regressions because trials within children were repeated and correlated. GEE accounts for the within-child correlation, assuming that trials from the same child are correlated and those from different children are independent. Thus, we used a robust-based estimator of the covariance structure and an exchangeable working correlation matrix to reflect the uniform correlations across pairs of trials within a child. Syntax for all analyses is available on Databrary. Preliminary analyses showed no effects due to children's sex, $r_s < .25$, $ps > .807$, or container orientation, $F_s < 1.20$, $ps > .307$, so these variables were collapsed for subsequent analyses.

Actions on Twist-Offs: Changes Across Age and Trial-to-Trial Variability

Findings supported our hypothesized developmental progression from exhibiting non-designed actions to displaying the designed action to successfully implementing the designed action. Non-designed actions were common in younger children and decreased with age, $r(61) = -.82$, $p < .001$, Figure 3A. The colored lines in the inset of Figure 3A show the variety of non-designed actions and their decrease with age, $r_s(61) > -.37$, $ps < .002$. Pulling, rotating, and shaking were most common ($M_s = 14.5\% - 20.7\%$), and mouthing, banging, and hitting were rare ($M_s = 1.9\% - 7.5\%$). Across children, the number of non-

designed actions per trial ranged from 0 to 5, $M = .80$. Although the average number of trials were relatively low for every non-designed action, at some point in the session, 81% of children tried to pull the lid off, 73% rotated the jar, 62% shook it, 25% mouthed it, 25% banged it against the table, and 19% hit the jar with their hand. Moreover, as shown in Figure 3B, performance of the designed twisting action preceded success at opening. The twisting action increased with age, $r(61) = .82, p < .001$, as did success at opening, $r(61) = .86, p < .001$. However, twisting the lid did not guarantee success as shown by the non-overlapping black and red lines in Figure 3B.

Trial-by-trial data likewise support the developmental progression. Figure 4A displays data for each trial for each child, with children ordered by age from left to right. Black lines denote trials when children merely held the container without displaying other actions. Blue squares denote trials when children performed non-designed actions. Only 7 children—all older than 30 months of age—did not display non-designed actions at some point in the session. White circles—most prevalent in the middle age range—show trials when children displayed the designed twisting action, but did not succeed. Red circles—most prevalent at the oldest ages—indicate success at opening. The lack of consistency of symbol types within each string indicates that children did not improve across trials or trial blocks. Likely, the random switching of container sizes prevented learning across trials.

Successful Implementation: The Affordance Fit and “Leftie-Loosie”

As we hypothesized, the lag between performing the designed action and successful implementation (i.e., knowing what to do and doing it) resulted from a mismatch between container size and children’s hand size (Figure 5A). Knowing the designed action was not enough. Even when children knew what to do, they frequently failed to implement the designed action. To test whether age and normalized container size predict developmental changes in implementation, we computed an ordinal *success score* for each trial: 0 = no designed action; 1 = designed twisting action; 2 = opened lid by twisting. We used a generalized linear model with an ordinal outcome (success score) and a logistic link function. As shown by the steep curves in Figure 5A, age strongly predicted improvement in success score, $Wald \chi^2 = 83.21, p < .001$. With each additional 6 months, children were 8.22 times more likely to increase their success score, $\beta = 0.38, p < .001$. Moreover, as shown by the non-overlapping curves in Figure 5A, container size also predicted improvement in success scores, $Wald \chi^2 = 49.05, p < .001$. Compared with the large containers, children had higher success scores for palm-size (odds ratio = 4.20), hand-size (odds ratio = 2.86), and small containers (odds ratio = 1.61), $\beta_s = .48, ps = .012$.

Latency to open the lid corroborated the effects of age and normalized container size (Figure 5B). Age strongly predicted latency, $Wald \chi^2 = 546.80, p < .001$, as did container size, $Wald \chi^2 = 79.92, p < .001$. With each additional 6 months, latency decreased by 6.9 seconds, $p < .001$. Compared with the large containers, children were 7.52 seconds faster at opening palm-sized containers, 4.71 seconds faster with hand-sized containers, and 2.87 faster with small-sized containers, $ps = .012$. Indeed, changes in latency to open the lid might be underestimated because of the arbitrary 30-second cut-off in trial length—younger children might have opened containers of any size with longer trial times.

Knowing the direction to twist posed an additional challenge. When children performed the designed action—twisting the lid—they did not always twist to the left and persist in doing so until the lid detached from the base. Indeed, children often twisted the lid and the base simultaneously, going back and forth, right and left, with both hands twisting in opposite directions. Thus, children often twisted the lid to the right the same number of times as they did to the left. As shown in Figure 5C, with age, children increased left to right twists, $Wald \chi^2 = 33.81, p < .001$. With each additional 6 months, children showed a .22 increase in the normalized relative number of left to right twists, $p < .001$.

Twist-offs: Summary

Results from Experiment 1 supported the hypothesized developmental progression from non-designed exploratory actions to discovery of the designed twisting action to successful implementation. Younger children showed a range of non-designed actions that decreased with age as performance of the designed action increased. Successful implementation lagged behind performance of the designed action at younger ages—that is, children displayed the designed action but were still unsuccessful in opening the jar. Why? Younger children often twisted back and forth with both hands twisting in opposite directions. As expected, larger lids were especially difficult to manipulate because children had to stretch their fingertips to grip the lid. In Experiment 2, we focused on children’s implementation of designed actions on containers larger than their hand size.

Experiment 2: Pull-Off Lids

Children’s difficulty in manipulating large twist-off lids suggests that successful implementation depends on the body-environment fit. In Experiment 2, we asked whether substantially increasing container size would lead children to adopt new bimanual strategies to implement the designed action. We tested children with Tupperware-style containers that required the designed action of pulling the lid. We focused on pulling because it was the most common non-designed action children applied to twist-offs. Moreover, as with twisting actions, pulling actions pervade activities of daily living and is common in toy exploration (Fagard & Lockman, 2005). However, the size of pull-off containers may affect implementation, just as we saw with the largest twist-off containers in Experiment 1. Merely pulling the lid of a large container will fail if the container base is free to move. Thus, we hypothesized that large pull-off containers have a second “hidden” aspect, requiring children to stabilize the base while pulling the lid.

Method

We tested 52 children (30 boys, 22 girls) between 11 and 37 months of age (Figure 1B). Data from 10 additional children were excluded due to experimenter error ($n = 4$) or because children did not complete $> 25\%$ of the trials ($n = 6$). All children were healthy and born at term. Parents reported children’s race as white (69%), black (2%), Asian (6%), multi-race (19%), and 4% chose not to respond; 81% were non-Hispanic, and 19% were Hispanic. We measured palm size in 44 children as in Experiment 1. Palm width ranged from 4.4 to 6.2 cm ($M = 5.1$ cm), and correlated with children’s age, $r(42) = .45, p = .002$. The study protocol was approved by the New York University Institutional Review Board.

The procedure was similar to Experiment 1 except that children received 7 pull-off, transparent Tupperware-style containers of 3 sizes—all larger than palm width: Two containers $M_s = 8.6$ -cm lid widths and 10.6-cm lid length slightly exceeded children's hand length (see y-axis in top panel of Figure 2); the container height averaged 4.1 cm. Four square containers had $M = 12.9$ -cm lid widths and lengths; the average height was 10.1 cm. One container had a 15.8-cm lid width and 23.6-cm lid length and 8.1-cm height. As in Experiment 1, we normalized container size relative to children's palm size: containers with widths $>1-5$ cm, $5-9$ cm, and >9 cm larger than children's palm size. The two larger groups of containers considerably exceeded children's hand length, meaning that children could not hold the base of the containers in one hand—they had to pull the lid while stabilizing the base. Containers were presented facing up or down because they could not balance on their sides.

Children received 11–14 trials ($M = 13.8$) with pull-offs and 2–31 sugar-bowl trials ($M = 13.3$). The experimenter presented at least one block of 7 trials, and ended the session after 2 blocks (14 trials) or when children refused to continue.

Data were coded and analyzed as in Experiment 1, except *pulling*, was defined as the designed action and *rotating*, *banging*, *shaking*, *hitting*, and *mouthing* were non-designed actions. Coders agreed on $>95.7\%$ of the behaviors, $Kappas > .85$, $ps < .001$. The correlation coefficient for latency was $r(349) > .99$, $p < .001$.

Results and Discussion

As in Experiment 1, across the entire session, children in all age groups opened the sugar-bowl on $M = 98.7\%$ of the trials with no change across age, $r(50) = .04$, $p = .774$. Sugar-bowl trials were excluded from all subsequent analyses. Preliminary analyses showed no effects of sex, $t_s < .82$, $ps > .409$, and container orientation had no effect on successful implementation, $t(48) = 1.74$, $p = .088$, so data were collapsed for subsequent analyses.

Actions on Pull-Offs: Changes Across Age and Trial-to-Trial Variability

As with twist-offs, findings supported the developmental progression from non-designed actions to the designed pulling action to successful implementation. Non-designed actions were common in younger children and decreased with age, $r(50) = -.69$, $p < .001$, Figure 3B. The colored lines in the inset of Figure 3B show the variety of non-designed actions and their decrease with age, $r_s(61) > -.31$, $ps < .024$. Rotating was most common ($M_s = 32.0\%$ of trials), whereas hitting, mouthing, and banging were rare ($M_s = 3.0\% - 5.8\%$). Across children, the number of non-designed actions per trial ranged from 0 to 5, $M = .44$. Despite the low proportions of non-designed actions, at some point in the session, 75% of children rotated the container, 52% shook it, 29% mouthed it, 27% banged it against the table, and 27% hit it with their hands. Moreover, performance of the designed pulling action preceded success at opening, Figure 3D. The pulling action increased with age, $r(50) = .82$, $p < .001$, as did success at opening, $r(50) = .78$, $p < .001$. However, pulling the lid did not guarantee success as shown by the non-overlapping black and red lines in Figure 3D.

Trial-by-trial data likewise support the developmental progression (Figure 4B). Only 9 children—all older than 30 months of age—did not display non-designed actions (blue squares) at some point in the session. Exhibiting the designed pulling action but failing to open (white circles) was most prevalent in the middle age range, and success at opening (red circles) was most prevalent in the oldest ages. The lack of consistency of symbol types within strings indicates that children did not improve across trials or trial blocks.

Successful Implementation of the Designed Pulling Action: Stabilizing the Base

The GEE testing age and normalized container size on success scores showed only a main effect of age, $Wald \chi^2 = 67.16, p < .001$, indicating that children's success scores did not differ by container size. With each additional 6 months, children were 7.8 times more likely to improve their success score, $\beta = .27, p < .001$.

So why the lag between performing the designed action (success score = 1) and successful implementation (success score = 2)? As we hypothesized, with age children increasingly stabilized the base by pressing the container against their chest ($M = 40.3\%$) or the tabletop ($M = 39.6\%$), or by stabilizing it with their forearm ($M = 7.1\%$) as shown by the line drawings in Figure 5D. Average success score was highly correlated with the proportion of times children stabilized the base, $r(48) = .94, p < .001$. A GEE confirmed that age was a significant predictor of whether children stabilized the base, $Wald \chi^2 = 41.00, p < .001$. With each additional 6 months, children were 7.02 times more likely to stabilize the base, $\beta = 0.16, p < .001$. Moreover, container size was also a significant predictor, $Wald \chi^2 = 23.61, p < .001$. As shown by the non-overlapping lines in Figure 5D, children were 3.19 – 4.15 times more likely to stabilize the two larger containers compared to the smallest one, $\beta_s = 1.42, p_s < .001$.

Pull-Offs: Summary

Results from Experiment 2 replicated the developmental progression observed in Experiment 1, from non-designed exploratory actions, to performance of the designed pulling action, to successful implementation. Non-designed actions (rotating, shaking, etc.) decreased with age; performance of the designed action and successful implementation increased with age. However, successful implementation lagged behind performance of the designed action at younger ages. Children had to generate new strategies to successfully pull the lids off large containers: They needed to stabilize the container against their chest, forearm, or tabletop with one hand while pulling the lid with the other.

General Discussion: The Hidden Affordances of Everyday Artifacts

In many cultures, children's everyday world is populated with artifacts that require specific motor actions to use the objects as their designers intended—packaged food and toiletries, fasteners on clothing, manipulative and construction toys, and so on. Often such designed actions are arbitrary (twist left, not right, to open a twist-off lid), motorically challenging (stabilize the base of a yogurt container with one hand while using a pincer grip to peel open the film), and not readily accessible to perception for a neophyte (pulling apart the two plastic films on a piece of string cheese). Despite the prevalence of artifacts in activities of

daily living, researchers know little about how designed actions are learned. This is the first study to provide a detailed, systematic description of when children learn to use everyday artifacts and what it takes to successfully implement the designed action.

Closures on containers are prime examples of hidden affordances—the goal is immediately apparent (open the lid), but how to accomplish the goal and what it takes to successfully implement it, is not. In two experiments, we investigated age-related changes in young children’s ability to display and implement the designed actions for two common containers—jars with twist-off lids and Tupperware-style containers with pull-off lids. All containers were transparent and had a snack inside, presenting children with a clear and highly motivating goal to open the container.

Normative Developmental Progression

Between 11 and 37 months of age, children showed a robust, three-step developmental progression. Non-designed actions predominated at the youngest ages. Although pulling was the most frequent non-designed action for twist-off lids, the youngest children displayed indiscriminate non-designed actions that could have been applied to any hand-held object—rotating, shaking, banging, and mouthing. By the middle age range, designed actions predominated: Children discovered the hidden affordance of the containers but they struggled to implement the designed action. Success at implementation increased dramatically with age, and became consistent across containers of different sizes by 30 months. However, non-designed actions did not disappear after 30 months. Although older children may have entered the study knowing the designed action, they still had to learn how the specifics of implementation.

A long tradition of research touts a moment of insight for children’s and chimps’ learning and implementing the designed action of tools and other artifacts (Köhler, 1925; reviewed in Lockman, 2000). However, our data argue against such an “aha” moment. Performing the designed action on one trial did not make the designed action more likely on the next trial. Likewise, successful implementation on one trial did not guarantee continued success on subsequent trials. From trial to trial, children vacillated between performing and not performing and implementing and not implementing the designed action. Thus, within each set of containers, we saw no immediate transfer across containers with similar requirements. Trial-to-trial variability suggests that initially children may learn to perform and implement the designed action of artifacts on a case-by-case basis, one object at a time. Children may learn the twisting action required to open a water bottle, for example, but not recognize that a jelly jar or toothpaste lid require the same left-twisting action. It takes many more months for children to generalize their actions across a common set of artifacts by generating strategies that accommodate the unique requirements of each exemplar. Age-related changes indicate a protracted period of learning that intermingles knowing what to do and being able to implement it, until learning solidifies into consistent success across trials for artifacts that share designed actions yet differ subtly in requirements for execution.

Motor Components of Implementation: Body-environment Fit

A large developmental literature considers the cognitive aspects of problem solving to be integral to learning to use tools, turn on “blicket boxes,” activate pop-up toys, use shape sorters, and so on (Barrett, Davis, & Needham, 2007; Griffiths, Sobel, Tenenbaum, & Gopnik, 2011; Lockman, 2000; Schulz & Bonawitz, 2007). Albeit less recognized by researchers, motor components are also critical for discovering and implementing the designed actions of artifacts. For example, fitting a rod into a slot requires efficient, simultaneous coordination of rotational and translational displacements (Jung, Kahrs, & Lockman, 2015). Building a block tower requires progressive slowing of the hand as each subsequent block is lifted and added to the stack (Chen, Keen, Rosander, & von Hofsten, 2010).

Regardless of whether the affordance is hidden or not, actions are possible only with the appropriate body-environment fit (Franchak & Adolph, 2014; Gaver, 1991). Every instantiation of an artifact is unique and requires modifications in the manual strategies for use. As we hypothesized, the body-environment fit—here, hand size relative to container size—affected children’s ability to implement the designed twisting and pulling actions. The largest twist-offs required children to stretch one hand across the container lid. And surprisingly, the smallest twist-offs were not necessarily easier than the hand-and palm-sized twist-offs, most likely due to the poor body-environment fit. With the smallest twist-offs, children had to curl their fingertips around the lid, which required precise fine control of their fingers. All of the pull-offs benefitted from stabilizing the base against the chest, table, or forearm, and the two largest ones required stabilization. Children in the younger age groups either did not realize the need to alter hand position for twist-offs and stabilize containers for pull-offs, or they lacked the hand strength, manual dexterity, or bimanual coordination to implement these strategies.

Motor Components in Discovering the Hidden Affordance

Discovery and implementation of the designed action are intertwined. In some cases, children have the ability to implement the designed action, but they do not know how to do it. Twisting and pulling actions are in infants’ repertoires prior to 12 months of age, but infants do not know to apply these actions to twist-off and pull-off lids. Similarly, think of your adult experiences failing to open an unfamiliar pill bottle before you read the instructions. Without instructions, how do children recognize where they are in the search space and when they are “getting warm”?

In other cases, children know what to do, but they lack the ability to implement the designed action, as when their finger strength is insufficient to budge the lid of a Tupperware container. Consider your adult experiences trying to open the stubborn lid on a pickle jar: You know you must twist the lid to the left, but you cannot. In still other cases, children do not know the specifics of the required action—they can execute a manual twist, but they do not know to twist only to the left. Such underlying motor components exacerbate the problem of using artifacts as their designers intended.

Presumably, contingent perceptual-motor exploration aids in the discovery and implementation of designed actions. Children generate perceptual information as they spontaneously act on surfaces and objects, and this contingent perceptual feedback guides their decisions about what to do next. For example, during infant locomotion, salient visual information from a distance (e.g., the sight of a steep slope) leads to haptic exploration via direct contact (touching the sloping surface), which in turn generates information about surface properties and the body-environment relations that specify affordances for traversability (Adolph, Eppler, Marin, Weise, & Clearfield, 2000; Adolph & Joh, 2009; Kretch & Adolph, 2017). Similarly, perceptual feedback from spontaneous interactions with artifacts can draw users into the appropriate area of the search space (Gaver, 1991). A good example is the lever handle on a door. Salient visual information about the overt affordance (metal handle visually “pops” against the wooden background of the door) leads the user to grasp the horizontal handle. Contingent perceptual feedback from this initial action (handle moves slightly downward due to weight of the arm) instigates the next action (twisting the handle downward), which provides additional feedback (door moves) that instigates a subsequent action (pull door), such that each perception-action feedback loop draws children into increasingly “warmer” regions of the search space until they implement the hidden affordance (de la Fuente, Gustafson, Twomey, & Bix, 2014). As Norman (2013) says, well-designed artifacts guide the user effortlessly to the right action in the right space at the right time.

However, the initial action (grasp container) can also yield misleading feedback (contents rattle), drawing the child into a “colder” region of the search space (shaking container) and making it more difficult to discover and implement the designed action (Gaver, 1991). Perceptual feedback can encourage children to persevere (lid moves in response to a twisting action) in a warmer region of the search space, without leading them to the specific—typically arbitrary—designed action (left twist). And without contingent feedback (e.g., children try to pull the Tupperware lid and nothing happens), the search space remains open. Children must continue to explore and they cannot distinguish between a “cold” exploratory action (shaking, rotating) and an implementation problem (lacking the hand strength to pull open the lid). Even adults struggle to implement the designed action on unfamiliar objects because the perceptual feedback is ambiguous or lacking. We often push, not pull, doors, or turn instead of push the unfamiliar shower knob in a hotel room.

Of course, social information is another likely guide to discovering the hidden affordances of artifacts. Children can watch an adult perform the designed action. However, many manual actions on artifacts are small, subtle, and often occluded by the object or the hand. Likewise, hands-on physical guidance (e.g. caregiver moves child’s hand) can demonstrate the possibility of implementing the designed action without revealing the details of implementation. Verbal instructions often require words beyond the vocabularies of young children (“twist it,” “stretch your fingers,” “turn it to the left”). Thus, social instruction from caregivers may help children to stay on task or draw children into warmer areas of the search space (twist or pull the lid) but fail to provide the requisite information about the specifics of the designed action (twist left or pull the corner while stabilizing the base). Possibly, implementing the fine grips, subtle adjustments, adequate forces, and bimanual coordination requires learning by doing not merely learning by watching.

Thus, it is unclear what mechanisms drive the developmental trajectory of discovering and implementing the hidden affordances of everyday artifacts. Prior experience (opening a familiar bottle), motor skills (opening a stubborn lid with sufficient strength), perceptual feedback (salient door handle), or social information could each contribute. Presumably, older children had more opportunity to learn through social-visual feedback—children likely see such culturally familiar objects acted on by their caregivers or older siblings. However, older children also have better manual skills compared to younger children and can better adjust their hands relative to the physical properties of artifacts. To disentangle the driving factors, future studies should test the role of perceptual-motor and social influences using non-conventional, unfamiliar artifacts.

Practical Implications for Mastering the Activities of Daily Living

Engineers and designers recognize the need to make consumer products and packaging accessible to elderly and disabled adults (Bix, de la Fuente, Pimple, & Kou, 2009; Langley, Janson, Wearn, & Yoxall, 2005). However, engineers and designers know surprisingly little about when and how children learn to use everyday artifacts—including toys and child-resistant packaging—and what it takes to successfully implement the designed actions (D. Weber from Fisher-Price®, personal communication, 2017; T. Phipps from OXO®, personal communication, 2016).

The hidden affordances of artifacts pose challenges to typically developing children for self-care at home and school, and are especially challenging for children with motor, perceptual, cognitive, or social disabilities (Bix, de la Fuente, Pimple, et al., 2009). Assessment scales such as the Self-Help domain of the Hawaii Early Learning Profile are limited to only a few items with artifacts and clothing and likely underestimate children's abilities (Teaford, 2010). Such scales present skill acquisition as a step-like trajectory—at first children cannot do the designed actions, and thereafter, quite abruptly, they can. Without the critical details about the trajectory of developmental change, training programs for parents, teachers, and therapists must rely on artistry and common sense rather than solid empirical evidence (e.g. Klein, 1983).

Children must master the use of many everyday artifacts by the time they enter preschool and kindergarten. And infants and preschoolers must be protected against implementing the designed actions of dangerous artifacts. Thus, it is critical for researchers to obtain a detailed understanding of how children learn the hidden affordances of everyday artifacts. This work has implications for designing artifacts that facilitate independence in activities of daily living, for developing training programs for caregivers, teachers, and occupational and physical therapists who aim to facilitate children's independence for activities of daily living, and for devising closures and tests of child-resistance to ensure children's safety.

Conclusions

Activities of daily living comprise the fundamental skills needed to manage basic physical needs—dressing, toileting, eating, and so on. Previous work largely ignored the developmental processes involved in activities of daily living. We demonstrate the

confluence of know-how and perceptual-motor factors that contribute to children's use of everyday artifacts as they were designed to be used.

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Research Highlights

- The designed actions required to use many everyday artifacts are nonobvious; the affordances are *hidden*.
- Children must discover and implement the hidden affordances that permeate activities of daily living.
- Learning to use everyday artifacts follows a developmental progression from non-designed actions to performance of the designed action, to successful implementation.
- A confluence of know-how and body-environment factors contribute to the developmental progression in learning to successfully implement the designed actions of everyday artifacts.

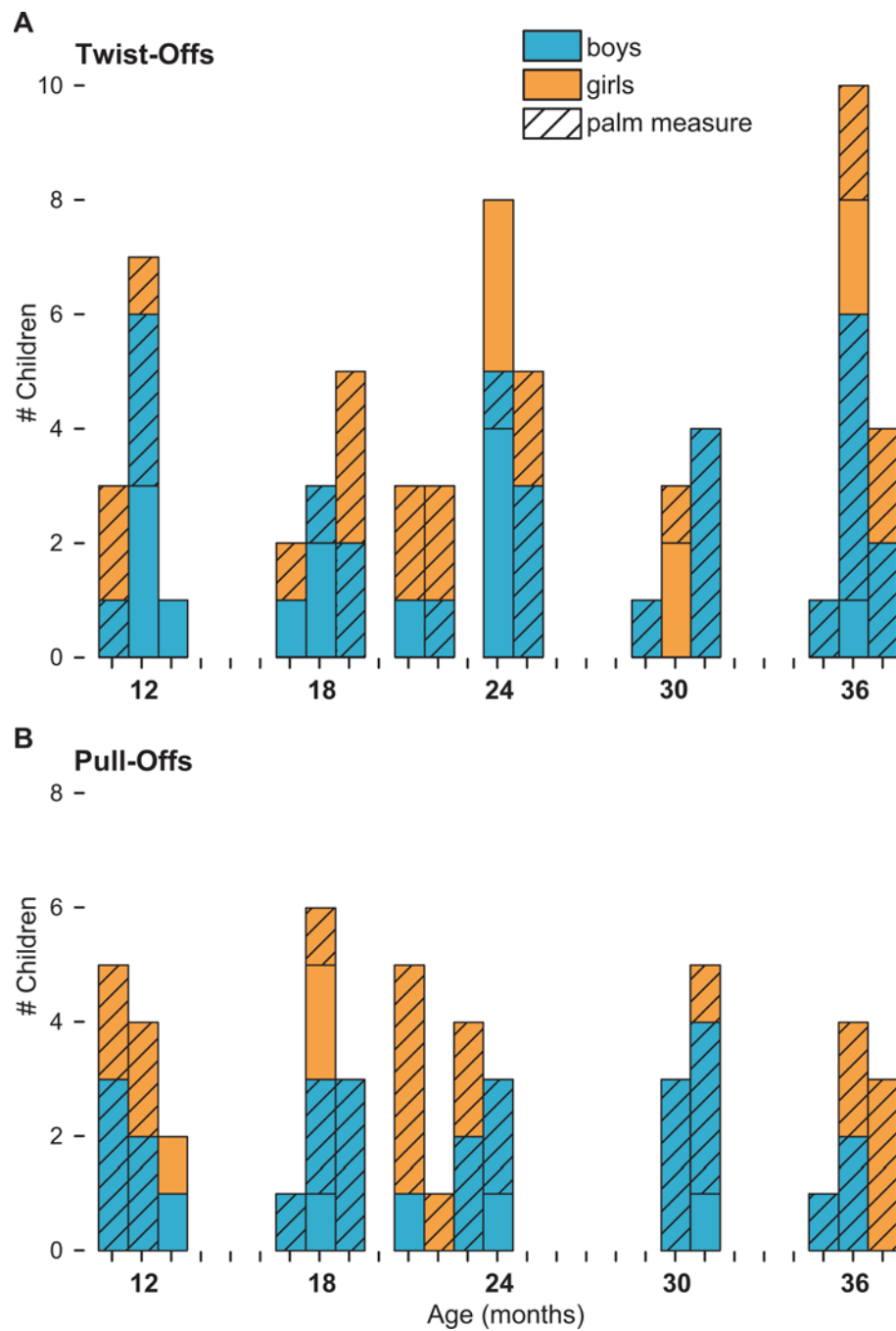


Figure 1. Number of children tested for (A) twist-offs and (B) pull-offs by children's sex and age. Striped bars represent children whose palm size was measured.

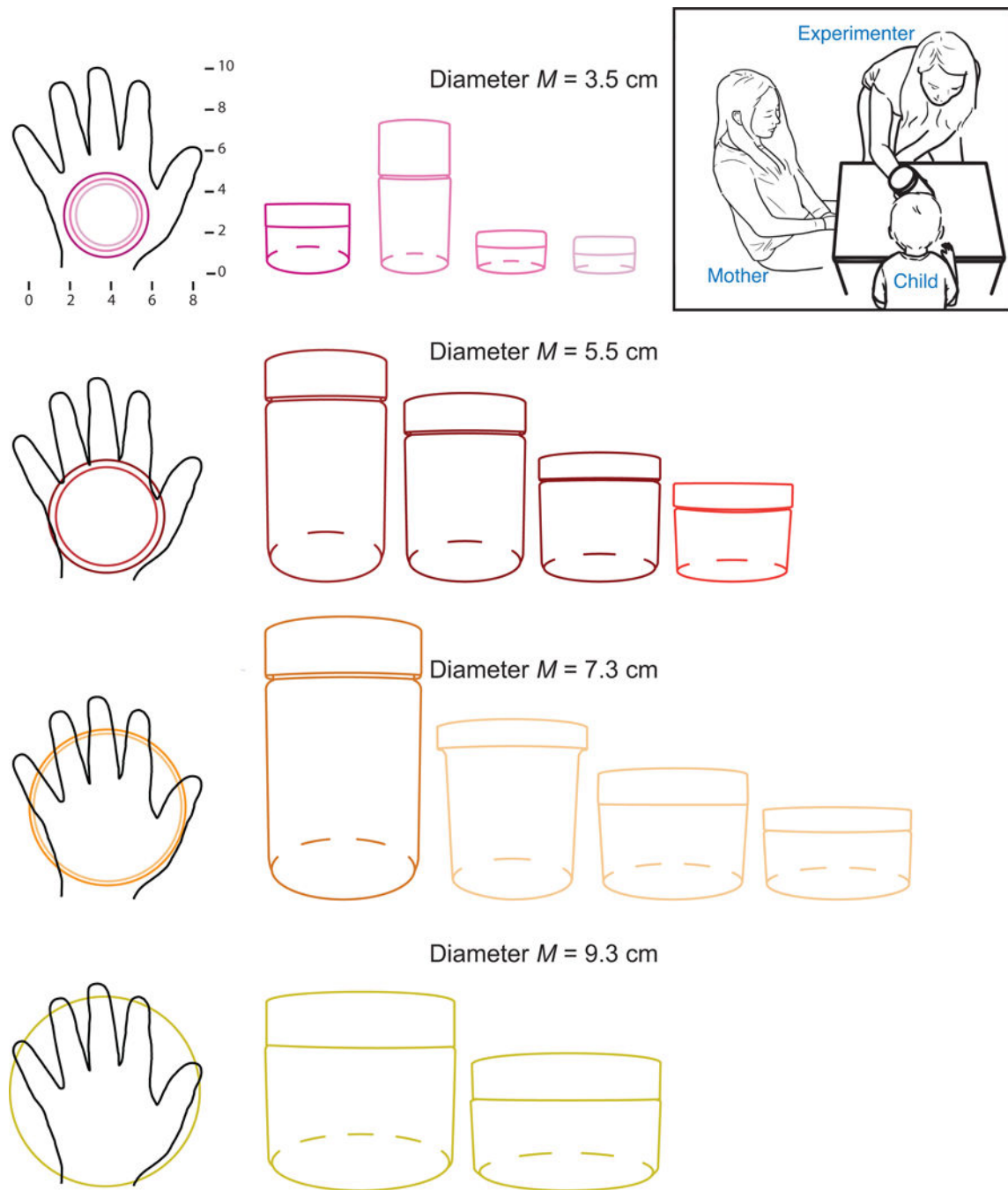


Figure 2.

Size of twist-offs relative to hand size. Left column displays children's hand size averaged across age relative to lid diameters. Right column displays drawings of all twist-off containers scaled to the axes assigned to hand size. Analyses used normalized container size relative to children's palm size. We considered containers $<1-3$ cm relative to children's palm size as small (requiring children to curl their fingers around the lid), containers within ± 1 cm as palm-sized, containers $>1-3$ cm as hand-sized (requiring children to bend their fingertips around the lid), and containers $>3-5$ cm as large (requiring children to stretch their

fingers to encompass the lid). Line drawing on top right corner shows experimental setup for twist-offs and pull-offs.

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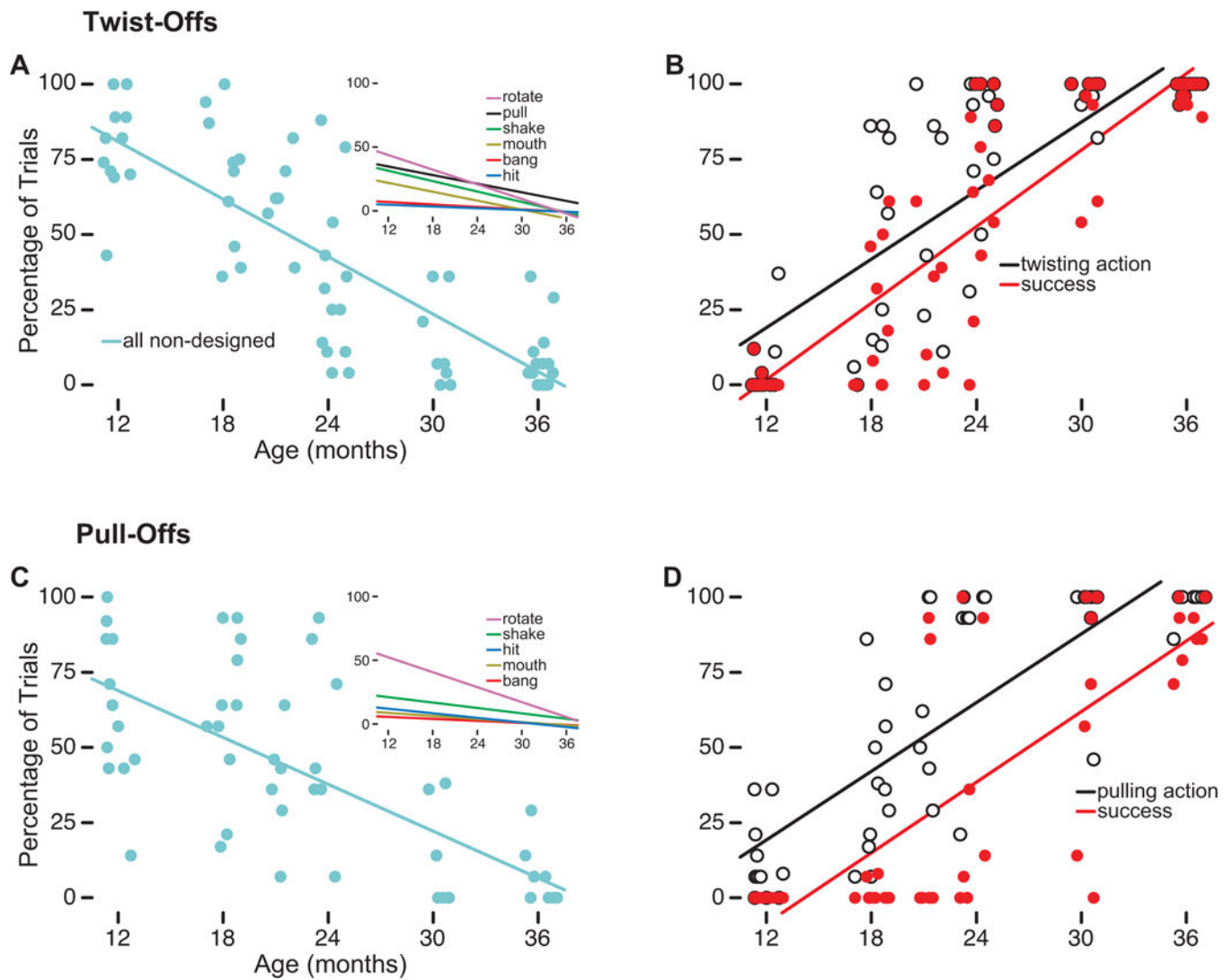


Figure 3. Actions on twist-offs and pull-offs across age. (A) and (C) show the proportion of trials with non-designed actions decreased with age. Insets show the variety of non-designed actions. (B) and (D) show that the proportion of trials with designed actions preceded successful implementation. Symbols represent the average per child. Curves denote best fit lines.

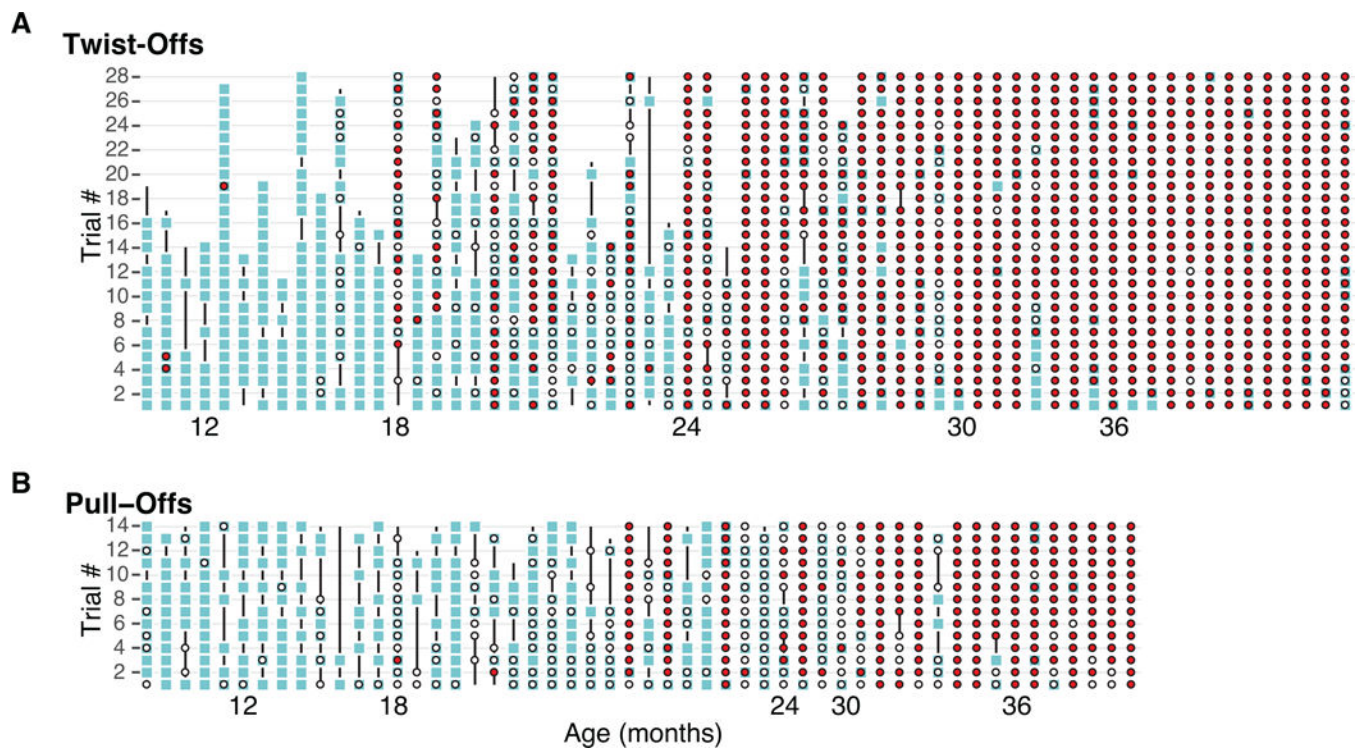


Figure 4.

Trial-by-trial data for (A) twist-offs and (B) pull-offs. Each string of symbols represents data from one child and each row represents data from one trial. Blue squares denote trials when children performed non-designed actions, white circles denote trials when children displayed the designed action but failed to open, red circles indicate success at opening, and black lines denote trials when children merely held the container without displaying other actions.

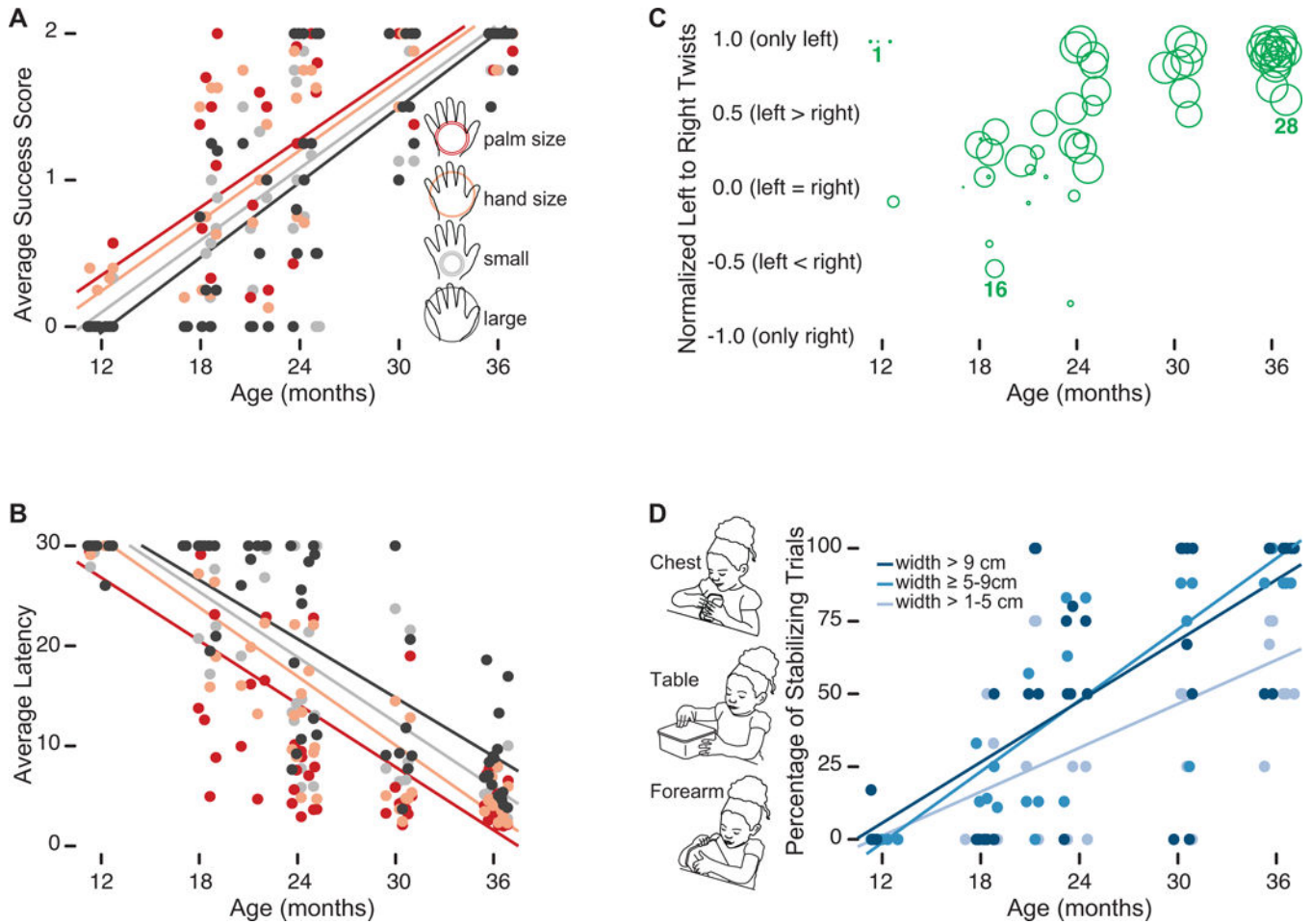


Figure 5. Factors affecting implementation for (A–C) twist-offs and (D) pull-offs. Drawings of children’s hands and the colors of lids with different diameters in (A) indicate the legend for (A-B). The top-down order of the legend follows the order of success across the different normalized container sizes, from greatest success for palm-sized containers to least success for large containers. (A) Average success score for twist-offs by age and container size (0 = no designed action, 1 = twisting the lid without opening, and 2 = opening the lid). (B) Average latency to open twist-offs by age and container size. (C) Average normalized relative number of left to right twists by age. Each symbol represents one child. The size of each symbol represents the number of trials in which each child twisted the lid (e.g. the largest symbol denotes 28 trials, the middle-sized symbol denotes 16 trials, the smallest symbol denotes 1 trial, and children who never twisted are excluded). (D) Proportion of trials when children stabilized the base of pull-offs by age and normalized container size. Line drawings show the types of stabilization strategies children performed.