Journal of Experimental Child Psychology 269 (2026) 106532

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Getting the proper grip: A longitudinal study of how infants learn to adapt action Plans

Tommaso Ghilardi [a,1], Rachel Keen [b,1], Emanuelle Benzaquen [a], Ori Ossmy [a,*]

[a] Centre for Brain and Cognitive Development, School of Psychological Sciences, Birkbeck, University of London, UK
[b] Department of Psychology, University of Virginia, UK

ARTICLE INFO

Keywords:
Object manipulation
Manual actions
Planning
Tool use
Multi-step planning
Infancy
Motor development
Longitudinal

ABSTRACT

Across ages and cultures, planning actions adaptively during tool use is a hallmark of human intelligence and a critical factor in human survival and proper function. Previous cross-sectional studies showed that adaptive planning begins in infancy and improves with age and experience. However, little is known about how developmental improvements in adaptive planning occur. Do infants gradually adapt their action planning with one object and then generalize this skill to other objects, or does learning remain tool-specific? Here, we longitudinally tested nine infants in weekly sessions across the age range when tool use is rapidly developing. Infants were presented with a familiar tool (spoon) and three unfamiliar tools (brush, hammer, magnet) with handles pointing to the right or left. For each trial, we scored whether infants used an adaptive radial grip (evidence of action planning) or an inefficient ulnar grip (no evidence of planning). Across several months of testing, every infant gradually learned to use an adaptive radial grip for the spoon, but none showed improvement for the unfamiliar tools. Adaptive planning with the spoon was further limited to self-directed actions (bringing food to their own mouth) rather than other-directed actions (feeding a puppet). Learning was characterized by high variability before stable achievement of an efficient grip. Across all tools, right-pointing handles elicited more radial grips than left-pointing handles. Our findings replicate previous cross-sectional research and provide new insights into the longitudinal progression of adaptive planning during tool use in infancy. Specifically, the development was gradual rather than abrupt, and learning remained highly tool-specific without generalization, emphasizing the critical role of specific and extensive experience with particular tool-action combinations.

Introduction

A remarkable aspect of motor skill is the ability to plan actions flexibly and purposefully with a variety of objects (Keen, 2011; Rosenbaum et al., 2012). Everyday environments are variable, unpredictable, and full of novel situations, thus performing the same actions over and over is not an option, and actors must learn to modify even the most basic and automatised actions (e.g., reaching) to suit the current demands (e.g., object orientation). To deal with the challenge of flexibility in tool use, children must master the ability to plan ahead rather than resort to trial-and-error learning (Ossmy & Adolph, 2020; Ossmy et al., 2020, 2022).

* Corresponding author at: 32 Torrington Square, London, WC1E 7JL, UK.
E-mail address: ori.ossmy@bbk.ac.uk (O. Ossmy).
[1] Shared first authorship.

https://doi.org/10.1016/j.jecp.2026.106532
Received 27 May 2025; Received in revised form 21 April 2026;
Available online 29 April 2026
0022-0965/

How do children develop the skill to plan the appropriate tool-use action at the appropriate moment? Traditionally, developmental researchers conducted cross-sectional studies testing children in creative tool-use planning problems. These studies established that planning development begins in infancy (Kevin Connolly & Dalgleish, 1989; Cowie et al., 2006; Lockman, 2000; Lockman et al., 1984; Lockman & McHale, 1989; McCarty et al., 1999, 2001; Willats, 1989) and improves with age and experience (Comalli et al., 2016; Keen, 2011; Wunsch et al., 2013). Learning new strategies to solve a problem relies on a "high level" cognitive skill—the ability to form an internal model of task contingencies to evaluate possible actions and predict the optimal act (Gerson et al., 2018; Keen, 2011; Monroy et al., 2017).

Tool use involves adaptive planning (Rosenbaum et al., 2012, 1990, 1996) because successful implementation of the tool requires accounting for a future end goal that is not immediately visible in the scene. For example, when adults want to use a spoon and the handle points toward their non-dominant hand, they plan ahead by grasping the spoon with an underhand grip in their dominant hand that allows for a smooth transition to a comfortable end-state grip (Rosenbaum et al., 2012). The logic is simple: If the same tool is grasped differentially depending on the actor's plan, then planning can be inferred from the way the tool was grasped in anticipation of the action to be carried out.

Tool use has been recognized by developmental researchers as a way to study problem solving in infants and young children (Keen, 2011; Lockman, 2000), as a sign of emerging cognition in apes and infants (Buttelmann et al., 2008), and increasing motor control in manual skills (Kahrs & Lockman, 2014; Lockman & Kahrs, 2017; Ossmy et al., 2020, 2022). Its advantages as a window into cognitive development include its use over a wide age range from infancy onward, its ready engagement of young children's motivation, and easy observation of errors.

For most tools with handles, using them correctly requires that a radial grip be applied to the handle. A radial grip is defined as a

Fig. 1. Adaptive grasping strategies in infants. (A) Schematic drawing illustrating grasp on a spoon, showing radial and ulnar grasping with both right and left hand. (B) Experimental setup: Left panel shows a sketch of an infant reaching for a spoon presented on a stand. Right panel displays the set of four tools (spoon, hammer, brush, and magnet) presented to infants during the experimental sessions.

grasp of the handle in which the thumb is toward the action end of the tool. For example, hammers, saws, screwdrivers, knives, flyswatters, cooking utensils, and eating utensils should be grasped with a radial grip on the handle in order to be used efficiently. A knife cuts through food better if the thumb is toward the blade. The tool user who chooses a radial grip shows anticipation for the next stage of goal-directed action. The consistent choice of a radial grip in young children unveils the emergence of multi-step planning in development. McCarty, Clifton, & Collard (1999) used a simple manipulation of a spoon's orientation to investigate when infants would begin to adapt their hand to achieve a radial grip. A spoon loaded with food was presented to the infant with its handle alternating between pointing to the left and right. If the right hand is dominant, the “easy” orientation is handle to the right because the right hand will naturally grasp the handle in a radial grip (shown in the top panel of Fig. 1A). The “difficult” orientation with handle to the left presents a problem. An overhand grip with the favored right hand will result in an ulnar grip, making it awkward to get food to the mouth. In those trials, getting a radial grip can be achieved by using the less-favoured left hand to avoid the ulnar grip (Fig. 1A shows examples of both radial and ulnar grips with left and right hands). Switching hands or using an underhand grip are both considered adaptive planning to the problem, although the underhand grip does not appear routinely until around 5 years of age (Comalli et al., 2016). Choice of the left hand is a multi-step process, as it requires (1) noticing that the spoon's orientation will affect the grasp; (2) inhibiting the dominant right hand; and (3) choosing the left hand to complete the action of bringing food to the mouth. McCarty et al. (1999) tested infants at 9, 14, and 19 months of age. Even in infancy, children tend to have a dominant hand, though this may shift between right and left from week to week. Handedness often does not become stable until the preschool years or beyond (Michel, 2018). In McCarty et al. (1999), infants typically tested as being right-hand dominant, but note that in the spoon task either side could be “easy” or “difficult” depending on which hand was dominant, so the procedure works regardless.

McCarty et al. (1999) found that 9-month-olds the youngest group did not plan ahead or seem to notice the spoon's orientation. They typically picked up the spoon with a radial grip on almost all easy trials, and with an ulnar grip on difficult trials, resulting in the handle end going into the mouth rather than the food end. At 14 months, infants also picked up the spoon on the difficult trials with an ulnar grip in the right hand, but they noticed that something was wrong. Rarely did the spoon's handle go into the older child's mouth. Typically the child made a correction of the grip, sometimes transferring the tool to the left hand for a radial grip, or placing the spoon on the table and re-positioning it for a radial grip with the right hand. Another solution was to proceed with the non-adaptive, ulnar grip but twist the wrist into an awkward posture to get the food end into the mouth. Finally, at 19 months, most infants readily adopted a left-hand grip on difficult trials. By adapting the hands to the alternating handles, they achieved a comfortable radial grip on every trial. At this age, toddlers noticed the changes in the handle's orientation prior to the reach and let perception guide them in choosing an appropriate action.

In a cross-sectional and longitudinal studies (Connolly and Dalgleish, 1993; 1989) of self-feeding over a similar age range, Connolly and Dalgleish tested infants as they ate a bowl of food with a spoon. In their longitudinal work, they followed 16 infants monthly for 6 months and documented four stages of skill development: from repetitive actions with the spoon, to construction of the action sequence (spoon-to-dish-to-mouth), to incorporation of function (successful food transfer), and finally integration of error-correction routines. A variety of awkward grips were observed in younger infants, but around 18 months, all infants had converged to some type of overhand radial grip on the spoon. Together, these findings demonstrate that by 18 months of age, infants consistently adopt a radial grip on the spoon in both naturalistic self-feeding contexts and laboratory settings. However, Connolly and Dalgleish's focus was on how infants learn to execute the spoon-feeding action—filling, transporting, and emptying the spoon—rather than on whether infants adapt their grip in anticipation of the tool's orientation.

In a subsequent study, McCarty, Clifton, & Collard (2001) tested whether infants' acquisition of a radial grip on the spoon generalizes to other tools. That is, were infants learning that radial grips were the most efficient to use generally, or was their learning specific to one tool, the familiar spoon? Infants of 9, 14, 19, and 24 months of age were tested with a spoon, brush, hammer, and magnet in the alternating handle task. The hairbrush and spoon were presented with either the self or a lion puppet as the action endpoint. On self-directed trials, children were instructed to eat food from the spoon or brush their own hair. On the other-directed puppet trials children were instructed to ‘feed the lion’ or ‘brush the lion’. Children selected the radial grip on ‘difficult’ trials (when the handle pointed to their non-dominant hand) only when the spoon and hairbrush were used on their own body. When spoon and hairbrush were directed toward the puppet and when other tools were presented, children reached for the handle with their dominant hand, resulting in an ulnar grip. Therefore, infants' learning about using a radial grip appeared not to be tied to one familiar tool (i.e., the spoon) but rather to the subsequent action in which the child would engage.

Although these cross-sectional studies were beneficial in identifying adaptive planning skills or lack thereof, they are limited in explaining *how* developmental improvements in planning occur. Group averages across an age range do not reveal how quickly individual infants learn to adapt their grip planning with the spoon, nor do they tell us when infants apply that skill to other tools. Do infants first learn to adapt their planning with one tool before generalising the skill to other tools? Or perhaps their vast and varied daily experience leads to immediate generalisation. Does the solution to the spoon problem appear suddenly and remain consistent? There are several reasons to believe that the transition from awkward ulnar grips to the comfortable, efficient radial grip is not sudden. That is, toddlers do not have a spurt of insight into the spoon problem and thereafter adopt the strategy of grasping with the non-dominant hand. Previous cross-sectional studies (Comalli et al., 2016; McCarty et al., 1999, 2001; Wunsch et al., 2013) reported considerable inter-trial variation within individual children such that the same child would exhibit mature radial grips on some trials but awkward ulnar grips on adjacent trials. Because children were tested only once, we do not know if this variability was fleeting or persisted over several weeks or even months. Multiple sessions with each infant over an extended period would reveal whether the transition to a comfortable radial grip appeared suddenly and dominated thereafter, or if it took several weeks or more to become stable. Dense longitudinal data would also answer the questions concerning the eventual generalizability of the radial grip to other tools.

Here, we present a longitudinal study that tests how infants plan their tool use with familiar (i.e., spoons) and unfamiliar (e.g., magnets) tools. Nine infants (9- to 18-month-olds) were tested repeatedly in an age range when they were learning to grasp and use a variety of tools. We adopted McCarty, et al.'s (1999) procedure of changing the handle's orientation and used similar tools to those in McCarty et al. (2001). Infants were presented with the same four tools in each session and we scored whether they applied a grasp that matched the direction of the tool handle. We also tested whether grasping was affected by how infants used the tools towards their own bodies or toward other objects. Our longitudinal design allowed us to test whether (1) adaptive planning emerges first for familiar tools (e.g., spoons) or immediately generalizes to unfamiliar tools (i.e., brush, hammer, magnet); (2) adaptive planning appears earlier for self-directed tool use than for other-directed tool use; (3) right-pointed handles elicit more radial grips than left-pointing handles across tools; (4) the development of adaptive planning is gradual or emerges abruptly, and (5) repeated weekly practice accelerates the developmental process.

Based on prior cross-sectional work, we predicted replication of three key findings: (1) the handle-to-the-right orientation would be easier than the handle-to-the-left orientation; (2) self-directed actions would have more adaptive grips than other-directed actions; and (3) radial grips would be more common with the spoon than with other tools. Crucially, the key advantage of our longitudinal approach was to address two knowledge gaps in the development of adaptive planning: *how these patterns emerge* over time—gradually through incremental learning or abruptly through an 'aha moment' of insight—and whether learning remains *tool-specific* or generalizes across implements.

Methods

Videos and demographic data are shared with authorized investigators in the Databrary web-based library at databrary.org/volume/1075. The Datavyu video annotation spreadsheets, Datavyu scripts, and processed data are publicly shared at databrary.org/volume/1075. All analysis scripts are shared in GitHub: https://github.com/Physical-Cognition-Lab/Getting-the-Proper-Grip-A-Longitudinal-Study-of-How-Infants-Learn-to-Adapt-Action-Plans.

A

		Age (weeks)		Age (months)		# of trials			
Id	# Session	First session	Last session	First session	Last session	Spoon	Brush	Hammer	Magnet
1	7	39.6	54.9	9.1	12.6	40	32	53	29
2	26	49.7	77.7	11.4	17.9	248	167	98	211
3	13	49.4	78.4	11.4	18.0	116	134	94	173
4	9	59.7	73.9	13.7	17.0	109	59	44	57
5	19	45.3	67.6	10.4	15.5	159	100	90	120
6	11	51.3	66.9	11.8	15.4	168	44	51	74
7	18	42.1	63.4	9.7	14.6	338	348	160	222
8	18	39.6	60.4	9.1	13.9	377	281	226	299
9	17	40.9	61.3	9.4	14.1	170	87	192	187

B

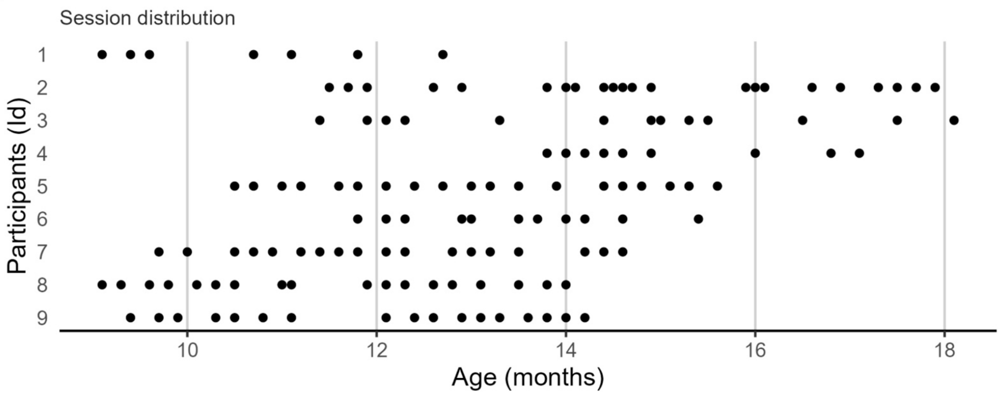

Fig. 2. Sessions and temporal distribution: (A) Summary table showing the number of sessions each participant (ID 1–9) attended, their ages at first and last sessions (in both weeks and months), and the total number of trials completed with each tool (Spoon, Brush, Hammer, Magnet). (B) Temporal distribution of testing sessions across the study period. Each dot represents a testing session for each participant, illustrating the longitudinal sampling density and age ranges covered during data collection.

Participants

Nine infants participated in this study. The median age at the initial session was 10.4 months, with a range of 9.2–13.6 months. The median age at the final session was 15.5 months (67 weeks) with a range of 12.7–18 months (see Fig. 2). The aim was to test each infant every week until they were able to reliably achieve a radial grip on the spoon in both orientations; this achievement varied with each infant. The number of sessions ranged from 7 to 26, with a median of 18. Although we aimed to maintain a consistent weekly testing schedule, practical constraints inherent to longitudinal infant research occasionally necessitated adjustments to the testing timeline. One participant had only 7 sessions because the parents were unable to continue the weekly meetings. Participants were recruited from a university daycare center and from the local community. Full data about participants' ages in each session and number of trials with each tool are shared at databrary.org/volume/1075.

Procedure

Children sat opposite the experimenter at a small table, with all the tools out of sight. Occasionally, testing was conducted on the floor when necessary to keep infants comfortable and engaged. Each session was videotaped to provide a full view of the child's upper body and the testing area. As a warmup the experimenter placed a toy on the table at midline within reach of the infant. Toys were small (e.g., toy car, toy animal, small plastic cups, etc.) to encourage one-handed reaches. Ten trials were presented using a variety of toys to maintain the child's interest. The tool tasks were then presented with the handle alternating right and left to provide two orientations. The aim was to present each tool task eight times (four trials in each handle orientation) in short blocks before moving to the next tool. The order of the four tool blocks was pseudo-randomised and counterbalanced across sessions so that each tool was presented equally often in each ordinal position. If an infant refused to reach for a particular tool when scheduled, that block was revisited later in the session; across sessions, the ordinal balance was maintained. For the spoon and brush, self-directed and other-directed actions were presented in separate blocks (eight trials per block), with the order alternated and counterbalanced across sessions. This design ensured that no tool systematically preceded the others and that self- vs. other-directed blocks did not occur in a fixed sequence, thereby mitigating order and familiarity confounds.

Tools were placed on a holder that supported each end of the tool above the table's surface to provide an unobstructed grip around the handle. The frequency and direction of tool presentations are outlined in Table 1, which details the number of times each tool was presented to the left or right side for each participant (ID 1–9). The unevenness in the number of presentations was due to infants' preferences for or indifference toward a particular tool. The number of trials for each tool reflects the infant's acceptance of that tool.

Tool-Use task

The spoon-to-self and spoon-to-other trials were similar to McCarty et al. (2001). For spoon-to-self, a Gerber infant spoon was loaded with baby food approved by each parent for their child (e.g., applesauce, sweet potatoes, etc.) and placed on the holder in a specified orientation. The direction of the spoon handle was manipulated to be either right or left. Infants were encouraged to pick up the spoon and eat the food. The experimenter retrieved the spoon, loaded it with food, and presented the next trial in the alternate orientation until a total of eight trials were finished. The spoon-to-other trials featured the same spoon but without food, along with a stuffed animal puppet (lion or bear). Infants were urged to feed the puppet by bringing the empty spoon to its mouth and were verbally

Table 1
Frequency of tool presentations by direction for each participant. The number of times each tool (Hammer, Brush, Magnet, Spoon) was presented to the left or right side for each participant (Id 1–9). The 'Direction count' columns show the frequency of left and right presentations for each tool per participant independently of the target of the action.

Id	Direction	Tools Spoon	Brush	Hammer	Magnet
1	Left	18	15	27	13
1	Right	22	17	26	16
2	Left	121	87	50	102
2	Right	127	80	48	109
3	Left	62	59	49	90
3	Right	54	75	45	83
4	Left	59	29	23	27
4	Right	50	30	21	30
5	Left	101	34	36	60
5	Right	58	66	54	60
6	Left	74	21	23	35
6	Right	94	23	28	39
7	Left	167	184	84	107
7	Right	171	164	76	115
8	Left	179	129	116	146
8	Right	198	152	110	153
9	Left	84	39	92	85
9	Right	86	48	100	102

praised when they did so. The hairbrush-to-self and hairbrush-to-other trials were also similar to McCarty et al. (2001). In these trials, an infant's hairbrush was placed on the holder, and infants were encouraged to brush their own hair or brush the puppet. The comparison of tool-to-self to tool-to-other trials (whether the tool was a spoon or hairbrush) was to determine if the location of the action's endpoint would affect the child's selection of a radial grip on the tool.

Two additional tool-use tasks were used that involved actions with other objects: a toy hammer (with a board embedded with wooden pegs; similar to Ossmy et al., 2022) and a magnet that picked up metal objects. The toy hammer was familiar to some children because it is commercially available and found in homes and day care centers. The magnet task consisted of a U-shaped magnet attached to a wooden handle. It could be used to remove a metal jar lid situated in a recessed hole in a wooden stand. The jar lid was flush with the surface of the stand and could not be removed with fingers. The experimenter demonstrated how the jar lid could be easily removed by touching it with the magnet. The magnet task was considered to be the most novel as both the tool and the recessed jar lid holder were made in the lab. As with the spoon and hairbrush, the hammer and magnet were presented on the holder with the handle alternated to the infant's left and right for 8 trials each.

Video coding

A primary coder annotated videos using Datavyu software (https://www.datavyu.org), a computerized video coding tool, to identify the presence or absence of specific behaviors (see coding manual in –***-details omitted for blind reviewing–***). The coder identified infants' initial grip in each trial (Fig. 1A demonstrates radial and ulnar grips) as radial (thumb toward the tool's action end) or ulnar (thumb facing away from the action end). The distribution of adaptive and non-adaptive grip orientations across all participants and trials is presented in Table 2. Note that because analyses focused on initial grip as a measure for infant planning, we only coded attempts when infants demonstrated an attempt to use the tool or to hold it. An unintentional touch of the infant's body with the tool was not considered a grasp. To ensure interobserver reliability, a second coder independently scored 25% of each infant's sessions. Interobserver agreement was 98.22%, $kappa = .88$, $p < .01$.

Statistical analysis

Effects of tools and target direction. We employed Bayesian logistic mixed-effects models to analyse the development of adaptive grasp across age, considering the effect of tool type and action target. This framework was chosen because it allows estimation of both fixed effects (capturing population-level influences such as tool type and age) and random effects concurrently, which account for individual differences in baseline performance (intercepts) and developmental trajectories (slopes). Thus, this approach enables robust inference with unbalanced data, accommodating unequal numbers of trials per condition, and variability in the number and timing of sessions across infants. The models were implemented using the brms package (Bürkner, 2017) in R. All models were estimated using standardized age in weeks. However, for ease of interpretation, model estimates and plots throughout the manuscript are back-transformed and converted to months (by dividing weeks by 4.33).

We first examined potential differences in adaptive grip across tools by fitting a logistic model that included fixed effects for and interactions between tool type, handle direction (right or left) and age. For the spoon and brush tools, we only considered self-directed trials in this analysis. Similarly, to investigate potential differences in adaptive grips based on the action target (self, other), we fitted a separate logistic model focusing only on the spoon and the brush. This model included fixed effects for and interactions between the target (self, other), tool (spoon, brush), handle direction (right, left), and age. All models were estimated using standardized age values (that is, age was Z-scored by subtracting the mean and dividing by the standard deviation).

For each model, we ran four Markov Chain Monte Carlo (MCMC) chains, each consisting of 8,000 iterations with a warm-up period of 6,000 iterations. This process yielded 8,000 post-warm-up samples per model for posterior inference. To account for individual variability, all models incorporated random effects, allowing for participant-specific intercepts and age slopes. This structure enables each participant to have a unique baseline adaptiveness level (random intercept) and a personalized age-adaptiveness relationship

Table 2
Distribution of Grip Type Across Participants. Caption: Distribution of radial (adaptive) and ulnar (non-adaptive) grips for each participant across all tool trials. Radial grips (thumb toward action end) represent successful adaptive planning, while ulnar grips (thumb away from action end) indicate failure to adapt grip strategy to tool orientation.

ID	Grip Radial	Ulnar	% Radial
1	90	64	58.4%
2	433	291	59.8%
3	285	232	55.1%
4	210	59	78.1%
5	236	233	50.3%
6	220	117	65.3%
7	607	461	56.8%
8	592	591	50.0%
9	337	299	53.0%

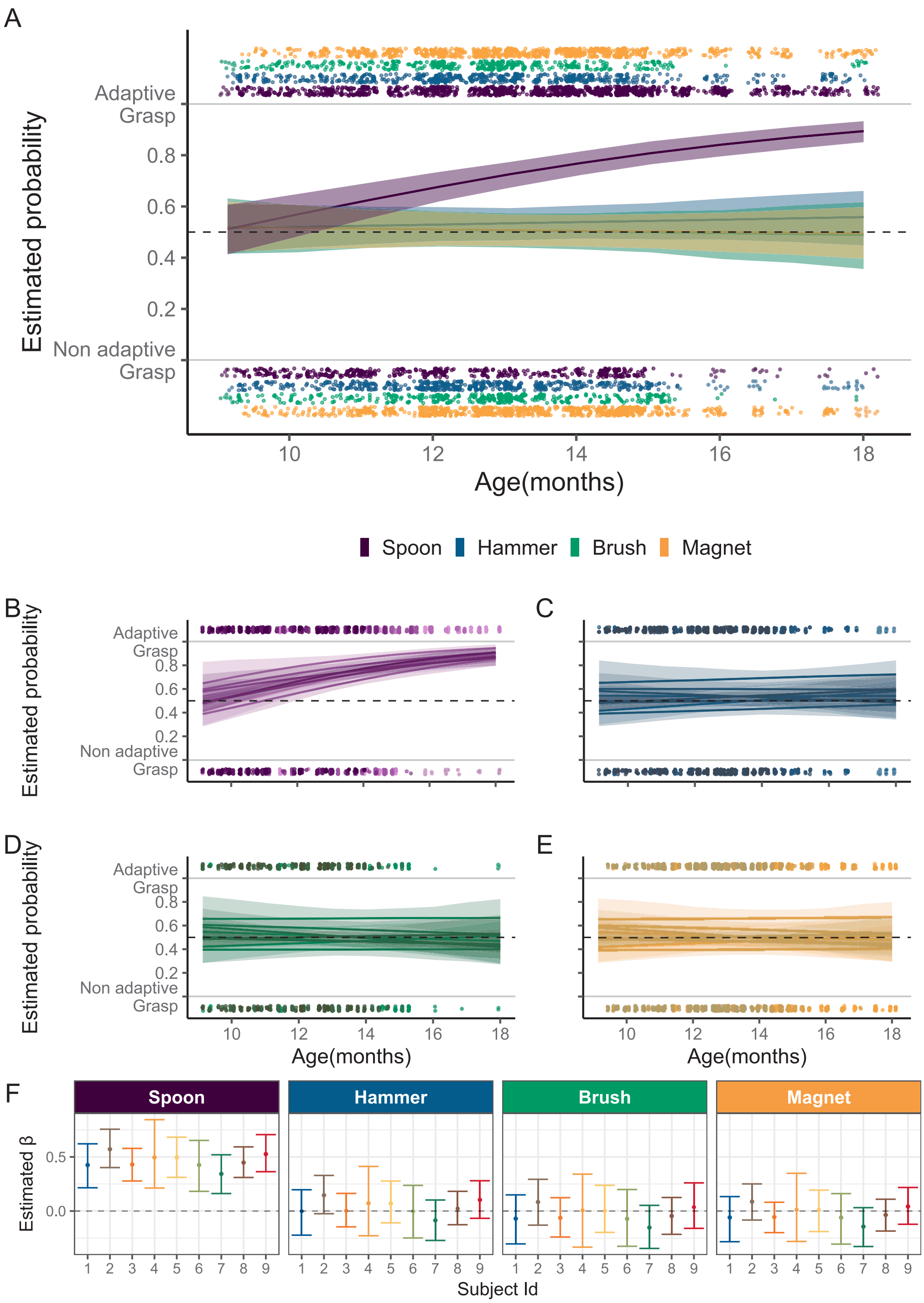

Fig. 3. Effect of different tools on the probability of adaptive grasp. (A) Posterior predicted probability of an adaptive grasp as a function of age (months) for four tools (spoon, hammer, brush, magnet), estimated with a hierarchical Bayesian logistic model including infant-specific intercepts and age slopes (1 + Age | ID). Lines represent the estimated probabilities, and shaded areas indicate standard errors. The dashed horizontal line at 0.5 probability indicates the chance level, representing the expected probability if subjects used their right hand consistently or switched indiscriminately between right and left hands while maintaining an overhand grip. (B–E) Infant-level trajectories for each tool: (B) Spoon, (C) Hammer, (D) Brush, (E) Magnet. Each line is an individual infant's posterior prediction; values > 0.5 indicate adaptive grasps are more likely than non-adaptive for that infant at that age. Shaded bands show 89% credible intervals. Dots above and bellow the model curves denote raw outcomes from individual trials. (F) Estimated age coefficients (β) for adaptive-grip probability by tool and infant; error bars are 89% credible intervals.

(random slope), thereby capturing individual differences in both overall performance and age-related changes. Details of the priors used in the models are provided in the supplementary materials.

Following the model fitting, we conducted post-hoc analyses to interpret the results. For significant categorical effects (such as tool type and action target), we extracted Estimated Marginal Contrasts using the *estimate_contrast* function from the model-based package (Makowski et al., 2020). This allowed us to quantify the differences between specific levels of these factors. For continuous variables (age) and their interactions with categorical predictors, we used the *estimate_slopes* function from the same package to extract estimated marginal effects. This approach enabled us to examine how the effect of age on adaptive grasp might vary across different tools or action directions.

Finally, to explore individual differences in the development of adaptive grasp across age, we extracted estimated marginal effects of tool over age for each infant using the *emtrends* function from the *emmeans* package (Lenth, 2024). This approach enabled us to examine how the effect of age on adaptive grasp might vary across different tools for each individual infant. For all analyses, we report 89% credible intervals (McElreath, 2018). These intervals represent the posterior probability distribution of our parameter estimates, such that there is an 89% probability that the true parameter value lies within the reported range.

Estimating the age of stable adaptive tool use. To determine the age at which infants reliably use an adaptive grasp for each tool, we employed a predictive approach using our fitted Bayesian model. We generated predictions for ages ranging from 38 to 86 weeks, in 2-week intervals. We extended the model's age range beyond the observed data to estimate when adaptive grip reaches a stable plateau. Because we had no a priori basis for assuming that stabilization would occur within (rather than beyond) our observation window, extrapolating the fitted trajectory allowed us to characterize the full developmental course. The plotted predictions are based on the model's population-level (fixed-effect) estimates and therefore represent the expected average developmental trajectory, while individual-to-individual differences are accommodated by the random-effects structure (i.e., participants are allowed to deviate from the mean trajectory).

For each prediction, we extracted 1000 posterior samples and then summarized these posterior distributions to obtain point estimates (means) and uncertainty intervals (89% Highest Density Intervals) for the probability of adaptive grasp at each age.

To identify the age of stable adaptive grip, we examined these estimates and their associated intervals. We defined "stable use" as the youngest age at which the probability of adaptive grasp is equal to or exceeds 0.75. To ensure confidence in this classification, we require the lower bound of the 89% Equi-tailed Interval (ETI) to be equal to or greater than 0.75. Accordingly, the probability of infants at this age or older using an adaptive grasp can be considered to be at least 75% with a 89% level of certainty. This indicates that there is a high degree of confidence in the consistency of adaptive grasping strategies employed by infants who have reached this age.

Gradual increase in performance. To determine whether our model's estimated β coefficients captured an accurate gradual increase in adaptive grasp probability—or instead reflected an abrupt step-like shift—we conducted a comparative analysis using simulated data. To that end, we generated simulated datasets representing abrupt changes in grasping strategy. For each participant and tool, we randomly assigned an age at which the grasp strategy abruptly switched from non-adaptive to adaptive, creating a stepwise function. We then applied our original model to these simulated datasets and extracted the resulting beta coefficients. This simulation process was repeated 1000 times to account for variability in the randomly assigned switch points. This yielded a distribution of beta coefficients representing stepwise changes in our data.

We then compared this simulated distribution to the beta coefficients obtained from our original model. If the two distributions did not overlap within an 89% credible interval, we could conclude that our actual data demonstrated a gradual development of adaptive grip, rather than a sudden shift in strategy. To optimize the computational efficiency, we employed frequentist statistics using the lme4 package (Bates et al., 2015).

Results

Infants learn to plan adaptively with spoons

Infants were presented with four different tools, each having a unique function, with the handles switching proximity to the right and left hands. If participants were to consistently use one hand, or switched indiscriminately between right and left hands while maintaining a conventional overhand grip, the baseline probability of 0.5 would accurately reflect the chance level for an adaptive radial grip (see Fig. 1). This chance level provides a crucial reference point for interpreting the observed developmental trajectories.

The Bayesian logistic mixed-effects model showed that infants were more likely to choose the adaptive grip when grasping the spoon (Fig. 3; $\beta = 1.04$, 89% CI [0.84, 1.25]), but not when grasping the brush, magnet, or hammer. Post-hoc contrasts confirmed that use of an adaptive grip in spoon trials was different from all other tools, showing higher odds of adaptive grasp compared to the hammer (*Difference* = 0.83, 89% CI [0.68, 0.98]), brush (*Difference* = 0.94, 89% CI [0.78, 1.11]), and magnet (*Difference* = 0.94, 89% CI [0.80, 1.08]).

Infants learned to adapt to the handle's changing orientation with age, but only with the spoon. In our Bayesian logistic mixed-effects model, the Spoon × Age interaction was positive ($\beta = 0.34$, 89% CI [0.14, 0.54]), indicating that, across infants, the probability of an adaptive grip increased with age for the spoon, whereas brush, hammer, and magnet showed no age-related change. Accordingly, Fig. 3B–E shows rising trajectories for spoon trials, with other tools remaining flat. The hierarchical, trial-level analysis (with partial pooling) also reveals substantial between-infant heterogeneity: a few infants started above 0.5 and stayed stable (early competence), while others showed age-related gains that crossed 0.5 later. This modelling framework naturally accommodates unequal trial numbers across sessions and infants.

Follow-up analysis using marginal effects confirmed an interaction with age only for the spoon (*Coefficient* = 0.46, 89% CI [0.32, 0.61]), whereas interactions for the hammer (*Coefficient* = 0.04, 89% CI [-0.11, 0.19]), brush (*Coefficient* = -0.03, 89% CI [-0.21, 0.15]), and magnet (*Coefficient* = -0.02, 89% CI [-0.16, 0.12]) were not present. Finally, marginal effects extracted over age for each tool and infant confirmed that every infant showed a positive beta coefficient over age when using the spoon (Fig. 3F; *Mean Coefficient* = 0.46, *Mean* 89% CI [0.27, 0.66]). However, the coefficient was not significantly different from zero when using the brush (Mean *Mean Coefficient* = -0.03, *Mean* 89% CI [-0.25, 0.19]), hammer (*Mean Coefficient* = 0.03, *Mean* 89% CI [-0.16, 0.24]), or magnet (*Mean Coefficient* = -0.02, *Mean* 89% CI [-0.21, 0.17]). These findings demonstrate that every infant in the study learned to adaptively grasp with the spoon, but showed no consistent improvement in adaptive grasping for the other tools over the observed age range.

Infants learn to plan adaptively when using spoons towards themselves

Two tools, a spoon and a hairbrush, afforded infants with parallel actions toward their own body and toward another object, specifically a stuffed animal puppet. Using a Bayesian logistic mixed-effects model (see Methods), we found a robust interaction between the action target (self/other) and tool type (spoon/brush; β = 0.77, 89% CI [0.35, 1.19]). Contrast analysis showed that using the spoon for self-directed actions had higher odds of adaptive grip compared to using the spoon for other-directed actions (*Difference* = 0.90, 89% CI [0.70, 1.11]). Moreover, self-directed spoon use demonstrated higher odds of adaptive grip compared to the brush for both self-directed (*Difference* = 1.04, 89% CI [0.85, 1.23]) and other-directed actions (*Difference* = 0.89, 89% CI [0.70, 1.08]; See

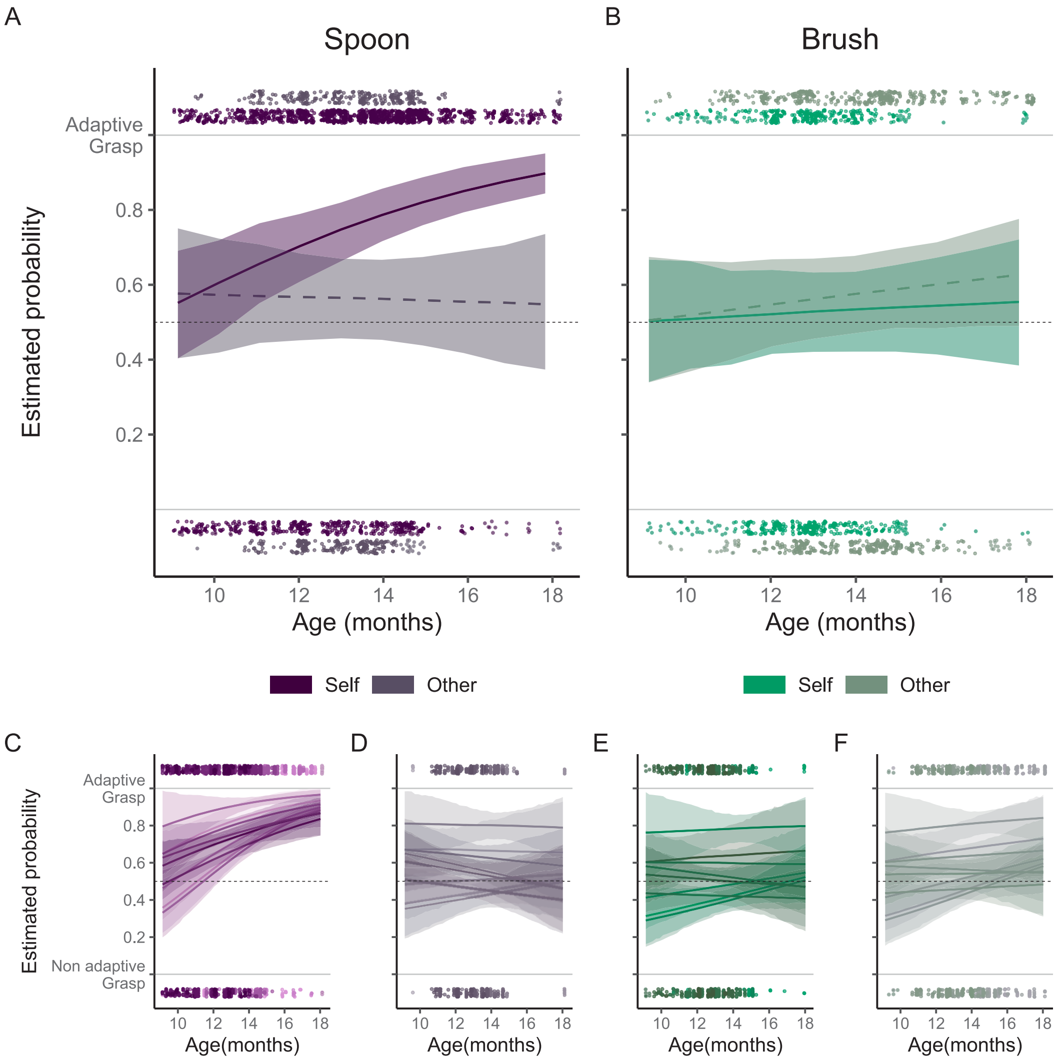

Fig. 4. Effect of the target action on the probability of adaptive grasp. (A–B) Posterior predicted probability of an adaptive grasp over age (months) for targets self and other when using the Spoon (A) and Brush (B), from the same hierarchical Bayesian model (1 + Age | ID). Lines are trial-level model predictions with 89% credible intervals; the dashed 0.5 line indicates chance. (C–F) Infant-level trajectories for each tool × target: (C) Spoon–self, (D) Spoon–other, (E) Brush–self, (F) Brush–other. Each line is an infant's posterior prediction; values > 0.5 indicate a higher likelihood of an adaptive grasp at that age. Shaded bands are 89% credible intervals. Dots above and below the curves show raw trial outcomes.

Fig. 4).

The model also revealed an interaction between age and adaptive grip with the spoon when the target was self-directed (β = 0.51, 89% CI [0.04, 0.96]). Such interaction suggests that the development of adaptive grip for the spoon increased with age, specifically when infants were using the spoon to feed themselves and not when the spoon was other-directed ('feeding' the puppet).

Follow-up analysis using marginal effects supported this interpretation. An interaction was confirmed only for the spoon when actions were self-directed (*Coefficient* = 0.44, 89% CI [0.25, 0.63]), whereas no interactions were found for the spoon with other-directed actions (*Coefficient* = -0.03, 89% CI [-0.30, 0.26]), or for the brush with self-directed (*Coefficient* = 0.05, 89% CI [-0.19, 0.30]) or other-directed actions (*Coefficient* = 0.11, 89% CI [-0.11, 0.33]).

Tool orientation affects adaptive planning

When testing the effect of tool orientation in our analyses, both models revealed that infants were consistently more likely to perform adaptive grips when tools were presented with the handle to the right compared to the handle to the left. This effect was strong in both the tool effects model (β = 0.85, 89% CI [0.64, 1.06]) and the action target model (β = 0.89, 89% CI [0.59, 1.19]).

In the tool effects model (Fig. 5A), we found that tool orientation affected adaptive grip differently across tools. When tools were presented in the handle-right orientation, infants showed more adaptive grips with the spoon compared to the hammer (*Difference* = 0.64, 89% CI [0.42, 0.86]), brush (*Difference* = 0.96, 89% CI [0.72, 1.20]), and magnet (*Difference* = 0.92, 89% CI [0.73, 1.13]). This advantage persisted even in the more difficult handle-left orientation, where the spoon maintained higher odds of adaptive grip compared to the hammer (*Difference* = 1.02, 89% CI [0.83, 1.23]), brush (*Difference* = 0.93, 89% CI [0.68, 1.17]), and magnet (*Difference* = 0.95, 89% CI [0.76, 1.14]). In the handle-right condition, infants also showed more adaptive grips with the hammer compared to both the brush (*Difference* = 0.32, 89% CI [0.08, 0.55]) and magnet (*Difference* = 0.28, 89% CI [0.09, 0.48]).

The second model, focusing on action target effects was limited to spoon and brush (Fig. 5B). It revealed a significant interaction between tool type and presentation direction (β = -0.62, 89% CI [-1.07, −0.19]). In this model, the spoon maintained its advantage over the brush regardless of orientation, showing higher odds of adaptive grip in handle-right (*Difference* = -0.34, 89% CI [-0.55, −0.13]) and handle-left conditions (*Difference* = -0.69, 89% CI [-0.89, −0.49]).

Finally, neither model showed interactions between tool direction and age or action target, suggesting that the advantage of handle-right tool orientation remained consistent across development and different action contexts.

Infants gradually learn to plan adaptively

By using the fitted Bayesian model per tool, we were able to estimate the age at which infants begin to consistently use adaptive grips, focusing on spoon manipulation. Our model estimates that infants reliably adopt an adaptive grip for spoons from approximately 15.6 months (68 weeks) onward (Fig. 6A). At this age, the probability of adaptive grip use reaches a high level of stability (M = 0.82, 89% CI [0.75, 0.9]). This suggests a high degree of confidence in the emergence of adaptive planning strategies for spoons around this developmental time point.

Next, we determined whether the development of adaptive planning followed a gradual progression or a sudden, stepwise change. To that end, we compared the estimated beta coefficients from our observed data model for each tool against the distribution of beta coefficients obtained from simulating stepwise changes in grasping. For all tools, the distributions of beta coefficients from our observed data model and the simulated stepwise changes did not overlap within the 89% credible intervals (Fig. 6B). Specifically: for the spoon, the observed data estimates (89% CI [0.9, 1.43]) were distinctly lower than the simulated stepwise changes (89% CI [2.20,

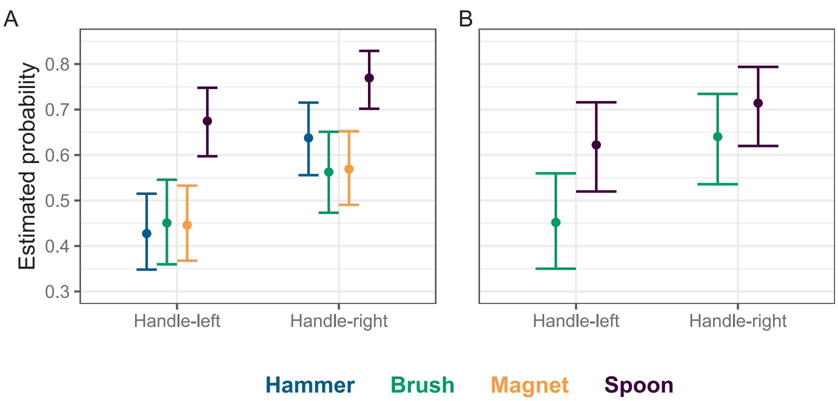

Fig. 5. Effect of tool direction on the probability of adaptive grasp: Estimated mean probability of adaptive grasp as a function of tool direction (handle-left, handle-right) for both run models. (A) Results from the model run to explore the effect of tools on adaptive grasp, showing probability estimates for all four tools (hammer, brush, magnet, and spoon). (B) Results from the model run to explore action target effects, showing probability estimates for only self-directed actions with the brush and spoon. In both panels, dots represent the estimated mean and error bars indicate 89% credible intervals.

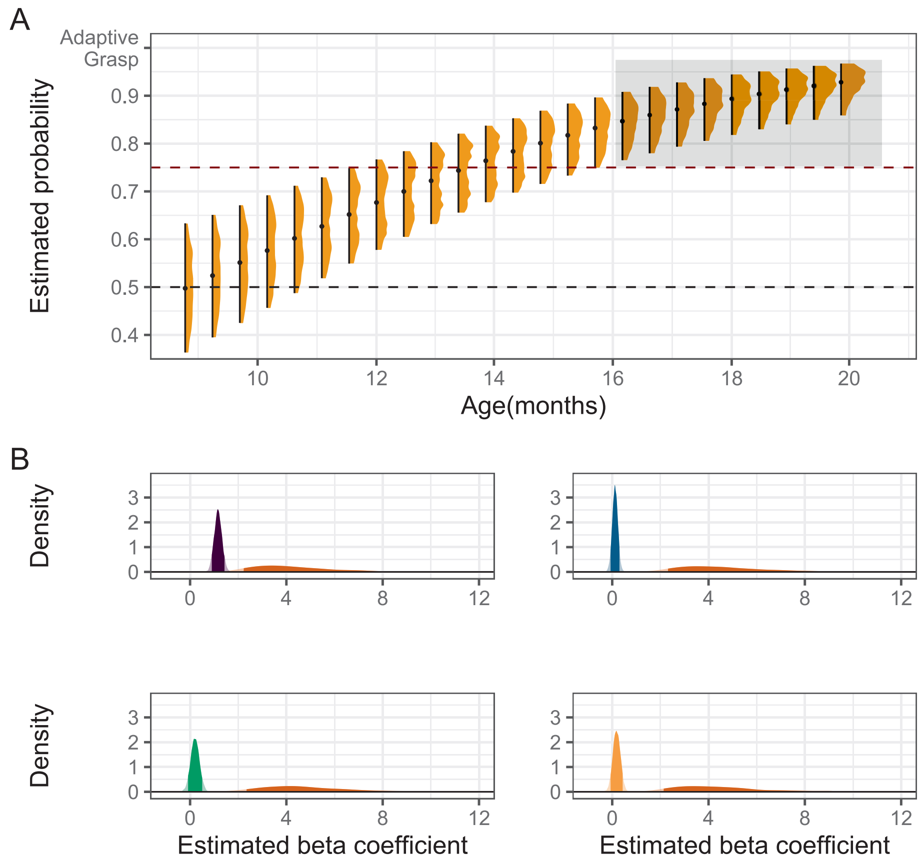

Fig. 6. Development of adaptive grasping strategies in infants. (A) Estimated probability of adaptive grasp for spoons as a function of age. Predictions extend beyond the observed data range (9–18 months) to identify when stability emerges. The black dots represents the mean probability, with error bars indicating the 89% Equi-tailed Interval (ETI). The dashed red line at 0.75 probability indicates the threshold for consistent adaptive grasp. The dashed black line at 0.5 probability represents chance level. The shaded area highlights the age range when infants consistently demonstrate adaptive grasping (lower bound of 89% ETI exceeds 0.75 probability). (B) Comparison of estimated beta coefficients from observed data (coloured distributions) and simulated stepwise changes (orange distributions) for each tool. Non-overlapping distributions, where the shaded areas fall outside of the 89% ETI, indicate gradual development rather than sudden shifts in adaptive grasping strategies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

8.92]). Similar non-overlapping patterns were observed for the brush (Observed: [-0.08, 0.5], Simulation: [2.35, 9.38]), hammer (Observed: [-0.07, 0.30], Simulation: [2.36, 10.22]), and magnet (Observed: [-0.07, 0.30], Simulation: [2.29, 9.30]). Taken together, the non-overlapping credible intervals suggest that the development of adaptive planning strategies for all tools follows a gradual trajectory rather than occurring as a sudden shift.

Finally, we verified that session attendance did not drive our results. Therefore, we conducted a post-hoc test examining the number of sessions to each infant's slope deviation (their deviation from the population age effect) in the tool-effects and target-direction models. We found no systematic association ($r = 0.41$, 95% CI [–0.35, 0.84], $p = .270$ and $r = 0.30$, 95% CI [–0.45, 0.81], $p = .427$, respectively). Therefore, infants with fewer sessions (e.g., Participants 1 and 4) did not show different developmental patterns from those with more sessions.

Discussion

In this longitudinal study, we tested the emergence of planning skills in early infancy by observing longitudinally how infants learned to grasp four different tools—spoon, brush, hammer, and magnet—over multiple weeks of testing. Planning for tool use was assessed by whether infants adjusted which hand they reached with, depending on tool orientation, to achieve a functional radial grip. Notably, each infant reproduced the cross-sectional pattern from previous work, although the age at which the pattern emerged differed across infants. Infants were most likely to use an adaptive grip with the spoon; performance was better for self-directed than other-directed actions; and there was a robust right-handle advantage consistent with early handedness. These effects emerged in hierarchical trial-level analyses and align with classic demonstrations that planning in tool use is strongest for familiar, well-practiced actions (e.g., self-feeding with a spoon). Beyond replication, the longitudinal testing also revealed how adaptive planning develops: Rather than an abrupt shift, infants exhibited a gradual age-related increase in adaptive grasp probability for the spoon, with substantial between-infant variability. A model contrasting stepwise "insight-like" changes with graded trajectories indicated that the observed slopes are inconsistent with a sudden transition, supporting an incremental, experience-dependent account.

Familiar vs. Unfamiliar tools: The specificity of learning

The superior performance for the spoon could have several, non-mutually exclusive explanations. McCarty, et al. (1999, 2001) speculated that spoons may be the first tool for which infants develop an adaptive grip strategy because of their familiarity and the frequency of self-directed feeding experiences. Parents typically feed infants with spoons from the introduction of solid foods, and infants soon begin to experiment with self-feeding. By the second year of life, many are proficient in using a spoon (Kevin Connolly & Dalgleish, 1989). Our findings, however, emphasize that familiarity with the spoon alone does not guarantee enhanced performance in every task. Skill with the spoon was limited to actions directed toward the body. When the same spoon was presented but the upcoming action was to feed the lion puppet, infants were more challenged. In this context, their grips on the spoon were similar to those with other tools. Therefore, the ability to choose a correct grip rests not only on tool familiarity but also on the anticipated action, highlighting that effective motor planning depends on both the tool and its intended goal.

In addition to its greater familiarity, the spoon also provides particularly salient feedback after it is picked up. If a radial grip delivers food to the mouth whereas an ulnar grip results in food sliding off the spoon, this contrast in outcomes may help explain why the spoon was the only tool to inspire planning for a radial grip. For the other tools, the consequences of action are comparatively less salient. To test the role of dramatic feedback, Claxton, et al. (2009) contrasted the spoon task with a waterwheel, in which infants could make the wheel spin by pouring water onto it. Infants were given a small dipper filled with water, with the handle alternating left and right. When infants picked up the dipper with an ulnar grip, water spilled onto the table. All infants completed both the spoon and waterwheel tasks. The waterwheel elicited a high proportion of radial grips on the dipper (79% of trials), although still fewer than on the self-directed spoon (93%). These findings suggest that salient feedback may play a role in supporting adaptive grip selection, though its relative contribution remains to be determined.

The role of the action target: Self vs. Other

Beyond tool familiarity, the action context itself also influenced planning. In our data, a self–other advantage was evident only for the spoon. This pattern contrasts with McCarty et al. (2001), who reported a self–other difference for both the spoon and the brush. Their evidence came from a cross-sectional design spanning four age groups (9, 14, 19, and 24 months), with the self–other comparison collapsed across ages. By contrast, our longitudinal sample covered a narrower developmental window (mean age range: 10.7–15.4 months), whereas the McCarty et al. results were more heavily influenced by older infants.

One plausible interpretation is that the brush becomes sufficiently familiar—and thus supports a reliable self–other distinction—later in development (e.g., around 19–24 months). In this view, the apparent discrepancy reflects age-related changes in experience with the brush rather than a difference in underlying mechanisms. Overall, our longitudinal findings suggest that the emergence of self–other effects depends jointly on the tool/task context and the child's developmental stage.

Handedness constraints on adaptive planning

A third factor influencing adaptive grip selection was handedness. Infants tended to act with their dominant hand (McCarty et al., 1999; Michel, 2018), producing a systematic, direction-dependent pattern. When the tool handle was oriented to the right, their default grip typically yielded an adaptive radial grip; when the handle was oriented to the left, the same overhand grip more often resulted in an awkward ulnar grip. Accordingly, on left-orientated handle trials, radial grasps were at chance for all tools–except the self-directed spoon. This right-hand advantage was stable across development and consistent across all tools, replicating the robust handedness effect previously reported in cross-sectional work using this paradigm (Claxton et al., 2009; Keen et al., 2014; McCarty et al., 1999).

Notably, the spoon's superiority extended even to the handle-right orientation (Fig. 5A): where a default right-hand overhand grasp should, in principle, yield an adaptive radial grip regardless of tool, the spoon still elicited more adaptive grips than the brush, hammer, and magnet. Two aspects of the data help interpret this observation. The first is that infants' reaching is not strictly lateralised at these ages: although right-hand use predominates, it is not uniform, so handle-right trials did not automatically produce radial grips across the board. Accordingly, early in the observation window, adaptive-grip rates hovered near chance for all four tools when collapsed across handle direction (Fig. 3). The second is that the orientation effects reported in Fig. 5A reflect estimated means collapsed across the entire age range. Because only the spoon showed age-related gains, the later sessions — when infants had learned to produce a radial grip on the spoon in both orientations — disproportionately elevated its aggregate estimates in both the handle-right and handle-left conditions. In this sense, the handle-right advantage is a general feature of infant reaching that applies across tools, whereas the spoon's superiority in both orientations reflects tool-specific learning confined to this familiar, self-directed action.

Developmental trajectory: Gradual and experience-dependent

Up to this point, our longitudinal findings largely confirm what previous cross-sectional research has established—the advantage of the spoon over other tools, the greater success with self-directed spoon actions, and the consistent preference for right-hand orientations. However, the uniqueness of our longitudinal data allowed us to capture the developmental trajectory of action planning at the individual level and to characterize *how* learning adaptive planning unfolds over time. Mastering the adaptation of grip on a spoon to different orientations was a gradual process. Infants required sustained experience over several weeks to achieve consistent correct grips. There was no sudden 'aha!' moment; instead, weekly sessions showed a mixture of correct and incorrect grips before infants consistently adopted the effective strategy. This gradual progression aligns with findings in older children (Comalli et al., 2016), reinforcing our interpretation that adaptive planning emerges through incremental learning.

Our findings underscore the central role of experience—and, crucially, the nature of that experience—in the development of action planning. Infants' adaptive planning with the spoon indicates that repeated engagement with a familiar tool, used in a consistent and meaningful action context, supports the emergence of prospective control. Learning was highly tool-specific: Improvements in achieving a radial grip were evident for the spoon, but did not generalize to the other implements. The infants did not learn that radial grips on a tool's handle were the most efficient grasps. Rather, they learned that a radial grip on a spoon's handle was the most efficient way to get food to their mouth. Importantly, repeated weekly sessions were insufficient to drive comparable learning for unfamiliar tools. Although infants completed 7–26 sessions (median = 18), providing repeated exposure to all four tools, age-related gains emerged only for the spoon—the tool they use routinely at home for self-feeding. In contrast, performance with the hammer, brush, and magnet did not improve despite equivalent laboratory exposure.

Comalli et al (2016) reported that even at 4 years of age, preschoolers still struggled to adopt a radial grip on a hammer. Using the same handle-orientation paradigm as in our longitudinal study (though with instructions to pound the peg fully flush with the board), they observed significant variability in children's initial grasps. Across a single session of 20 trials, most of the 20 four-year-olds (after exclusions) used a wide range of grips and frequently adjusted mid-trial when an awkward grasp proved inefficient. As with infants learning to use spoons, these findings highlight that successful performance in tool-use tasks often depends on trial-and-error experience with a specific tool and action. This, in turn, raises a broader developmental question: Is early planning best characterized as tool- and context-specific, or does it reflect a more generalized capacity that transfers readily across implements? The gradual, selective improvement we observed points to a strongly experience-dependent account, in which infants' motor planning is shaped by repeated engagement with particular tools in particular action contexts. In this view, planning develops in a context-bound manner rather than unfolding uniformly across situations.

Limitations and conclusion

Our longitudinal approach provides valuable insights into developmental trajectories, yet several limitations are worth considering. Our statistical model, which explored when toddlers consistently adopt adaptive grips extrapolated slightly beyond the observed age range. Such predictions should be interpreted carefully in light of our sample size ($N = 9$) and the individual variability inherent in infant development. While these findings may not be broadly generalizable to all infants, they remain valid and valuable for understanding the developmental patterns within our sample. Importantly, the estimated age for consistent adaptive grip use (approximately 15.6 months) falls within the upper range of our empirical observations (9–18 months), lending further credibility to these estimations. This approach allows us to make data-driven predictions about developmental milestones, though future research with larger samples across broader age ranges would further validate these patterns.

A further consideration is the role of tool properties beyond familiarity and goal salience. Although we minimized confounds by using implements with comparable handle geometry, presenting all tools on the same stand, and analyzing the initial grasp choice at contact (i.e., planning prior to execution), complete standardization of mass, inertia, surface texture, and precision demands was not feasible. We therefore acknowledge that residual physical differences could modulate planning (Bourgeois et al., 2005; Kahrs & Lockman, 2014). Follow-up work could orthogonally manipulate mechanical properties (e.g., mass/inertia, friction) and goal requirements using matched "mock" tools to test their causal contribution to planning, thereby dissociating effects of experience with a tool–goal mapping from those of the tool's biomechanics.

Beyond these statistical and tool properties considerations, it remains challenging to disentangle motor learning from motivational influences. The spoon-to-self condition was the only one in which food was present, providing an immediate and salient consequence of grip choice that the other tool conditions lacked. As a result, our data cannot fully dissociate the contributions of tool familiarity, self-directed action, and food-related feedback in accounting for the spoon-to-self advantage. Claxton et al. (2009) showed that salient but non-food feedback—a spinning waterwheel—can also support adaptive grips in 19-month-olds, but it remains unclear whether comparable effects would emerge at younger ages or with food specifically. Further research is therefore needed to tease apart these contributions. For example, would infants show comparable adaptive grips if asked to offer food on a spoon to the experimenter rather than to themselves?

Moreover, although our data inform manual action planning, caution is warranted in extending these conclusions to other motor domains such as locomotion, where variability in environmental demands and bodily constraints may shape planning differently.

These limitations motivate combining fine-grained longitudinal approaches with broader designs that test generalization across skills and contexts. For example, longitudinal work on other motor behaviors (including locomotion) could determine whether the gradual developmental pattern we observed is specific to manual planning or reflects a more domain-general linkage between motor and cognitive development. More broadly, characterizing incremental, experience-dependent learning in infancy has implications beyond developmental science, offering concrete inspiration for artificial intelligence (AI) and robotic systems that must learn and adapt gradually and in context-sensitive ways.

CRediT authorship contribution statement

Tommaso Ghilardi: Writing – review & editing, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Rachel Keen:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Data curation, Conceptualization. **Emanuelle Benzaquen:** Methodology, Formal analysis. **Ori Ossmy:** Writing – review & editing, Writing – original draft, Supervision, Resources, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the ESRC New Investigator grant ES/W009242/1, Leverhulme Trust research grant RPG-2022-327, and the Birkbeck/Wellcome Trust Institutional Strategic Support Fund to Ori Ossmy.

Data availability

Videos and demographic data are shared with authorized investigators in the Databrary web-based library at databrary.org/volume/1075. The Datavyu video annotation spreadsheets, Datavyu scripts, and processed data are publicly shared at databrary.org/volume/1075.

All analysis scripts are shared in GitHub: https://github.com/Physical-Cognition-Lab/Getting-the-Proper-Grip-A-Longitudinal-Study-of-How-Infants-Learn-to-Adapt-Action-Plans.

References

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R. H. B., Singmann, H., Dai, B., Grothendieck, G., Green, P., & Bolker, M. B. (2015). Package 'lme4. *Convergence, 12*(1), 2.

Bourgeois, K. S., Khawar, A. W., Neal, S. A., & Lockman, J. J. (2005). Infant manual exploration of objects, surfaces, and their interrelations. *Infancy: The Official Journal of the International Society on Infant Studies, 8*(3), 233–252.

Bürkner, P.-C. (2017). brms: An R Package for Bayesian Multilevel Models using Stan. *Journal of Statistical Software, 80*(1), 1–28.

Buttelmann, D., Carpenter, M., Call, J., & Tomasello, M. (2008). Rational tool use and tool choice in human infants and great apes. *Child Development, 79*(3), 609–626.

Claxton, L. J., McCarty, M. E., & Keen, R. (2009). Self-directed action affects planning in tool-use tasks with toddlers. *Infant Behavior & Development, 32*(2), 230–233.

Comalli, D. M., Keen, R., Abraham, E. S., Foo, V. J., Lee, M.-H., & Adolph, K. E. (2016). The development of tool use: Planning for end-state comfort. *Developmental Psychology, 52*(11), 1878–1892.

Connolly, K., & Dalgleish, M. (1989). The emergence of a tool-using skill in infancy. *Developmental Psychology, 25*(6), 894–912.

Connolly, K., & Dalgleish, M. (1993). Individual patterns of tool use by infants. In A. F. Kalverboer, B. Hopkins, & R. Geuze (Eds.), *Motor Development in Early and Later Childhood* (pp. 174–204). Cambridge University Press.

Cowie, D., Smith, L., Braddick, O., Atkinson, J., & Nardini, M. (2006). The development of visually guided locomotor planning. *Cognitive Processing, 7*, 123.

Gerson, S. A., Burdett, E., & Beck, S. R. (2018). *Preschoolers use analogy to facilitate innovative problem-solving.* CogSci.

Kahrs, B. A., & Lockman, J. J. (2014). Building tool use from object manipulation: A perception-action perspective. *Ecological Psychology, 26*, 88–97.

Keen, R. (2011). The development of problem solving in young children: A critical cognitive skill. *Annual Review of Psychology, 62*(1), 1–21.

Keen, R., Lee, M.-H., & Adolph, K. (2014). Planning an action: A developmental progression in tool use. *Ecological Psychology: A Publication of the International Society for Ecological Psychology, 26*(1–2), 98–108.

R.V. Lenth emmeans: Estimated Marginal Means, aka Least-Squares Means 2024 https://rvlenth.github.io/emmeans/.

Lockman, J. J. (2000). A perception-action perspective on tool use development. *Child Development, 71*, 137–144.

Lockman, J. J., Ashmead, D. H., & Bushnell, E. W. (1984). The development of anticipatory hand orientation during infancy. *Journal of Experimental Child Psychology, 37*, 176–186.

Lockman, J. J., & Kahrs, B. A. (2017). New insights into the development of human tool use. *Current Directions in Psychological Science, 26*, 330–334.

Lockman, J. J., & McHale, J. P. (1989). Object manipulation in infancy: Developmental and contextual determinants. In J. J. Lockman, & N. L. Hazen (Eds.), *Action in social context: Perspectives on early development* (pp. 129–167). Plenum.

Makowski, D., Ben-Shachar, M. S., Patil, I., & Lüdecke, D. (2020). *Estimation of Model-Based Predictions, Contrasts and Means*. CRAN.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: The emergence of an action plan. *Developmental Psychology, 35*(4), 1091–1101.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. *Infancy, 2*, 233–256.

McElreath, R. (2018). *Statistical rethinking.* Chapman & Hall/CRC.

Michel, G. F. (2018). Development of infant handedness. In *Conceptions of development* (pp. 165–186). Psychology Press.

Monroy, C. D., Gerson, S. A., & Hunnius, S. (2017). Toddlers' action prediction: Statistical learning of continuous action sequences. *Journal of Experimental Child Psychology, 157*, 14–28.

Ossmy, O., & Adolph, K. E. (2020). Real-Time Assembly of Coordination patterns in Human infants. *Current Biology: CB, 30*(23), 4553–4562.e4.

Ossmy, O., Han, D., Cheng, M., Kaplan, B. E., & Adolph, K. E. (2020). Look before you fit: The real-time planning cascade in children and adults. *Journal of Experimental Child Psychology, 189*(104696), Article 104696.

Ossmy, O., Kaplan, B. E., Han, D., Xu, M., Bianco, C., Mukamel, R., & Adolph, K. E. (2022). Real-time processes in the development of action planning. *Current Biology: CB, 32*(1), 190–199.e3.

Rosenbaum, D. A., Chapman, K. M., Weigelt, M., Weiss, D. J., & van der Wel, R. (2012). Cognition, action, and object manipulation. *Psychological Bulletin, 138*, 924–946.

Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J., & Jorgensen, M. (1990). Constraints for action selection: Overhand versus underhand grips. In M. Jeannerod (Ed.), *Attention and Performance XIII: Motor representation and control* (pp. 321–342). Lawrence Erlbaum Associates.

Rosenbaum, D. A., van Heugten, C., & Caldwell, G. (1996). From cognition to biomechanics and back: The end-state comfort effect and the middle-is-faster effect. *Acta Psychologica, 94*, 59–85.

Willats, P. (1989). Development of problem-solving in infancy. In A. Slater, & G. Bremner (Eds.), *Infant development*. Erlbaum.

Wunsch, K., Henning, A., Aschersleben, G., & Weigelt, M. (2013). A Systematic Review of the End-State Comfort effect in Normally developing Children and in Children with Developmental Disorders. *Journal of Motor Learning and Development, 1*(3), 59–76.