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A Perception–Action Perspective on Tool Use Development

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In this essay I argue for a new wave of research on tool use development. Advances in the literature on perception–action development hold important clues for how tool use unfolds in children. These advances suggest that tool use may be a more continuous developmental achievement than has been previously believed. On this view, tool use is rooted in the perception–action routines that infants employ to gain information about their environments. Although tools alter the properties of effector systems, children use tools to explore and change their environments, building on efforts that originate in infancy. Based on this approach, new research directions are suggested, including efforts designed to investigate the processes by which children detect and relate affordances between objects, coordinate spatial frames of reference, and incorporate early-appearing action patterns into instrumental behaviors.

INTRODUCTION

Technology is a defining feature of human culture. The most advanced forms of human technology are rooted in our capacities to fashion the materials of our environment into tools and employ them adaptively in diverse contexts. Clearly, the hammer used by a toddler is far removed from the computer used by a scientist, but in the tool behaviors of young children, one may begin to see the first glimmer of our remarkable technological potential.

The ontogenetic and phylogenetic origins of tool use, however, have been the subject of considerable controversy. Across and within the fields of anthropology, ethology, and psychology, investigators have disagreed about the extent to which tool use is a uniquely human or primate capacity and the kinds of cognitive skills embodied in tool use (K. R. Gibson & Ingold, 1993; Goodall, 1986; Kohler, 1927; Tomasello, 1998; Tomasello & Call, 1997).

Indeed, some researchers have portrayed tool use as primarily a human capacity, requiring a form of representational or relational thinking that is not available to most other creatures. Applied to human ontogenesis, this view suggests that tool use is a later-developing ability, demanding a level of symbolic thinking that is beyond the capacity of most infants during the first year (Bates, 1979). In contrast, other researchers have questioned whether tool use is a capacity that only humans display, pointing out that nonhuman primates and even other animals engage in forms of tool use that were claimed previously to be distinctively human (Beck, 1980; Goodall, 1986; Tomasello, 1998). From a developmental perspective, these types of observations suggest that the first instances of human tool use may occur well before the end of the first year, even in the absence of more advanced representational skills.

In view of these contrasting viewpoints and the accumulating evidence that many forms of tool use may not be a singularly human phenomenon (K. R. Gibson & Ingold, 1993; Tomasello, 1998), I believe that this is an opportune time to take a new look at tool use development. I suggest that advances in our understanding of motor behavior and perception–action coupling (Bertenthal & Clifton, 1998; Goldfield, 1995; Lockman & Thelen, 1993; Thelen & Smith, 1994) provide a valuable new perspective from which to consider tool use in young children. A key implication of this perspective is that tool use is not a discontinuous developmental achievement requiring a new level of representational thinking, as some have maintained. Instead, I argue, the origins of tool use in humans can be found during much of the first year of life, in the perception–action routines that infants repeatedly display as they explore their environments. In making this argument, I also suggest how conceptualizing tool use as a problem of action development can inform our understanding of the development of other psychological processes (e.g., coordinating spatial frames of reference) not typically associated with tool use.

DEVELOPMENTAL APPROACHES TO TOOL USE

During the second year, if not before, human children begin to employ the tools of their culture during their daily activities. Such tool use takes varied forms. In Western societies, young children may hold a spoon to transport food to their mouths (Connolly & Dalgleish, 1989; McCarty, Clifton, & Collard, 1999), grasp a crayon to scribble marks on a page (Gardner, 1980; Golomb, 1989; Goodnow, 1977; Kellogg, 1969),

or clutch a hammer to pound an object into a surface (Gesell, 1940).

Although children practice behaviors like these over long stretches of developmental time, the research literature on tool use leads to a very different type of psychological picture. In much of this literature, tool use has been treated as some sort of cognitive advance involving insight. A chimp or child is said to induce, often suddenly, how an object may be employed in a novel relational way to achieve a goal (e.g., see Kohler, 1927). Underlying this view is the premise that tool use requires a cognitive leap beyond information that is immediately given. Developmentally, a cognitive leap is implicated as well, involving the capacity to engage in a new form of symbolic or relational thinking. For instance, Bates (1979) has argued that mature tool use requires the ability to engage in a type of representational means–end analysis, involving the mental substitution of one means for another.

Likewise, in accounts that emphasize the social transmission of various cognitive skills (Rogoff, 1990; Vygotsky, 1978), caregivers are said to bridge gaps in children's current cognitive abilities before children develop the ability to use particular tools on their own. Here, too, tool use is predicated on a cognitive leap of some sort, one that is negotiated by caregivers, who may supply information that is not immediately available in the environment.

In contrast to these depictions of tool use as either a discontinuous developmental achievement and/or a product of insight based on advances in representational processes, I will begin to outline a view of tool use development with a different emphasis. I suggest that there is much to be gained by viewing tool use as an extension of the perception–action coupling that infants begin to evidence in the first year of life. Indeed, this view of tool use has several important implications.

First, it implies that the development of tool use may not be as abrupt an acquisition as it is typically portrayed to be. Instead, tool use development may entail a more continuous and gradual process of discovery and exploration, not entirely dependent on some newly emerging form of relational or representational reasoning. On this view, variability considered in real and developmental time at the *within-subject* level can provide clues about the processes of exploration and discovery that underlie the achievement of tool use. In this connection, the trial and error behaviors that often precede early instances of successful tool use should not necessarily be considered evidence of cognitive gaps or deficiencies. These behaviors may better be considered as exploratory attempts, affording opportunities for perceptual learning. Accordingly, trial and error behaviors and the variability in performance associated with them need to be scrutinized for what they may reveal about how children learn to use tools (see also Siegler, 1996; Thelen & Smith, 1994, for related discussions about variability in other developmental realms).

Second, and in keeping with the notion that tool use and insight do not suddenly appear but emerge more gradually over developmental time, I contend that tool use may arise from infants' instrumental attempts to relate objects to other objects and surfaces in the world. This involves detecting affordances that may exist between objects or object parts, based on information that is directly perceptible. In this connection, it is known that infants under a year of age are adept at detecting objects' manual affordances. For instance, before 9 months, infants finger textured surfaces more than smooth ones or bang hard objects more than soft ones, presumably to produce noise (Bushnell & Boudreau, 1993; E. J. Gibson & Walker, 1984; Lockman & McHale, 1989; Palmer, 1989; Ruff, 1984). I suggest, however, that tool use involves a different type of affordance detection problem (see also Smitsman, 1997). In tool use, the task is to detect affordances not of individual objects, but of relations that may exist between objects or object parts. As I hope to show, analysis of the problem of (1) detecting potential affordances between objects and (2) establishing these relations may help us understand the psychological achievement entailed by tool use.

Finally, I suggest that a perception–action perspective on tool use development directs us to consider the act of tool use or *tool using.* More specifically, I argue that we have not paid enough attention to the actions that young children employ when they learn to use tools. Instead, the focus has often been on insight: whether the child selects a novel but appropriate tool in an unfamiliar experimental situation (e.g., see Brown, 1990). In contrast, I propose that a new focus on the actions that young children exhibit while using the common tools of their cultures may reveal whether these actions are similar or even identical to those used by infants throughout the first year when they explore objects or surfaces in their environments. Consideration of such a possibility may lead to additional insights about the developmental and even evolutionary origins of tool use.

MODAL AND VARIABILITY ACCOUNTS OF TOOL USE DEVELOPMENT

In most psychological research on tool use development, investigators have tried to determine the earliest ages at which children can infer that some object may serve as a tool in a novel task situation. In a re-

lated vein, investigators have asked at what developmental point can children induce that an object may be employed as a tool under different levels of environmental support—as a function, for instance, of various distances between a tool and a goal (Bates, 1979; Brown, 1990). These types of efforts are motivated largely by modal concerns, that is, establishing the age norms at which tool use or insight occurs. Similarly, in the motor development literature relating to tool use, researchers have mainly considered modal issues, describing year-by-year and sometimes month-by-month changes in the grip forms that children display (Connolly & Elliott, 1972; Gesell, 1940).

These efforts are clearly informative. Nevertheless, they do not directly address the processes by which individual children come to use tools effectively. Moreover, they may contribute to the impression that tool use is an all-or-nothing proposition—that at a given age and/or under specific environmental conditions, children will evidence insight, engage in tool use, and grip a tool only in a certain way.

More recently, however, the results of a number of studies on early tool use indicate that this modal caricature may misrepresent the way individual development proceeds. In a longitudinal study on early spoon use, Connolly and Dalgleish (1993) reported that individual infants show considerable variability in how they hold a spoon at a given age before they begin to use one type of grip predominantly, early in the second year. Likewise, Greer and Lockman (1998) recently found substantial within-subject variability in the ways 3-year-old children gripped a writing instrument and oriented it in relation to a page. For instance, in some cases individual children displayed a so-called adult grip during one trial and more of a clutch-hold in the next.

What is the significance of this type of within-subject variability? Although I have cited examples with only two types of tools, I suspect that such variability is less the exception than the rule. Moreover, this type of variability does not necessarily indicate that the skill of tool use is immature or that children are engaging in unproductive trial and error behaviors. Tools change the properties of the hands or arms or, more generally, the manual effector system. Based on the lessons learned from a dynamic systems approach to motor development (Thelen & Smith, 1994; Thelen & Ulrich, 1991), I suggest that children may be exploring forms of tool use that promote stability and efficiency, enabling them to meet task demands in an adaptive manner. Trying out different grips or ways of using a tool may provide children with self-generated opportunities to master the act of using a particular tool (see also Sporns & Edelman, 1993). On this view, trial and error behaviors should not necessarily be considered as fruitless attempts to solve a problem or as a lack of insight. Instead, these types of behaviors need to be examined carefully for what they might reveal about the processes by which children learn to use tools.

For this to occur, we need to think more in terms of variability than in terms of mean scores. In particular, we need to look to variability at the within-subject level as a potentially rich source of information and not simply as empirical or methodological noise. For instance, in the aforementioned study on graphic ability, Greer & Lockman (1998) employed a multivariate method to assess within-subject variability under a number of different but routine writing conditions (e.g., writing with a thin or thick pen at different locations on a page). More generally, particular patterns of within-subject variability may provide clues regarding the points at which children are about to attain increasingly stable forms of tool use or where developmental transitions are beginning to occur (see Thelen, 1989). Moreover, research efforts that focus on within-subject variability may provide insights into the kinds of developmental accounts—modal or otherwise—that are most appropriate for characterizing the emergence of tool use in young children.

DETECTING AND RELATING AFFORDANCES

As noted, tools change the properties of the effector systems. These changes in turn alter the possibilities for action in the environment (Smitsman, 1997). Such new ways of acting on the world, however, may pose special challenges for infants. After all, infants in the second half-year have become quite skilled at controlling their hands and fingers to detect the manual affordances of surfaces and objects around them (Bushnell & Boudreau, 1993; Lockman & McHale, 1989; Palmer, 1989; Ruff, 1984). But with increasing exposure to tools, infants may discover that their usual hand and finger movements have different consequences on the world. Put another way, new affordances have been introduced. How may the development of tool use be understood within such a framework?

In this connection, I suggest that tool use development may be formulated as a twofold problem of (1) detecting and (2) relating affordances. In my view, such a formulation has a number of interesting implications for theory and research. Consider first the notion that tool use is a problem of affordance detection. In this formulation, tool use may be less a matter of insight based on some constructive representational process than one of detecting potential relations between objects based on information that is directly

perceptible in the world (see also Smitsman, 1997). But even in the affordance literature, such a possibility has received little empirical attention. Indeed, in most past work on infants' detection of affordances, the focus has been on the relation embodied directly between infants' effector systems and objects or surfaces in their environments. For example, E. J. Gibson and her students have asked what makes a surface traversable for newly locomotor infants (Adolph, Eppler, & Gibson, 1993; Gibson et al., 1987). Here the affordance in question involves the relation between the infant's mode of locomotion and the properties of a surface. In contrast, in the case of tool use, the individual's effector organ is changed by virtue of a tool. As a consequence, tool use will depend on the properties not only of the surface or object to be acted upon, but of the tool as well. In sum, tool use may be conceptualized as a problem in which children begin to appreciate the affordances entailed by different tool–surface or tool–object combinations.

Such a perspective may be beneficial for guiding research on a number of tool use skills. To illustrate, we have recently applied this perspective to study how young children learn to use graphic instruments. Previous work in this area has emphasized the grips that young children display at various ages (Connolly & Elliott, 1972; Gesell, 1940). An affordance perspective, however, directs us to examine other aspects of the tool use situation, particularly the relation between the tool and the surface based on the action capabilities of the individual. With respect to graphic tools, we have asked, "What makes a surface writable?" (Lockman & Nelson, in preparation). To address this question, we give young children different graphic tools (e.g., a pencil or paintbrush) and ask them to draw or paint on different types of surfaces (e.g., bumpy, nonrigid, rough, and so on). Our findings suggest that even 3-year-old children are sensitive to the properties inherent in different graphic tool–surface combinations. For instance, when presented with a surface that is entirely liquid, young children will attempt to use a paintbrush in it (and change the color of the liquid) but not a pencil.

More broadly, this work illustrates the types of questions and studies that may originate from an affordance perspective on tool use. Similar questions may be asked about the development of children's sensitivity to other tool–surface combinations. In addition, conceptualizing tool use as a problem of affordance detection may help us view tool use in a different developmental light. From this perspective, tool use is seen as a more continuous developmental achievement, emerging from infants' early and continual efforts to detect and act on the affordances of the world around them.

But is affordance detection enough? It is important to recognize that detecting affordance relations may be only one, albeit a major, part of the achievement of tool use. Even if children can detect potential affordances constituted by interrelations among objects, they still need to be able to establish these relations through action. Specifically, to use a tool properly, the actor typically must align one particular object surface with another. For example, effective hammering requires that the actor keep the flat part of the hammer head flush with the nail. Although some have recently suggested that the primary cognitive achievement underlying tool use involves an advance in causal understanding (Tomasello, 1998; Tomasello & Call, 1997), the spatial demands underlying human tool use should not be overlooked. I believe that the act of relating objects or particular surfaces of objects to one another is a complicated and interesting spatial problem, deserving of research attention. In particular, I propose that as a spatial achievement, relating objects together can be viewed as a type of localization task that is largely new for infants, involving the coordination of mobile frames of reference.

How can the frame of reference notion be applied to the analysis of tool use? Usually when we talk about frames of reference, we talk about how we code location. Sometimes we code location with respect to the body—egocentrically—and sometimes we code location with respect to the environment—objectively (see Pick & Lockman, 1981). Objective or environmental coding is often considered a more reliable code because it is more stable. In fact, we know from the results of a number of studies that infants can code location objectively under some conditions in the second half-year (Acredolo & Evans, 1980; Bremner, 1978; Keating, McKenzie, & Day, 1986; Rieser, 1979).

I suggest, however, that tool and similar manipulation problems also require the use of an environmental frame of reference. Parts of objects need to be localized in relation to other parts of objects. But unlike the frames of reference examined in prior research, the environmental frame of reference is not stable in the usual sense. Objects do not occupy fixed positions in space. They can be moved, rotated, and so on. What is stable about an object are the relations within it, although the absolute locations of particular surfaces or parts of the object can change. My suggestion is that in early tool use it is this new type of localization problem, involving the coordination of multiple and mobile frames of reference, that young children need to master in addition to detecting potential affordances between objects.

This approach may help illuminate what young children must achieve in many tool-like tasks. To il-

lustrate how such tasks can be analyzed as a problem of coordinating spatial frames of reference, let me mention briefly the results of a longitudinal study that we conducted on infant banging (Lockman & Wright, 1989). In this work we gave infants pairs of identical cubes that varied in surface properties. In one such pair, each cube was composed half of wood and half of sponge. To make noise with this cube if banging it singly, the infant needed to orient the cube so that the hard side collided with the table surface. But to make noise with these cubes if banging them together, the infant needed to align the cubes so that the hard sides collided with each other. We found that between 6 and 10 months of age infants displayed the former type of banging, but not the latter.

The difficulty is not due to an inability to bang objects together. Infants bang objects together by these ages (Gesell, 1940; Thelen, 1981), and they did in fact bang the cubes together in our study. What our infants did not do, however, was align the cubes appropriately in relation to each other. To interpret this difficulty, I suggest that we think about it as a problem requiring the coordination of frames of reference. Aligning these objects appropriately can be thought of as a localization problem: one side of each object needs to be positioned in relation to the other. Put another way, two relative, not absolutely fixed, frames of reference must be coordinated.

This spatial analysis, in my view, offers some new directions for research on tool use. First, it suggests that investigators should focus on how children go about aligning object surfaces in tool use tasks. Such a process-based approach is consistent with investigating questions about *tool using*. By comparison, more outcome-based approaches, which are currently the norm in the developmental literature on tool use, focus on whether insight has been achieved. Second, considering tool use as a problem of coordinating multiple frames of reference also helps us understand why some types of tool use tasks are more difficult for young children than are others. In this connection, McCarty et al. (1999) recently found that young children more often orient their grips appropriately when, for instance, they use a spoon to feed themselves rather than someone else. More generally, additional consideration of the spatial demands entailed by tool using may enhance our understanding of how the perceptual, motor, and cognitive abilities that underlie tool use become coordinated in young children.

ACTION PATTERNS IN EARLY TOOL USE

In this final section, I raise an issue that in my view has not received enough attention in the tool use literature. In a good deal of the work on the origins of tool use, particularly from anthropological and comparative perspectives, investigators have attempted to describe the structure or forms of tools that our ancestors created during different periods of human evolution (Toth & Schick, 1993). I suggest, however, that answers to questions about the structure of early human tools cannot be divorced from a consideration of the actions of the hand and/or arm that embody tool use. More broadly, to address issues about the evolution of tool structure and tool use, we also need to consider the evolution of the actions that individuals employ during tool use and how our action capabilities (e.g., the oscillatory dynamics of the arm) have shaped the tools of human culture.

By the same token, developmentalists have not typically addressed analogous issues. Most often, the developmental focus has been on whether children achieve insight. But I suggest that consideration of the actions that toddlers use with the everyday tools of their cultures is likely to reveal that these actions initially incorporate many of the action patterns that infants employ with their hands and arms to explore and act on the environment.

Possible linkages between earlier and later appearing action patterns in nontool and tool use situations merit further empirical and theoretical consideration. In a related vein, Thelen (1981) has suggested that some early appearing rhythmical stereotypies may sometimes serve as the foundation for later appearing instrumental behaviors. To explore such linkages for tool use, future research needs to focus more on the everyday tools that young children employ in their daily activities. The current research practice of designing novel tools and tasks to study insight, while understandable for methodological reasons, may mask such potential relations.

The idea that the motor precursors of tool use may already be evident in the infancy period is illustrated in the following study. Cralley, Ellman, & Lockman (1999) gave infants hammer-like objects that consisted of a handle attached to a cube. The rigidity of the cube or "mallet" part varied, however. In some instances, the mallet was hard, composed of wood, and in other instances the mallet was soft, composed of sponge. The results revealed that as early as 8 months of age, infants were more likely to bang the hard than the soft "hammer" by holding the handle. These findings indicate that infants show important elements of tool use. First, they used a handle as an extension of an object, a critical component of effective tool use. And second, they employed a well-practiced action pattern (banging) in an instrumental fashion to effect a change (the production of noise) in the environ-

ment. More broadly, the results are consistent with the notion that some well-practiced infant manual exploratory behaviors become incorporated into early tool use.

Besides banging, other types of infant manual behaviors may serve a similar purpose. The back and forth oscillatory motor patterns that infants manifest when scooting and sliding objects (Palmer, 1989) appear to share some surface similarities with the motor patterns that toddlers evidence in early scribbling. By the same token, the hand-to-mouth coordination that infants achieve early in life appears to be incorporated into later spoon use (Connolly & Dalgleish, 1989). Of course, more direct evidence for this proposal might be gathered by comparing the patterning of these individual behaviors across tool and nontool use situations and developmental time. Such an approach is similar to the strategy employed by Thelen & Fisher (1982) to demonstrate that early kicking and the so-called "stepping reflex" are the same actions in young infants.

Consideration of the actions employed in tool use and their developmental precursors may also offer some theoretical insights into the emergence of tool use. The possibility that earlier appearing manual actions and later appearing tool use behaviors are related is consistent with the idea that tool use is a more continuous developmental achievement than has been previously believed. It is also consistent with the idea that tool use is a form of exploratory behavior involving the detection of affordances, and serves the same function as direct manipulation for younger infants. These types of developmental connections would clearly be adaptive. If the actions required for tool use are already mastered, then infants and toddlers may begin to focus more on the particular demands of a given problem so that the tool can be deployed successfully.

Finally, let me speculate on an evolutionary implication of these general ideas. In discussions of the possible evolutionary advance constituted by the emergence of tool use, a number of theorists have argued that the advance—whatever type it might be—does not involve the creation of altogether new abilities, but builds on capacities or potentials that are already available to the organism (Bates, 1979; Gould, 1977). The possibility that many infant actions become incorporated into subsequent tool use behaviors is not only consistent with this idea, but may also tell us something about the reasons why tools take the form that they do. Put another way, the evolution of tool use may in large part be a case where the action capabilities of humans, and in particular children, determined the form of our earliest tools.

CONCLUSIONS

In this essay I have argued for a new wave of research on tool use development. I have suggested that advances in the developmental literatures on motor behavior and perception–action coupling contain important clues for how tool use emerges during early childhood. These advances direct us to consider young children's trial and error tool use behaviors as self-generated opportunities for perceptual learning. These advances also direct us to consider tool use as a problem of detecting and relating affordances between objects or surfaces of objects. And finally, these advances suggest that we pay greater attention to the actions embodied in tool using; these actions may be based on motor patterns that infants have been practicing throughout the first year.

In coming years we need to go beyond traditional developmental views of tool use as a cognitive problem primarily requiring insight and largely thought to be dependent on an increase in processing capacity or relational reasoning ability. Instead, there is much to be gained from both developmental and evolutionary perspectives by considering tool use as an extension of infants' active attempts to explore and gain information about the world. From this vantage point, tool use may turn out to be a much more continuous developmental acquisition than has been previously believed. Indeed, the remarkable technological accomplishments achieved by our species may be rooted in infant perception–action skills.

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