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Planning an Action: A Developmental Progression in Tool Use

Rachel Keen,

Department of Psychology, University of Virginia

Mei-Hua Lee, and

Department of Psychology, New York University

Karen Adolph

Department of Psychology, New York University

Abstract

How children pick up a tool reveals their ability to plan an action with the end goal in mind. When presented with a spoon whose handle points away from their dominant hand, children between infancy and 8 years of age progress from using an awkward ulnar grip that causes food to spill from the spoon to consistently using a radial grip. At 4 years of age children's grip strategies are highly variable, including the awkward grips of infancy and use of the non-dominant hand, but they also employ adult-like grips never seen in infancy. By 8 years of age the infantile ulnar grip has completely disappeared and is replaced by more mature and effective grips that indicates better planning for the end goal.

Learning to control arms, hands, and fingers to accomplish a goal is the basis of manual action. Reaching an arm out toward a desired object and shaping the hand and fingers to grasp is one of the great accomplishments of infancy, and coordinating a sequence of manual actions to use a tool is one of the premiere achievements of the toddler period. Even the simplest manual actions are psychologically complex. Reaching and grasping entail much more than motor control over joints and muscles. Perception, motivation, and goal orientation are intimately involved. Manual actions become more complex in the second year of life as toddlers become capable of fine finger control and more cognitively demanding sequential actions. The toddler begins to express this greater complexity by using tools such as spoons, toy hammers, and rakes to achieve less immediate goals. Tool use offers the researcher an ideal way to study action planning because successful sequences, errors in grip strategy, and subsequent corrections reveal a developmental progression in infants' action plans (Keen, 2011). Such behaviors are readily observable and have enabled researchers to outline the planning process for learning to grasp tools in different orientations (McCarty, Clifton, & Collard, 1999; McCarty, Clifton, & Collard, 2001), for retrieving an object with a rake or cane (Chen & Siegler, 2000; Rat-Fischer, O'Regan, & Fagard, 2012; Smitsman & Cox, 2008), and for self-feeding with a spoon (Connolly & Dalgleish, 1989).

This paper focuses on how children learn to pick up a spoon with the most efficient, successful grip. Previous work established a distinct progression in action planning from around 9 to 24 months of age (McCarty et al., 1999; 2001), but several questions remain that will be addressed here with new data. The basic procedure McCarty et al used with infants and toddlers was to present them with a spoon loaded with food, and to encourage them to pick it up and eat. The spoon was presented horizontal to the child's body, with the handle pointing right or left in alternating orientations. The handle to the right side was considered the "easy" orientation because for a right-handed person, a normal overhand reach with the right hand results in a radial grip, defined as the thumb pointed toward the action end of the spoon. With such a grip, the bowl of the spoon can be brought directly to the mouth. The majority of the adult population is right-handed, with this tendency evident even in infants (Fagard & Lockman, 2005; Ramsay, 1980). Indeed, with the spoon in the easy orientation, the default reach from 9 to 24 months of age was an overhand (palm down), right hand reach (Figure 1, panel A). Thus, even 9-month-olds achieve a radial grip in the easy orientation.

The more interesting orientation is with the handle to the left. McCarty et al (1999, 2001) considered this the "difficult" orientation because—rather than using the default radial grip with the right hand—children must plan their hand selection and/or hand orientation to achieve a radial grip. If they reach out as usual with the right hand, palm down, then an ulnar grip results with the bowl end laden with food sticking out of the ulnar side of the hand (Figure 1, panel B). With this awkward grip, the food is likely to spill as infants carry the spoon to the mouth. Two choices for a radial grip are possible when the handle is to the left: an overhand grip with the left hand, or an underhand grip with the right hand (Figure 1, panel C for display of the latter). The difficulty with the former is inhibition of the dominant right hand whereas the difficulty with the latter is that it seems absent from the infants' and toddlers' repertoire. Not until around 19 months of age did the majority of infants achieve consistent radial grips in this condition. They used their left hand with an overhand grip. Not once did McCarty et al (1999; 2001) observe an underhand grip, despite placing the spoon on a holder that elevated it above the table's surface to allow infants to fit their hand easily under the handle. In contrast, the solution most adults choose when faced with a similar problem is a right-handed reach with an underhand radial grip (Rosenbaum, Marchak, Barnes, Vaughn, Slotka, & Jorgenson, 1990). Thus, the first question remaining from previous work is when children begin to use the underhand grip with the dominant hand.

A second question concerns differences in planning a reach that brings the tool back to the body or ends elsewhere. McCarty et al. (2001) enlarged the selection of tools presented to 9- to 24-month-old infants (hammer, magnet, and hairbrush in addition to spoon). The hammer and magnet were always directed toward another object, but both spoon and hairbrush could have action directed toward the self (eat food, brush hair) or toward another object ("feed" puppet, brush puppet's hair). Infants were tested on all tools, and for self- and other-directed actions with the spoon and hairbrush. In every case, the tool's handle was alternated between left and right orientations. Beginning at 14 months and increasing over age, infants used a radial rather than ulnar grip on a higher percentage of trials for self- than for other-directed tasks. This difference in action planning held for both spoon and hairbrush, with no difference between them for overall number of radial grips. All other-directed grips were

similar regardless of tool: Spoon and hairbrush as well as magnet and hammer elicited more ulnar grips when directed toward other objects (Figure 2).

The authors' explanation for the self-other difference was that planning is privileged for a self-directed action compared to object-to-object actions (McCarty et al., 2001). Why should this be so? In a variety of tasks, previous research shows that infants have better spatial skills when orienting their own body to an object compared to relating one object to another (Acredolo, 1978; Bremner & Bryant, 1977; Lockman & Ashmead, 1983; Rochat, 1998). Better planning for future self-directed actions may be an extension into toddlerhood of this early self-referent system, perhaps similar to Piaget's (1952) notion of the young infant's egocentric coding of spatial relations.

But before devising elaborate theoretical explanations for the superior planning of self-directed action, alternative reasons must be addressed. In discussing their results, several possibilities were raised by McCarty et al (2001). Could infants' familiarity with the spoon be the cause of superior planning of self-oriented grips? Unlikely, because the less familiar hairbrush showed the same self-other difference. Other differences between the two conditions, however, cannot be so easily discounted. For example, only the spoon for self-feeding had food on it, and the food was likely to spill when infants tried to bring it to the mouth with an ulnar grip. Moreover, the goal state for self-feeding was clear: Food arrived in the mouth. In the 2001 study, feeding a puppet with an empty spoon had no obvious change in end state and no food ever spilled from an ulnar grip. However, end state is also unlikely to be the cause of differences in planning actions toward self and other. Claxton, McCarty, and Keen (2009) devised an other-directed action with an explicit goal state, plus negative consequences for an ulnar grip, to encourage better planning of actions directed toward objects. Only 19-month-olds were tested because most children at this age have mastered the radial grip in both orientations of the spoon. The new task featured a toy waterwheel with a small ladle filled with water placed on a holder in front of the child. The ladle's handle was oriented to the right or left, as in the tool presentations of McCarty et al (2001). When water was emptied into a funnel atop the waterwheel, it spun for several seconds to the children's obvious delight. Both tasks had a clear goal with a change in end state and spilled contents from an ulnar grip. The self-other difference remained, with more radial grips when picking up the spoon compared to the ladle with water. This replication and extension to a new task reinforced the finding that toddlers have more difficulty in planning an efficient reach and grasp when the goal involves an object-to-object action.

A final critical issue raised by McCarty et al (2001) but not clarified by Claxton et al (2009) was the difference in spatial location of the goal object for self (i.e., child's mouth) and goal object for other (puppet or waterwheel placed opposite the child). From early infancy, objects are picked up and typically brought back toward the body for visual inspection or mouthing. These highly practiced arm movements may be responsible for the self-other difference in toddlers' planning. To test the possibility that it is the object's spatial location, not the body itself, that gives an advantage in planning, the external goal object could be located by the child's side or on the lap rather than opposite (McCarty et al., 2001).

Thus, in the current work we addressed several unresolved questions from the earlier spoon studies. How would preschoolers respond if presented with a tool and task similar to that used with toddlers? Would they engage in underhand radial grips with the dominant hand rather than switching to the non-dominant hand? Has the more sophisticated grip appeared in their repertoire and perhaps even dominates? Would the self versus other advantage for planning a radial grip persist into the preschool years, or were toddlers showing a leftover tendency from early infant hand-to-mouth practice? If still present in preschoolers, is the advantage for self-oriented action due to a general arm movement back toward the child's body or could the critical variable be the body itself as endpoint of the action? If the latter is true, then the self versus object difference should persist if the external goal object (e.g., puppet) was placed just in front of the child's torso. But if the advantage of self-directed action is due simply to the highly practiced arm movement back toward the body, a puppet on the lap should show the same advantage as when food is going into the child's own mouth.

We tested 18 4-year-olds ($M = 4.06$ years, $SD = 0.11$ years, 12 girls) feeding themselves with a spoon, feeding a puppet on their lap, and feeding a puppet held opposite them (Figure 3). The spoon had the same food for the puppet (Cheerios) as for the child, so consequences for spills were the same. The end state of the action was also definite and visible: Cheerios were deposited into the puppet's mouth and disappeared. For comparison with the preschoolers, we tested 11 8-year-olds ($M = 8.22$ years, $SD = 0.32$ years, 6 girls) because their choice of grips was expected to approach that of adults. All of the children were right-handed based on parents' report of the hand children used to hold a toothbrush, self-feed with a spoon, and cut with scissors. Handedness was confirmed by children's behavior when asked to use a marker and cut with scissors. Data from four children were excluded because they were not right hand dominant (two 4-year-olds and one 8-year-olds were left-handed and one 4-year-olds was ambidextrous).

The procedure with these older children was modeled closely after that with infants and toddlers. The spoon was presented with the handle alternating left and right resting on a holder. The three conditions (self-feeding, puppet opposite, puppet on lap) were presented to every child for 4 trials (2 "easy" and 2 "difficult" orientations) for a total of 12 trials. As with toddlers, in the easy orientation the spoon's handle pointed to the child's right because an overhand radial grip is readily achieved by using the dominant right hand. As expected, the children used the overhand radial grip on 90% of the easy trials. They only used the awkward ulnar grip on 2%. On the remaining 8% of easy trials, children used an adult-like fingertip grip with the spoon resting between the fingers and the thumb (Figure 1, panel D). The difficult orientation was with the handle on the child's left. Only difficult trials were subjected to further analyses because an efficient strategy requires planning of hand choice, orientation (overhand or underhand), and grip (radial or fingertip). Conditions and spoon orientations were counterbalanced across children so that puppet location and spoon orientation changed continually over the 12 trials, which prevented children from falling into stereotyped responses.

Figure 4 shows the percentage of radial and ulnar grip types in the difficult orientation for each condition and age group. Stacked bars designate the percentage of trials when children

made ulnar grips with the right hand, overhand radial grips with the non-dominant left hand, and underhand radial grips with the right hand (note: the bars do not add to 100% because children sometimes used a fingertip grip). To test if the self-other difference persisted in 4-year-olds, the percentage of radial grips (collapsed over underhand and overhand grips) was compared for the three conditions. There was no difference for this comparison at either age, Friedman $\chi^2(2) = 4.67, p = .09$. However, when only left hand-overhand grips were considered, direction of the action made a difference, with a significant effect of condition for 4-year-olds, Friedman $\chi^2(2) = 8.67, p < .05$, and for 8-year-olds, Friedman $\chi^2(2) = 7.60, p < .05$. Like the toddlers, 4-year-olds used the left hand to achieve a radial grip when self-feeding more frequently than when feeding the puppet on the lap, Wilcoxon $Z = -2.53, p = 0.01$, and when the puppet was opposite, Wilcoxon $Z = -2.12, p = 0.03$. For 8-year-olds, this difference was only significant when the puppet was opposite, Wilcoxon $Z = -2.07, p = 0.04$. Thus, there is a lingering tendency for the self-other distinction at older ages that is not entirely driven by the spatial location of the goal object.

A second question explored in this study was whether preschoolers would engage in an underhand grip with the dominant right hand. The answer is yes; in contrast to toddlers who never used an underhand radial grip in the difficult orientation, 4-year-olds did so occasionally (20% of all trials) spread across all conditions (Figure 4, striped bars). It is not the majority grip in any condition, but sometime between 2 and 4 years of age this more mature grip appears as a solution, allowing the preferred hand to be used in a new action. Like the toddlers, the 4-year-olds favored their left hand in the overhand grip on the largest percentage of trials (42%) despite evidence that they were strongly right-handed. However, 4-year-olds also occasionally made the ulnar grip error (14% of trials), and they did so in every condition, albeit less frequently than do 2-year-olds. This finding is somewhat surprising but illustrates the difficulty in decision-making this motor problem still presents. The photographs in Figure 3 show a child making this error for the puppet at both locations. By 8 years of age, the ulnar grip has completely disappeared.

Here it is useful to examine individual data rather than the group means. Did only a few children discover the more mature underhand grip and use it almost exclusively, or was its use widespread, but infrequently performed by any individual? Did only a few children retain the ulnar grip and this drove the group means in Figure 4? Or were grip strategies highly variable across most children? Figure 5 shows individual data for the 18 4-year-olds (left panel) and the 11 8-year-olds (right panel); stacked bars show the percentage of various grip types pooled over the three conditions. The most striking aspect of the individual data is the variability in how children solved the “difficult” orientation problem. Six of the preschoolers engaged in underhand grips, and two used it almost exclusively. Five 4-year-olds persisted in the toddler-like error of ulnar grips, and two made this awkward grip on every trial. Most children engaged the non-dominant left hand to get a radial grip, just as the successful toddlers had done. But more important, a third of the 4-year-olds had discovered the underhand grip as noted above, and in addition half of the group displayed the adult-like fingertip grip. Eight of the 8-year-olds preferred the fingertip grip above all others. The overhand and underhand radial grips are called power grips because the whole palm grasps the tool’s handle. The fingertip grip is a precision grip, requiring more hand dexterity and

control over individual fingers. Consider how the spoon must be rotated and repositioned before use when picked up with a fingertip grip in the difficult orientation by imagining this action for your own hand. The advantage of the fingertip grip is that it allows finer adjustments and subtler movements, good reasons for why adults prefer it for certain tools. Both fingertip and underhand grips are seen in adults, but the size of the object in relation to hand size probably determines which is used. In studies testing adults' choice of grips, Rosenbaum et al (1990) used bars or cylinders too thick to be picked up with a fingertip grip. Adults resorted to the underhand radial grasp when the action end of the cylinder was on the right (like our difficult orientation). One assumes that adults would use a fingertip grip for small diameter objects like pencils and spoons, but this must be settled by future research.

In conclusion, the 4-year-old has mastered many aspects of tool use since toddlerhood. When picking up a tool, the preschool child displays two new grips, the underhand position and the fingertip grip. However, preschoolers' problem solving in this motor task is still in transition, shown by high inter- and intra-individual variability, and the persistence of the ulnar grip in some children. Better planning for self-directed compared to other-directed action has largely disappeared, suggesting that the dramatic difference found in toddlers results from greater practice during infancy when much hand action is self-directed. Future research may reveal that the self-action advantage is stronger for tools less familiar than the spoon. Learning to use a tool appears to be highly specific in that toddlers' planning is affected by the tool, by its orientation with respect to the body, and where the action is to be directed. With age and practice, children become highly flexible in type of grip and how it is executed. Studying how this flexibility develops is revealing. Immature and awkward motor patterns first dominate, then co-exist, and finally give way to more effective and comfortable patterns. The development of grip strategies appears to be a motor analog to Siegler's (1996, p. 89) "overlapping waves" seen in cognitive development, suggesting this may be a general model for the way development proceeds.

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Figure 1.

Illustrations of the overhand radial (A), overhand ulnar (B), underhand radial (C), and fingertip (D) grips on a spoon. Only (A) and (B) are observed in infants and toddlers. Preschoolers showed two new grips (C and D) that are also seen in adults.

Figure 2.

Percentage of radial grips in each age group for all six tools used in McCarty et al (2001). Note the difference between tools directed toward self (solid symbols) and tool directed toward objects (open symbols). [Reproduced from Figure 3 in McCarty, et al. (2001), *The beginnings of tool use by infants and toddlers*, *Infancy*, 2, pp. 233–256. Copyright 2001 by Lawrence Erlbaum Associates, Inc. Reprinted with permission.]

Figure 3.

Photographs of a 4-year-old in the three conditions of self-feeding, feeding puppet on lap, and feeding puppet opposite. For the trials shown here, the child has grasped the spoon with a radial fingertip grip for self-feeding, but with an ulnar grip for feeding the puppet.

Figure 4.

Average percentage of ulnar and radial grips for the difficult orientation of the spoon for the 3 conditions. Two types of radial grips are shown: the overhand grip with the left hand and the underhand grip with the right hand.

Figure 5.

Grasp strategies for individual children at 4 years (left panel) and 8 years of age (right panel). Each bar represents one child's data. Note the decrease of the awkward ulnar grip and the increase of adult-like fingertip grips in the older children. One 4-year-old used a grip unique from all others—an overhand radial with the right hand coming from behind the object—and thus this child's data do not add to 100%.