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Building Tool Use From Object Manipulation: A Perception-Action Perspective

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Abstract

Tools are a universal feature of human culture. While most past research on tool use has focused on its cognitive underpinnings, in the present article we adopt a perception-action approach to understand how tool use emerges in early development. In this context, we review our work on infant object banging and how it may serve as a motor substrate for percussive tool use. Our results suggest that infants use banging to act on environmental surfaces selectively. Additionally, with increasing age, banging becomes more controlled and manifests many characteristics associated with skilled hammering. Taken together, the results suggest that there is much to be gained from considering the emergence of tool use as an ongoing process of perceptuomotor adaptation to handheld objects.

One of the primary lessons of the Gibsons' ecological approach is that the environment is rich in information that specifies basic properties of the world and that our actions are geared to this information. Herb Pick helped to open our eyes to these crucial insights and made many of us aware of the implications of these ideas for understanding development and behavior in the real world.

In our work, we have been applying these ideas to the study of tool use. Tools are a universal feature of human behavior. We employ tools to change the properties of our limbs, change our range of actions and even the kinds of actions that we can perform. Think of a surgeon who uses a laparoscope or a child using scissors. Regardless of age or the scale in which an action is performed, we are able to use many different objects adaptively to change our action capabilities to achieve goals that we would otherwise be unable to accomplish with our bare hands alone.

The traditional view of tool use and the one that is most often employed to explain the onset of these kinds of behaviors is that these achievements stem from some sort of cognitive change. From an ontogenetic perspective, the cognitive change involves a qualitative shift in thinking. According to this perspective, around the second year, children become able to imagine future outcomes and the means to achieve these outcomes based on the emergence of symbolic or representational thinking abilities (Bates, 1979; Piaget, 1952). Applied to tool use, this view suggests that employing an object as a tool is representationally based and tied

to advances in causal understanding. Children imagine how an object may be used as a tool and then immediately put that insight into action.

From a microgenetic perspective, insight accounts have also dominated explanations of tool use and problem solving. Köhler's (1927) classic work with chimpanzees is often cited to illustrate the idea that a sudden insight can replace trial and error exploration and lead to an object being used in a novel or unconventional way as a tool to solve a problem. Since Köhler's time, investigators have extended this approach to examine the conditions that facilitate the achievement of insight or the mental restructuring of a problem space (Brown, 1990).

In contrast, in our work, we have turned to the Gibsons' ecological theory (E. J. Gibson, 1982; J. J. Gibson, 1979) and its dual emphases on direct perception and the coupling of perception and action to formulate an alternate account of tool use and its development (see also Smitsman, 1997). According to this perspective, tools change the properties or affordances of the limbs. The challenge for the would-be tool user is to learn how these new affordances can be exploited for adaptive ends in the environment. This process is typically an extended one, and involves exploration and learning. Thus, this viewpoint directs us to think about trial and error behaviors that often accompany the use of a novel tool in a different light. Rather than indicating an absence of insight or representational thinking, a perception-action approach suggests that trial and error behaviors are an integral part of the process of perceptual learning and exploration.

This viewpoint also helps us to resolve a paradox in the tool use literature. Many animals, from crows (Weir, Chappell, & Kacelnik, 2002) to non-human primates (Cummins-Sebree & Frigaszy, 2005) have been shown to use objects in their niches as tools to extend or change their action capabilities. Rather than ascribing these forms of tool use to advanced cognitive functioning in all these species, a perception-action perspective suggests instead that a common process of affordance learning underlies these kinds of adaptive behaviors.

In our work, we have used the Gibsons' ecological approach to understand the development of tool use. Our application of Gibsonian theory suggests that the achievement of tool use is rooted in infants' abilities to explore objects and learn how objects change the properties and action capabilities of the limbs (E. J. Gibson & Pick, 2000; Lockman, 2000). On this view, tool use is a gradual achievement, based less on a qualitative change in cognitive abilities than on repeated exploration of the physical properties of objects in relation to surfaces in the environment. This view, therefore, suggests that the origins of tool use can be found in the perception-action routines that infants use to explore their environments. Because tools, however, change the properties of the limbs, infants need to explore how particular tools introduce new opportunities for action or affordances in the environment. A corollary of this viewpoint is that infants adapt existing motor abilities when they attempt to use tools. Hence, this view also suggests that at a motor level, infant manual abilities may serve as a substrate for the motor behaviors that older children employ when they use tools. In our empirical research, we have been applying these ideas to examine how tool use emerges from the object manipulation skills of infants, especially from infants' attempts to relate objects to surfaces in their environments.

We start with the premise that tool use typically entails an individual relating an object (tool) to another object or surface to achieve a goal. From this starting point, we have focused on two related questions. First, do infants relate objects to surfaces in a discriminating manner, based on the material properties of each? To the extent that infants do, this would suggest that the subsequent achievement of tool use by toddlers entails an extension of this earlier object relational ability. Second, at a motor level, we ask whether the actions that infants employ to manipulate objects are similar to the ones that older children employ when they engage in tool use. To the degree that these actions are isomorphic, this would indicate that the early manual actions of infants serve as a motor substrate from which tool use arises. Taken together, evidence that addresses how infants relate objects to surfaces and whether object manipulation behaviors are incorporated into later tool use would suggest that tool use emerges gradually over developmental time, building on earlier appearing manual skills. We consider our research on these issues in more detail below.

Relating Objects to Surfaces

Do infants relate objects to surfaces in a discriminating manner, based on the physical properties of the hand-held object and the type of surface that the object contacts? Evidence that they do would indicate that infants have the capacity to adapt to changes in the properties of the hand associated with holding an object. To examine this issue, we conducted a series of studies in which we systematically varied the material composition of objects and the tabletop surfaces on which infants manipulated these objects.

In one study, we presented 6- to 10-month-old infants with either a hard or soft object on tabletop surfaces that also differed in terms of their material make-up (Bourgeois, Khawar, Neal, & Lockman, 2005). Tabletop surfaces were either rigid (particle board), flexible (foam), discontinuous (netting) or liquid (water in a large tray). Each object-tabletop combination was presented one at a time. We analyzed how infants related the objects and surfaces together. The results indicated that infants combined the objects and surfaces selectively, by taking into account the material properties of each. This was especially true at the older ages. For instance, older infants were more likely to rub the objects across the rigid tabletop surface, presumably because this surface provided the least amount of friction during this action. Additionally, across age, infants were more likely to bang the hard object on the rigid and discontinuous surfaces than the flexible and liquid surfaces. More generally, these findings, along with others indicating that infants combine objects and surfaces appropriately (Morgante & Keen, 2008; Palmer, 1989), suggest that infants are already sensitive to the ways in which objects can change the affordances of the hand—a basic ability that contributes to successful tool use.

Using Handled Objects

We next asked whether infants show similar forms of adaptive behavior when they explore handled objects and hold the object by the handle rather than the object itself. Many human tools consist of handles attached to objects. Handles, however, pose potential challenges for tool users. Handles introduce an intermediate element between the hand and the functional end of the tool. As a consequence, the object is also lengthened due to the addition of the

handle, which potentially creates further control demands. For individuals to use handled objects adaptively, they must gear their manual actions to the functional end of the object, and not to the handle alone. Indeed, handled-tools appear relatively late in the lithic record (Ambrose, 2001), suggesting that manufacturing and using handled tools entail difficulties beyond those involved in using tools without handles.

To investigate whether infants use handled objects in a functionally appropriate manner, we adapted the procedures of the Bourgeois et al. (2005) study. We presented a new sample of 6- to 10-month-old infants with hammer-like objects: hard or soft cubes attached to handles. These hammer-like objects were placed on different kinds of tabletop surfaces: rigid, flexible, discontinuous or liquid (Walthall, Bourgeois, Neal, & Lockman, in preparation), one at a time. Handles were simply thin wooden dowels encased in a firm rubber coating. The focal question was whether infants would use the handles as extensions of the objects. That is, would infants relate the cubes to the surfaces appropriately even when infants were holding the handle and not the cube?

Our results indicated that infants indeed treated the handle as an extension of the object. They tailored their manual behaviors to the functional end of the object—that is, the type of cube located at the end of the handle and the surface contacted by that cube. For instance, when holding the handle, infants banged the hard cube more than the soft cube against the rigid surface, presumably to produce noise. By contrast, when still holding the handle, infants banged the soft cube an equivalent amount against the different tabletop surfaces. Taken together, the results suggest that infants were using the handle as an extension of the object, gearing their behaviors to the physical composition of the object at the end of the handle and the surface that it contacted. Infants thus treat handled objects as a unified whole, much like adults who are able to gain information about the overall properties of an extended object by action on only a limited portion of it (Turvey, 1966).

More generally, the results of these two studies suggest that objects, including ones with handles, function as extensions of the hand and that infants can adapt their actions to the new affordances entailed by these objects. This is exactly the type of capacity that would be needed to link tool use and object manipulation. Tools, like objects, change the action capabilities of the hand. That infants can already adapt to object-induced changes in the properties of the hand suggests a continuous mechanism over developmental time by which young children can learn to use tools in a functionally appropriate manner.

Motor Precursors to Tool Use

As noted, a perception-action perspective on tool use development suggests that at a motor level, there is some continuity between the motor behaviors that infants perform when they manipulate objects and when they begin to use tools. Rather than learning entirely new motor behaviors to engage in tool use, older children may adapt actions that they already perform as infants. To examine this possibility, we have been focusing on object banging or more generally, percussive behaviors. Percussive action is a common tool use behavior, found in both human and non-human primates (Inoue-Nakamura & Matsuzawa, 1997). Nevertheless, how percussive action develops in human infants and how it may transition to

tool use in the post-infancy years are issues that have received little theoretical or empirical attention.

To address whether banging may serve as a motor substrate for percussive tool use, we have been using kinematic methods to study developmental changes in object banging during infancy. In two recent studies (Kahrs, Jung, & Lockman, 2012a, 2012b), we presented infants between 6-14 months with a 2.5 cm cube or a cube of the same dimension attached to a 10 cm handle. Infants were seated at a table in their parent's lap and were allowed to explore freely. Kinematic data from reflective markers placed on their torso and arm were recorded at 240 Hz. Overall, we collected data for 513 strikes from 34 infants. Since we were interested in the functional implications of banging, our analyses focused on the movements of the hand, rather than the component movements of the arm joints and torso that were also associated with banging. Furthermore, we were interested in studying the additional motor challenges that accompany the use of handled objects and tools. The introduction of a handle, in essence, adds an extra link to the infants' arm, placing more emphasis on the wrist compared to directly held objects.

Theories of skill development postulate that through repetition infants become more efficient and also more consistent in their movements (Engelbrecht, 2001). The results of both of our studies on object banging confirmed that older infants showed more consistent and efficient hand trajectories as they banged objects compared to their younger counterparts. With increasing age, infants' hand movements when banging became straighter, more consistent from one strike to the next and more efficient in terms of the spatiotemporal characteristics of the hand's trajectory. These changes over the course of the first year make banging well suited for percussive tool use, in part because this action and the force delivered by the hand become more consistent and predictable. Furthermore, since the most efficient way to move the hand up and down is to eliminate sideways movements, hand movements became straighter, thus keeping the hand directly over a possible target and thereby making aiming easier. Together, these age-related changes suggest that banging is becoming pre-adapted for instrumental use.

Another challenge for potential tool users is to accommodate the changes in body properties that are introduced when wielding a tool. In our studies, we were interested in whether infants would act differently depending on the type of object they were holding: a cube or a handled cube. Holding a cube alters the physical properties of the hand. When holding a handled cube, however, additional changes to the properties of the entire motor system are introduced, centering on the wrist joint. Because of these additional demands, we expect infants at younger ages would show more variability in their hand trajectories as they attempt to gain control of the handled cube compared to the directly-held cube. To test this hypothesis, we compared how infants banged the regular cube and the handled cube.

We focused on four variables associated with skilled banging movements during infancy: Distance traversed, straightness ratio, peak velocity and strike-to-strike consistency (Kahrs et al., 2012b). For each data set involving banging a cube (Kahrs et al., 2012a) and banging a handled cube (Kahrs et al., 2012b), we compared performance along the above variables. Comparisons for each variable across age (Table 1) reveal a consistent pattern:

Developmental change for each variable was greater for the infants banging a handled cube compared to those banging a regular cube. Furthermore, infants at the youngest ages (i.e., 7 months) started out with higher values on each variable when banging a handled cube rather than the cube alone, suggesting less skill in their movements with the handled object. Younger infants also showed equal or greater levels of variability around the mean on every measure when banging the handled cube compared to the regular cube (Table 2).

Taken together, these analyses show clear differences between the effects of the two objects. Young infants who banged the handled cube evidenced less control and were more variable than their counterparts who banged the simple cube. This pattern suggests that young infants explored a greater space of possible motor solutions when presented with an object that changed the properties of their bodies to a greater extent. In contrast, no such systematic differences were found for the older (14-months-old) infants. While these cross-sectional data provide clues about the process of developmental change, longitudinal data from infants using handled and non-handled objects will be necessary to understand the process of change more directly.

Conclusions

Tool use has long been considered a cognitive advance regardless of the developmental time scale (phylogenesis, ontogenesis and microgenesis) under consideration. In contrast, by employing the Gibsons' ecological approach, our work on the early development of percussive behavior suggests that the achievement of tool use is less a cognitive advance than one that entails a continuation of processes evidenced in affordance learning and perception-action coupling. Infants adapt to changes in the properties of their hands when holding objects. They combine objects and surfaces together selectively, based on the material properties of each. Just as important, they do so when they hold handled objects and appropriately relate those objects (located at the end of the handle) to surfaces. Likewise, at a motor level, there is continuity in the behaviors that support the emergence of tool use. Infants adapt the percussive movements involved in banging in ways that make these actions ideally suited for instrumental tool use. Nevertheless, controlling handled objects at a motor level introduces additional demands. Our findings indicate that infants achieve such control later in comparison to similar forms of control when they bang objects without handles.

More broadly, our work suggests that there is considerable utility in framing the problem of the emergence of tool use as an ongoing process of perceptuomotor adaptation. Such a process-oriented approach not only offers a way of linking the manual behaviors of infants to the tool use behaviors of older children, but also provides a way of viewing tool use as a product of more general perception-action processes that characterize the functioning of all organisms.

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Table 1
Changes in the mean as a function of age for infants' movement parameters when banging.

Measure	Object	b _{Age}	t	p	7-months (mean)	14-months (mean)
Distance traversed	Cube	-.705	-1.62	.13	302 mm	157 mm
	Handled-Cube	-1.00	-4.72	<.01	349 mm	143 mm
Straightness ratio	Cube	-.001	-2.53	<.05	1.31	1.13
	Handled-Cube	-.001	-3.27	<.01	1.40	1.09
Peak velocity	Cube	-.007	-1.09	.29	13.8 m/s	10.2 m/s
	Handled-Cube	-.020	-5.20	<.001	15.9 m/s	6.7 m/s
Strike-to-strike consistency	Cube	-.003	-0.04	.97	44 mm	43 mm
	Handled-Cube	-.110	-2.61	<.05	52 mm	30 mm

Note. Comparison of four movement parameters changing as a function of age for infants performing banging movements with a cube (Kahrs et al. 2012a) and a handled cube (Kahrs et al. 2012b). Shown are the regression parameters for age (b_{Age}), and their associated t-statistics and p-values. In addition the predicted values for the very young (7-months) and older infants (14 months) are shown for each movement parameter.

Table 2

Changes in variance as a function of age for infants' movement parameters when banging.

Measure	Object	δ_{Age}	χ^2_1	p	7-months (SD)	14-months (SD)
Distance traversed	Cube	0.11	0.33	.56	63.3 mm	69.8 mm
	Handled-Cube	-0.69	12.6	<.01	87.6 mm	51.0 mm
Straightness ratio	Cube	-2.12	74.3	<.001	0.18	0.06
	Handled-Cube	-1.34	44.0	<.001	0.18	0.08
Peak velocity	Cube	0.97	23.2	<.001	2.28 m/s	3.74 m/s
	Handled-Cube	-0.61	9.89	<.01	4.05 m/s	2.60 m/s
Strike-to-strike consistency	Cube	-0.41	2.41	.12	12.6 mm	12.5 mm
	Handled-Cube	-0.06	0.09	.76	12.7 mm	15.7 mm

Note. Comparison of the variance around the mean changing as a function of age (heteroscedasticity) for each of the four movement parameters computed on infants' banging movements with a cube (Kahrs et al. 2012a) and a handled cube (Kahrs et al. 2012b). Shown are the estimated changes in variance as a function of age (δ_{Age}) modeled as $Var(\hat{\epsilon}) = \sigma^2_{Age} \delta_{Age}^2$, and the associated χ^2 -statistics and p-values. In addition the predicted standard deviation around the mean for very young (7-months) and older infants (14 months) are shown for each movement parameter. SD = Standard Deviation.