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Tool Using

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Abstract

Research on the development of tool use in children has often emphasized the cognitive bases of this achievement, focusing on the choice of an artifact, but has largely neglected its motor foundations. However, research across diverse fields, from evolutionary anthropology to cognitive neuroscience, converges on the idea that the actions that embody tool use are also critical for understanding its ontogenesis and phylogenesis. In this article, we highlight findings across these fields to show how a deeper examination of the act of tool using can inform developmental accounts and illuminate what makes human tool use unique.

Keywords

tool use; motor development; cognitive development; action

Humans use objects extensively to change the functional capabilities of their limbs. We use objects routinely to overcome environmental challenges that we would be unable to accomplish with our bare limbs alone. For instance, our arms and hands can become pounding devices when holding a stone or a hammer. Our legs and feet traverse snowy surfaces more effectively when fitted with skis or snowshoes. These examples illustrate how objects can function as tools and why tools have so much adaptive value. Tools can extend the length of our limbs, modify their capabilities to act, and at the same time, protect limbs from injury. Indeed, by using tools, we are often better equipped to negotiate environmental demands, gather information, and adjust our actions to accomplish desired goals. In short, because tools can transform the properties of our limbs, they enable us to adapt more effectively to a range of environments.

Perspectives on the Development of Tool Use

In this article, we first consider prevailing views on the development of tool use within the field of psychology. Then we look at interdisciplinary work on tool use in neuroscience, animal behavior, and anthropology, addressing the implications of this work for the development of tool use. In this overview, we highlight the idea that action is integral to understanding the ontogenesis of tool use. In the final sections of the article, we review

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recent research on the motor bases of early tool use and explore how this research can inform our understanding of the development of tool use more generally.

Tool Use: Cognitive Accounts

In psychology, the foundational work of Köhler (1927) and other Gestalt psychologists like Lewin (1936) on problem solving and insight still influences the study of tool use. According to this view, tool use is the result of a new way of envisioning the surrounding field, and imagining relations between elements in the environment and how they may be combined, often in a nonobvious way, to achieve a goal. Similarly, in developmental psychology, tool use has often been viewed as a window to representational capacity. Piaget (1952) famously presented different manual problem-solving tasks, some requiring the use of objects as tools, to his infant children to gauge their ability to imagine solutions to problems without relying on trial and error. A combination of the Gestalt and Piagetian views has influenced much subsequent work on the development of tool use. Investigators have asked how elements in the environment should be arranged to facilitate infants' representation of an object as a potential tool (Bates, 1979) and whether young children succumb to functional fixedness, able to use an object as a tool in only one habitual way (Barrett, Davis, & Needham, 2007). In related work on representation, investigators have asked about learning and transfer—specifically, the underlying causal understanding that enables young children to use an object as a tool and the basis for transferring this ability to other objects (Brown, 1990). More recently, researchers have extended questions about representation to ask about children's concepts of tools, particularly their understanding that tools are typically designed with a purpose (Deák, 2014; Keleman & Carey, 2007). Despite attention to these different aspects of the development of tool use over the last 90 years, we share the concern that “the topic of tool use has never taken center stage in developmental psychology” (Keen, 2011, p. 3).

Tool Use: Interdisciplinary Approaches

Although tool use has been in the spotlight infrequently in developmental psychology, recent advances in other fields, such as paleoanthropology, animal behavior, neuroscience, and motor behavior, have led to a new understanding of tool use. These advances, in turn, have implications for how we might conceptualize and study the development of tool use in human children. The advances converge on the idea that the actions that embody tool use are critical for understanding both its ontogeneseis and phylogenseis. That is, the actions themselves can illuminate how tool use unfolds over developmental and evolutionary time. Focusing on the actions involved in tool use can also inform the questions that should be asked about the development of tool use in children.

Tool Using Versus Tool Choosing

Focusing attention on the actions intrinsic to tool use would constitute a shift in research on the development of tool use. In past research, investigators have focused more on the immediate problem of tool choosing rather than the longer-term achievement of tool using (see Cummins-Sebree & Frigaszy, 2005; Lockman, 2000), reflecting perhaps the continuing influence of insight-based approaches to the study of tool use. Becoming skilled in using an object as a tool and as an extension of the hand typically occurs over a long period (Greer &

Lockman, 1998; Rosenbloom & Horton, 1971) and often after an individual can select an appropriate tool reliably. Consider the process of learning to use a spoon: Before the end of the first year, infants select spoons to feed themselves, but the process of becoming skilled in using spoons, as well as planning and selecting an appropriate grip, occurs over most of the second year (Connolly & Dalgleish, 1989; McCarty, Clifton, & Collard, 2001). More broadly, the distinction between tool choosing and tool using as separable abilities is consistent with recent findings from different disciplines, which we consider next.

Neuroscience

Research in neuroscience highlights the motor basis of tool use and in so doing, distinguishes tool choosing from tool using. Neuroscientists and clinical neurologists have identified two distinct types of apraxia in tool use: ideational apraxia and ideomotor apraxia (De Renzi & Lucchelli, 1988; Macauley & Handley, 2005). Ideational apraxia is characterized by a loss of knowledge about a tool's function. Patients who suffer from ideational apraxia have difficulty choosing the correct tool for an action, using a razor instead of a comb or attempting to use scissors to write, for example (Pick, 1905). Ideomotor apraxia is characterized by the inability to execute movements. Patients with ideomotor apraxia choose the correct tool for a given purpose but often err in the way they hold and move that tool (Macauley & Handley, 2005).

Work using neuroimaging techniques in adults has substantiated this distinction. When humans use tools skillfully, a wide network of cortical areas is recruited, and these cortical areas may be composed of separate but interconnected networks (Johnson-Frey, 2004; Lewis, 2006): One network processes conceptual aspects of tools and another network underlies the physical use of tools. Although studies of apraxia and functional neuroimaging have been conducted with adults, these studies highlight the importance of action that most developmental research on tool use has lacked.

Research on monkeys trained to use novel tools also supports the idea that action is integral to the neural representation of tools. After extensive exposure to a tool, the brain begins to treat that tool as though it were part of the body by incorporating it into the body schema (Maravita & Iriki, 2004). Monkeys require 2 to 3 weeks of training (equivalent to about 2000 trials) before they use a rake to retrieve food (Hihara, Obayashi, Tanaka, & Iriki, 2003). Moreover, these behavioral advances occur concurrently with neural changes: The physical act of learning to use a tool creates connections between neurons in the visual, frontal, and parietal cortex that subserve the integration of the tool into the body schema in monkeys (Hihara et al., 2006). Before these connections are created, monkeys fail consistently to use a rake correctly, but success rates skyrocket afterward. Furthermore, the specific action and functional properties of the tool are critical to the way a tool is incorporated into the body schema: Objects that extend the reach of the arm (such as a rake) become part of the neural representation of the forearm (Iriki, Tanaka, & Iwamura, 1996), while those that function like fingers (pliers) become incorporated into the representation of the fingers (Umiltà et al., 2008).

Animal Behavior

Research on the development of tool use in living nonhuman primates also supports the idea that tool using presents its own developmental challenges apart from tool choosing. Research on how young chimpanzees learn to crack nuts using hammer stones and anvils indicates that learning occurs over several years (Inoue-Nakamura & Matsuzawa, 1997). Young chimpanzees do not sequence the different elements of cracking nuts (take, place, hold, hit, and eat) correctly until 3 and a half years, although they perform each subaction individually two years before then. And even when ordering all the actions correctly, chimpanzees often fail to open a nut when hitting it. Thus, the development of nut-cracking skills in chimpanzees unfolds gradually, shaped not by sudden insight but by accumulated experience.

Tool Use and Evolution

A direct focus on *tool using* is also consistent with contemporary approaches in disciplines concerned with the evolution of tool use. Work in paleoanthropology highlights the strong link between the evolution of the structure of the human hand and how it functions, particularly in connection with the emergence of tool use. A suite of adaptations in the morphology of the human hand allows it to manufacture and use stone tools (Marzke, 2013). These adaptations include the capacities to form precision grips (while keeping the functional part of the tool exposed), accommodate relatively large forces while maintaining such grips, and flex the wrist considerably. These adaptations are anchored in action—specifically, the percussive actions that are deployed when using and manufacturing stone tools.

The importance of these adaptations is apparent when we look at efforts to train nonhuman primates in using stone tools. Kanzi, a bonobo, was trained for three years in stone knapping (the use of hammerstones to chip off flakes from a target stone to create new shapes), using techniques similar to those of the early Stone Age. While training improved performance, Kanzi continued to have difficulty controlling forceful blows, presumably due to biomechanical constraints (Schick et al., 1999). Even after years of training, the stone flakes Kanzi produced did not show the level of skill evident in archaeological artifacts of our earliest human ancestors from about 2 million years ago (Toth, Schick, Savage-Rumbaugh, Sevcik, & Rumbaugh, 1993).

Taken together, studies on the evolution of tool use have implications for the kinds of questions that should be asked about the ontogenesis of tool use in human children. These studies highlight not just how hand structure and manual behavior may have co-evolved, but what makes tool use in humans unique at a motor level.

Motor Origins of Tool Use in Human Children

Given the importance of action for understanding the development of tool use, what actions should be targeted for study? Once reaching has developed in the first half year (Piaget, 1952), infants can perform many kinds of manual actions. Although crawling and walking are the obvious early motor milestones of locomotor development (Adolph & Berger, 2006;

Gesell, 1928; Thelen, 2000), analogous actions to study in regard to the use of manual tools are less clear.

However, closer attention to the evolutionary origins of tool use can identify those manual actions. Research from paleoanthropology and animal behavior suggests that percussive action is a prime candidate for linking the ontogeny of tool use in humans to its evolutionary origins. In human development, the infants' earliest percussive action is banging, defined as repetitive up-down motion of the arm while holding an object and striking a surface. Infants in the first year devote considerable time and energy to banging objects. Object banging becomes prevalent around six months, but declines dramatically in the second year (Belsky & Most, 1981). However, this behavior may not disappear from children's action repertoire. Much like early stepping and kicking may be the motor building blocks of upright locomotion (Thelen & Fisher, 1982; Thelen & Ulrich, 1991), object banging may serve as the foundation for percussive tool use.

This possibility is supported by a recent series of studies using high-speed motion capture technology (Kahrs, Jung, & Lockman, 2012, 2013, 2014; Kahrs & Lockman, 2014). Infrared cameras recorded the three-dimensional position of reflective markers at 240 Hz. Markers were placed at bony landmarks of the upper body to enable a full reconstruction of torso and arm movements. Researchers examined the kinematics (the position and motion of individual body segments and their associated joint angles) of arm and hand movements as infants banged objects spontaneously (Kahrs et al., 2012, 2013) and as toddlers used hammers to pound pegs into a hole (Kahrs et al., 2014; see Figure 1).

In one study (Kahrs et al., 2013), infants between 6 and 15 months were given objects while seated at a table and encouraged to explore. Motion-tracking data indicated that during this developmental period, banging transitions from an inefficient and variable motor behavior to an efficient and highly consistent one. When younger infants banged objects, their hand trajectories were circuitous, varying greatly in direction and height from one strike to the next (Figure 2a). In contrast, when older infants banged objects, they exhibited many of the motor characteristics expected of a skilled tool user: Their hand trajectories were not only spatially and temporally efficient, but consistent from one strike to the next. Older infants also eliminated unnecessary hand movements (sideways or forwards) and moved their hands almost perfectly straight up and down (Figure 2b). Infants also showed consistent amplitude and velocity of movement, leading to strikes that were predictable with respect to both hand location and the amount of force imparted. Thus, at the end of the first year, object banging had become well suited for percussive tool use. This occurred after months of experience banging objects, but before children began using hammers instrumentally as tools.

A subsequent study (Kahrs et al., 2014) explored how early percussive action becomes incorporated into hammering. Toddlers between 17 and 31 months held a simple wooden hammer in their dominant or nondominant hand and were asked to drive a peg into a pegboard while researchers recorded kinematics of the children's upper bodies and the trajectory of the hammer. As noted, children in the second year already display hand trajectories that are well adapted for percussive tool use. Therefore, the additional challenge in learning to hammer is controlling the tool's functional end, which extends from the hand.

Individuals skilled in hammering typically achieve this control by engaging the wrist. As discussed, the human wrist and hand are unique among primates, allowing for fine motor control during percussive tasks (Marzke & Marzke, 2000). Thus, developmental advances in percussive tool use beyond infancy may center on increased involvement of the wrist.

Consistent with this hypothesis, in the study of toddlers (Kahrs et al., 2014), children began to use their wrists extensively while hammering in the third year. Furthermore, increased use of the wrist was limited to the dominant (right) hand and only when children gripped the hammer close to its head. Once children displayed this pattern of hammering with the dominant hand, their strike became much more accurate. In short, children's reliance on the wrist, this uniquely human form of percussive tool use, started to emerge only in the third year. Taken together, these studies suggest that percussive tool use develops gradually during the first few years, building on earlier-appearing motor patterns that infants show when they bang objects.

Looking Ahead

Tool use is inherently about action. Nevertheless, direct consideration of how the actions that embody tool use develop has largely been absent in developmental research. One challenge for developmentalists has been to identify the manual action patterns that merit study. By considering the literature on tool use from a variety of disciplines (e.g., anthropology, comparative psychology, motor behavior, neuroscience), we can pinpoint those actions. Moreover, such an integrated perspective can deepen our understanding of how tool using becomes distinctively human.

At the same time, examining the motor bases of tool use should extend beyond infancy. To the limited extent that the motor foundations of tool use have been examined in developmental research, researchers have investigated how infants relate objects to surfaces (Bourgeois, Khawar, Neal, & Lockman, 2005), grip common tools (McCarty et al., 2001), and sequence component actions (Connolly & Dalgleish, 1989). Even less attention has been devoted to the motor foundations of tool use beyond infancy and the early toddler years (but see Keen, Lee, & Adolph, 2014). Perhaps this age bias reflects an assumption among developmentalists that changes in cognitive ability primarily underlie advances in tool use after infancy. Yet the studies we have reviewed in this article point to the possibility that throughout childhood, important advances occur in the manual actions children deploy for tool use.

Incorporating action into discussions of tool use also broadens consideration of the potential mechanisms that underlie developmental changes in this ability. Prior work largely attributed changes in tool use to neuromotor maturation (Gesell, 1928) or cognitive ability (Piaget, 1952). However, more recent discussions about action development have also highlighted the importance of situating advances in motor skill within children's surrounding physical and social environments and the learning opportunities they afford (Karasik, Tamis-LeMonda, & Adolph, 2011; Thelen, 2000). The implications of this idea for understanding the mechanisms underlying the development of tool use are at least twofold. First, young children explore their physical environments and in so doing, gain control of

the action patterns that will be recruited during tool use (Kahrs et al., 2013). Second, this process occurs within a larger sociocultural context; caregivers may promote action learning by providing opportunities for observation, making artifacts available, and engaging in direct tutelage (Tomasello, 1999).

In conclusion, prior work on the development of tool use has focused more on outcome (i.e., whether a child chooses a correct tool) than on process. A new commitment to understanding the act of tool using can yield novel insights into the developmental as well as evolutionary origins of this fundamental human ability.

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Figure 1. The experimental setup for the different experiments

by a) Kahrs, Jung, and Lockman (2012), b) Kahrs, Jung, and Lockman (2013), and c) Kahrs, Jung, and Lockman (2014). Kinematics were recorded from 11 markers: one at the sternum and 5 on each arm at the following locations: shoulder, elbow, thumb side of the wrist, little finger side of the wrist, and knuckle.

Figure 2. Examples of representative hand trajectories for a young infant

a) 238 days old, and an older infant b) 356 days old. All available strikes for each infant, 10 and 7 respectively, are presented and starting locations for each strike are normalized to be at the origin (reproduced from Kahrs, Jung, & Lockman, 2014). All axes are in mm.