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New Insights into the Development of Human Tool Use

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Abstract

If tool use requires higher-level cognitive abilities, how is it that many animals show the capacity to use tools? New research on the development of human tool use offers a way to resolve this paradox. The research suggests that there is a developmental synergy between affordance detection and motor learning: As juveniles continually explore affordances entailed by object-surface combinations in real time, they tune the actions that will be incorporated into tool use over developmental time. We illustrate these ideas with research on how object banging in infancy serves as the motor substrate for later developing percussive tool use. Collectively, the new research suggests that basic types of tool use in young humans and animals are rooted not in higher-order cognitive abilities, but shared principles of sensorimotor learning.

Keywords

tool use; object manipulation; motor development

A crow in New Caledonia holds a twig with its beak, inserts the twig into a crevice in a decaying tree to probe for beetle larvae (Bluff, Troscianko, Weir, Kacelnik, & Rutz, 2010). A chimpanzee in Bossou, Guinea grasps a stone and then pounds it against a nut to crack it open (Inoue-Nakamura & Matsuzawa, 1997). A young child in preschool grips a crayon, puts point to page and moves the crayon back and forth to scribble. And a surgeon in a hospital gently guides a laparoscope with a camera to inspect suspect tissue in a patient.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Recommended Readings

Inoue-Nakamura, N., & Matsuzawa, T. (1997). (See References). One of the first studies that systematically investigates the development of stone tool use by chimpanzees in the wild.

Kahrs, B. A., Jung, W. P., & Lockman, J. J. (2013). (See References). Describes research using motion capture technology to suggest that infant object banging is the motor substrate of later developing percussive tool use.

Kenward, B. E. N., Schloegl, C., Rutz, C., Weir, A. A., Bugnyar, T., & Kacelnik, A. (2011). (See References). Reviews developmental research on behaviors that lead up to tool use in New Caledonian crows and considers the evolutionary origins of these behaviors.

Lockman, J. J. (2000). A perception-action perspective on tool use development. (See References). Describes how a perception-action approach based on the work of E. J. & J. J. Gibson can be used to understand the development of tool use.

Mangalam, M., & Frigaszy, D. M. (2016). Transforming the body-only system into the body-plus-tool system. *Animal Behaviour*, 117, 115–122. <http://dx.doi.org/10.1016/j.anbehav.2016.04.016>. Offers an embodied approach for understanding the biomechanics of tool use emergence, which can be applied across species.

Needham, A. W. (2016). *Learning about objects in infancy*. New York, NY: Routledge. This volume provides a clear synthesis of research relating to object knowledge in infancy and how such knowledge culminates in tool use.

These seemingly disparate examples share a common thread. They illustrate the remarkable ability of creatures to use objects to change their action capabilities by deploying objects as tools. While definitions of what constitutes a tool have varied, an influential one offered by Beck (Beck, 1980; Shumaker, Walkup, & Beck, 2011) based on a review of comparative research highlights the idea that tools are objects that organisms orient and manipulate in order to transform another entity—whether that entity be an object, another organism and/or even the user.

The evidence catalogued by Beck and documented by others that non-human primates as well as non-primates engage in tool use introduces a paradox for any discussion of human tool use development. The paradox is as follows: If human tool use reflects a set of advanced and perhaps uniquely human cognitive skills as has often been claimed, how is it that many members of the animal kingdom also demonstrate the capacity to deploy objects as tools?

One way to resolve the paradox is to argue that similar abilities underlie at least the basic types of tool use that are seen in animals and humans. The potential difficulty here is that most accounts treat human tool use and its development as a cognitive achievement, dependent on advanced forms of representational and causal thinking (Köhler, 1927; Piaget, 1952). If even basic forms of tool use depend on higher order cognitive skills, then we would have to attribute such mental abilities to a wide range of species, a controversial position for many.

But recent theoretical and empirical work on the development of tool use in young humans suggests another way to arrive at a solution to the paradox. Rather than considering tool use across species as stemming from a shared set of cognitive abilities, the new work on tool use development explains its origins by integrating work on affordance learning (Gibson & Pick, 2000; Lockman, 2000; Smitsman, 1997) and the motor substrates of skilled action (Dominici et al., 2011; Thelen, 1981; Thelen & Ulrich, 1991).

In the following sections, we describe how a synthesis of recent research on affordance learning and the motor substrates of skilled action can shed new light on how tool use comes about in humans. Collectively, this research suggests that tool use in young humans does not arise primarily from a cognitive advance, but is built from basic perception-action processes and motor behaviors that are already evident in the infancy period. Critically, this work offers an alternate way of explaining how some forms of tool use in humans and other animals originate from similar underlying processes.

Tool Use as an Affordance Learning Problem

The starting point for considering how tool use can be viewed as a problem of affordance learning is to view objects as having the potential to change the action capabilities of the limbs (Lockman, 2000). In the case of manual tool use, when an organism holds an object, the actions of that organism have the potential to produce new effects that would otherwise be unachievable by that same body part alone. Objects may function as extensions of hands, not just in a literal sense by extending the reach of the arms, but in terms of what outcomes the hands can produce once objects are held.

When do humans begin to show sensitivity to the possibility that objects can change the functional capabilities or affordances of the hands? To answer this question, it is necessary to study how infants manipulate objects and relate them to surfaces in their environments. For a long time following the claims of Piaget (1952), it was accepted that infants during much of the first year manipulate objects either in an indiscriminating manner, by acting on most objects similarly regardless of the objects' physical characteristics, or by repeating accidental actions on objects that lead to interesting outcomes. Similarly, in subsequent accounts, infants' attempts to explore and combine objects were characterized as inappropriate and indiscriminate, geared neither to the objects' conventional uses nor their functional properties (e.g., see Belsky & Most, 1981).

Recent research on infant object manipulation and understanding of surface properties (Rips & Hespos, 2015) has challenged these accounts. This newer work suggests that infants explore objects and relate them to surfaces selectively, based on the physical properties of each—a key requirement for using objects as tools. In one study, Bourgeois, Khawar, Neal and Lockman (2005) found that infants in the second half-year used different action patterns based on the object they were holding and the surface immediately before them, suggesting that they are already sensitive to how hand-held objects bring about new possibilities for action. Similarly, other researchers have reported that infants differentially combine objects and surfaces when given simple objects or toys on a rigid or foam tabletop surface (Palmer, 1989) or when they play with objects on hardwood or carpeted floors (Morgante & Keen, 2008).

Moreover, infants show these selective patterns of exploration even when confronted with surfaces with abrupt transitions in material composition. When 8–10 month old infants are given an object to manipulate on such composite surfaces (e.g., tabletop surfaces that are half-rigid and half-flexible), they adjust their manual behaviors based on the particular substrate that the object contacts (Fontenelle, Kahrs, Neal, Newton, & Lockman, 2007). In short, even within narrow areas, infants evidence specificity in their manual actions, combining objects and substrates differentially, based on the physical properties of each.

Specificity of action in combining objects and surfaces is not restricted to humans. Crucially, such object-surface specificity has been demonstrated in non-human tool use contexts, where organisms need to take into account the material characteristics of objects and surfaces and their combination to achieve a goal. Capuchin monkeys select stones, nuts and anvils with physical properties that optimize successful nut-cracking when these elements are brought into contact with one another (Visalberghi et al., 2009). Such selectivity is not limited to primates: New Caledonian crows select tools (twigs) based on task demands, relating tool length to hole depth (Chappell & Kacelnik, 2002).

Collectively, the new work on the specificity of even young organisms' transactions with the physical world can help us understand how different species, despite presumed differences in cognitive level, manifest tool use. Sensitivity to affordances between objects appears crucial for effective tool use regardless of the species under consideration. Furthermore, a formative consequence of organisms' ongoing efforts to combine objects and surfaces is that

over developmental time, these efforts might result in tuning the motor behaviors that are incorporated into tool use. We turn to this possibility next.

Motor Origins of Tool Use

Recent work on the motor substrates of skilled action is also relevant for understanding how young members of a species come to use objects as tools. The extended period of time that juveniles of tool using species devote to combining objects and surfaces (Inoue-Nakamura & Matsuzawa, 1997; Kenward et al., 2011) might have longer-term functional consequences in terms of not only learning affordances, but also preparing them to perform the actions needed for tool use. Research on locomotion, for instance, indicates that some aspects of neonatal stepping are incorporated into mature locomotion (Dominici et al., 2011; Thelen & Ulrich, 1991). In a related vein, investigators have suggested that some early appearing motor stereotypies are adapted for volitional use, forming the basis of later skilled action (Thelen, 1981).

New research on tool use from a motor substrate perspective has similarly focused on how infants' manual behaviors become incorporated into tool use. A key question here is whether there exist early forms of manual action that might function in an analogous fashion to the early appearing motor primitives of locomotor development (Dominici et al., 2011). Like the affordance learning perspective, the motor substrates approach departs from prevailing accounts that trace the development of tool use primarily to advances in cognitive ability. Furthermore, it can illuminate how tool use across species may originate from similar processes of sensorimotor learning.

To address the motor origins of tool use in humans, investigators have examined infants' oscillatory arm movements. In the second half-year, infants often bang their bare hands or objects against surfaces with gusto, but the function of these high-energy percussive behaviors has received little attention. Lockman (2000), however, suggested that it is precisely these movements that may later serve as building blocks for manual tool use such as hammering and pounding. Recent research utilizing high-speed motion capture technology with human infants confirms this possibility.

Kahrs, Jung and Lockman (2012) used motion tracking to study the arm trajectories of 7–14 months-old infants as they banged a cube on a hard tabletop surface (see Fig 1). Younger infants struck the object against the surface inefficiently. Arm trajectories were not straight and quite variable from strike to strike. By comparison, older infants were beginning to display key signatures of skilled percussive behavior. Arm movements were controlled and straighter, resulting in improved aim and better delivery of force. Collectively, these developmental changes suggest that at a time when infants are not yet using tools, their arm movements are becoming tuned for percussive tool use, a possible consequence of the self-generated experience derived from banging objects over many months.

Furthermore, this protracted period of motor preparation prior to emergence of goal-oriented tool use may correspond to preparatory periods of other species who manifest tool use. Chimpanzees (Inoue-Nakamura & Matsuzawa, 1997), capuchin monkeys (Resende, Ottoni

& Frigaszy, 2008) and New Caledonian crows (Kenward et al., 2011) all spend extended periods of developmental time practicing forms of the actions that will eventually be incorporated into their respective types of tool use.

Percussive action and handled objects

A protracted period of motor preparation would also equip human infants with the rudimentary skill needed to engage some of the basic but more complex tools that are unique to human culture, such as objects attached to handles. Handled artifacts present significant challenges for would-be tool users. Individuals must control the functional end of the artifact located at some distance from the hand. Despite these challenges, a motor substrate perspective suggests that the ability to control handled objects might also build on earlier appearing motor primitives.

To explore this possibility, Kahrs, Lockman & Jung (2013, 2014) studied how 6–15 month-old infants bang a handled cube versus a simple cube. Younger infants' percussive actions were even less controlled (i.e., more circuitous and faster) than when they were given a simple cube. However, by one year infants' percussive actions with handled objects were now comparable to the trajectories that infants displayed when banging simple cubes. Functionally, the advances in the motor control of handled objects suggest that by the end of the first year, infants' percussive actions are becoming readied for tool use.

In humans, this process continues throughout the preschool period. Adults achieve fine control of handled tools through involvement of the wrist (Marzke, 2013). Recent research suggests that this distinctively human pattern is an outgrowth of infants' percussive behaviors (Kahrs, Jung, & Lockman, 2014). In a motion capture study of hammering in children between 19–35 months of age, younger children used a form of hammering that is very similar to one that infants display when they bang objects by relying on their proximal musculature (i.e., shoulder and elbow). In contrast, three-year-olds began to manifest a form of hammering that is distinctively human involving the wrist of the dominant hand, resulting in improved accuracy. Collectively, these findings suggest that young humans, like the young of other species, adapt and refine available action patterns for new instrumental ends.

Conclusions

This essay began by introducing a paradox: If human tool use requires higher-level cognitive abilities, how is it that many animals also show the capacity to use tools? New research on the development of tool use in humans offers a way of resolving the paradox. The research shows how human tool use development is based on a) detecting affordances and b) adapting and incorporating early behaviors available for detecting affordances into later appearing behaviors performed with tools. If, as suggested, tool use development in young children can be explained through mechanisms involving sensorimotor learning, then this approach allows for the possibility that tool use in other species can be explained by similar mechanisms without invoking processes that require symbolic or abstract forms of thinking.

The new findings reviewed on tool use development in humans describe how banging transitions to more skilled forms of percussive tool use over the first three years. More

generally, the findings suggest a developmental synergy between affordance detection and motor learning: As juveniles continually explore affordances entailed by object-surface combinations in real time, they practice the actions that will be incorporated into tool use over developmental time. Such a mechanism would also ensure the emergence of tool use across different species despite differences in cognitive level.

Of course, it is highly unlikely that human infants or juveniles from other tool using species initially practice precursor actions with the explicit goal of becoming proficient tool users. Kacelnik and colleagues have proposed that what may have been selected for in the evolution of tool use in New Caledonian crows is a motivation to use objects as extensions of the body to act on the environment, with tool use as the downstream result (Kacelnik, 2009; Kenward et al. 2011). Likewise, the new findings reviewed here suggest that the development of human tool use unfolds from a more general propensity to discover, explore and act on affordances in the environment, which engender opportunities for practice and modification of foundational motor actions over developmental time. In short, basic forms of tool use, across different species, may be rooted in common processes of sensorimotor learning.

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Figure 1.

A) One of the infants from the study while banging. The placement of all 11 markers is illustrated by the green dots. The axes of both graphs are measured in mm. Depicted are hand trajectories (the marker is placed on the knuckle of the middle finger) for the first 5 strikes of a B) 214 days old infant and C) 408 days old infant. All strikes were standardized to begin at the Cartesian origin. The figure illustrates the curved hand trajectories seen at younger ages and the straighter up-and-down trajectories typical of older infants. Adapted from “What is the role of infant banging in the development of tool use?” by Kahrs, Jung & Lockman, 2012, *Experimental Brain Research*. Copyright 2012 by Springer Verlag. Adapted with permission.