From: Gedeon O. Deák, Development of Adaptive Tool-Use in Early Childhood: Sensorimotor, Social, and Conceptual Factors. In Janette B. Benson, editor: *Advances in Child Development and Behavior* Vol. 46, Burlington: Academic Press, 2014, pp. 149-181.
ISBN: 978-0-12-800285-8
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Academic Press
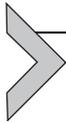
> CHAPTER SIX

Development of Adaptive Tool-Use in Early Childhood: Sensorimotor, Social, and Conceptual Factors

Gedeon O. Deák[1]

Department of Cognitive Science, University of California–San Diego, La Jolla, California, USA
[1]Corresponding author: e-mail address: deak@cogsci.ucsd.edu

Contents

Abstract

Tool-use is specialized in humans, and juvenile humans show much more prolific and prodigious tool-use than other juvenile primates. Nonhuman primates possess many of the basic motor and behavioral capacities needed for manual tool-use: perceptual-motor specialization, sociocultural practices and interactions, and abstract conceptualization of kinds of functions, both real and imagined. These traits jointly contribute to the human specialization for tool-using. In particular, from 2 to 5 years of age children develop: (i) more refined motor routines for interacting with a variety of objects, (ii) a deeper understanding and awareness of the cultural context of object-use practices, and (iii) a cognitive facility to represent potential dynamic human–object interactions. The last trait, which has received little attention in recent years, is defined as the ability to form abstract (i.e., generalizable to novel contexts) representations of kinds of functions, even with relatively little training or instruction. This trait might depend not only on extensive tool-using experience but also on developing cognitive abilities, including a variety of cognitive flexibility:

specifically, imagistic memory for event sequences incorporating causal inferences about mechanical effects. Final speculations point to a possible network of neural systems that might contribute to the cognitive capacity that includes sensorimotor, sensory integration, and prefrontal cortical resources and interconnections.
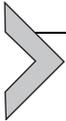
1. *ECCE HOMO HABILIS*: COGNITIVE AND DEVELOPMENTAL BASES OF HUMAN TOOL-USE

Tool-using is a hallmark of human intelligence but its fundamental nature remains a matter of controversy. All human cultures show prolific, diverse, early-emerging tool-use. This capacity for tool-use is even evident in very young children. Toddlers, for example, show great interest in artifactual objects and will act on representational objects (e.g., toy cars) based on their apparent function (DeLoache, Uttal, & Rosengren, 2004; Mandler & McDonough, 1998). This suggests that humans from a very early age are forming abstract representations of object function and are motivated to interact behaviorally with a wide variety of artifacts. The central question, then, is: What is the developmental basis of human tool-use? The hypothesis pursued here is that specialized tool-use is supported by specialization of perceptual-motor skills, by human enculturation practices, and partly by the cognitive ability to flexibly and rapidly represent possible functions of objects.

The remainder of this section will briefly summarize evidence of specialization of human tool-use. Section 2 outlines gross changes in tool-using skills in children, including the development of sensorimotor and sociocultural factors. Section 3 examines how higher-order cognitive skills, including flexible representations of abstract function-types, contribute to specialized human tool-using capacities. Section 4 explores how these skills develop during childhood. In each section I will consider relevant data on neural systems and processes that support tool-use.

1.1. Are Humans Uniquely Adept Tool-Users?

Nonhuman primates, like humans, possess the perceptual-motor skills to use tools. An abundance of research shows that many primate species, most notably apes and gibbons, have the cognitive capacity to rapidly learn new tool-using skills (e.g., Bjorklund, Yunger, Bering, & Ragan, 2002; Cunningham, Anderson, & Mootnick, 2006). Even juveniles nonhuman apes can represent and reproduce others' motor behaviors (e.g., Custance, Whiten, & Bard, 1995). We can legitimately ask whether humans, or more

broadly hominins, are so specialized in our tool-using capacities. The difficulty in answering this question is that we are surrounded by a rich "artifact culture" unlike any other species. Relatedly, humans (and presumably hominins) can use language to learn about tools and functions. Considering these factors, it is not entirely clear that humans are cognitively specialized for tool-use.

There is accumulating evidence of tool-using skills in nonhumans. Enculturated apes learn to use human artifacts, and wild chimpanzees show selective use and conservation of tools (Boesch-Achermann & Boesch, 1993; Mulcahy & Call, 2006). More distantly related primates—New World monkeys such as tamarins and cebus—also show tool-use, as do other vertebrates including dolphins (Krützen et al., 2005) and crows (Weir, Chappel, & Kacelnik, 2002).

Yet there is reason to believe that tool-using skills of nonhuman primates, even those raised in environments with many artifacts, do not match those of humans, even taking into account humans' greater experience and cultural support (e.g., Custance, Whiten, & Fredman, 1999; Gomez, 2006; Tomasello, 1999). Monkeys, infer and adopt new object functions slowly and laboriously: Tamarins, for example, produce means-end manual actions with objects only after extensive practice, and even then many animals show no evidence of discriminating physical properties that afford particular functions (e.g., Visalberghi & Limongelli, 1994). Even apes show what in humans would be considered limited ability. Only recently was proto-tool-use observed in wild gorillas (Breuer, Ndoundou-Hockemba, & Fishlock, 2005), and even adult enculturated chimpanzees sometimes fail to learn simple tool-uses such as nut-cracking with stones after extensive demonstrations and practice (Birch, 1945; Hayashi, Mizuno, & Matsuzawa, 2005). Moreover, the range of functions and tools tested with nonhuman primates is quite limited. Most studies focus on poking or reaching/raking functions (e.g., Köhler, 1927), although apes certainly can learn a wider range (e.g., Bjorklund et al., 2002). If we compare the handful of tool-uses taught to all nonape primates in all studies to the range of tools and functions used by 4-year-old children in a typical Western preschool, it becomes clear that the tool-using skills of nonapes differ radically from that of humans.

In every human culture studied, present and past, hominin groups have extensively manipulated available materials in a variety of ways for a variety of purposes. There is a diverse fossil record of bone, stone, and shell tools and artifacts from African Mid-Palaeolithic peoples dating from 60 to 30 kya

(Henshilwood et al., 2001; Klein, 2000). These findings point to a continuous fossil record going back to the Late Pleistocene, possibly as far back as 190–250 kya (McBrearty & Brooks, 2000). The oldest examples of Acheulean stone tools[1] are attributed to *Homo erectus* of 1 mya or older. This is significant, in part, because mechanisms for broad promulgation of tool-use (e.g., written records, long-distance travel, formal educational systems) were virtually non-existent. Thus, we might speculate that the individual cognitive capacity to innovate and improve upon more primitive available tools was a not-uncommon achievement. In sum, the hominin capacity for tool-using adaptations is apparently rather old and not completely dependent on elaborate existing technological infrastructure. Also intriguing is the scant fossil evidence that prehistoric *Homo sapiens* children made, modified, and used size-appropriate adult-like tools, plausibly for purposes including play, and learning adult tool-making and tool-using skills (Park, 2006; Smith, 2006). Though the existence of fragments from early hominins does not prove their cognitive equivalence to us, it is possible that children's capacity for tool-use stretches far into our pretechnological prehistory.[2]

The question, then, is how to characterize the specialization of human tool-use and its development. I turn first to research on human infants and young children because it is reasonable to expect that the capacity for individuals to integrate an "artifact culture" emerges progressively with age and experience.
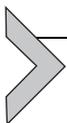
2. THE DEVELOPMENT OF HUMAN TOOL-USING ABILITIES

Humans' propensity to manipulate objects starts almost as early as our infantile perceptual-motor abilities support it (Claxton, Keen, & McCarty, 2003; Connolly & Dalgleish, 1989; McCarty, Clifton, &

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[1] These were more complex and deliberately crafted than earlier stone artifacts.

[2] It could be argued that learning tool-uses "from scratch" does not differ much between humans and chimpanzees. Preliterate humans require about 10 years to master the construction of high-quality stone tools (Stout, 2002), and there is evidence that preschool children have difficulty innovating tools (Beck, Apperly, Carlie, Guthrie, & Cutting, 2011). Although wild chimpanzee infants learn from their kin to crack nuts within about 3.5 years (Inoue-Nakamura & Matsuzawa, 1997), this is tool-*use*, not tool-*making* or innovation. Tool-*making* requires different and refined perceptual-motor skills, as well as, particularly refined representations of the desired functional affordances of an imagined tools. Also, as juvenile chimpanzees are learning nut-cracking skills they are acquiring at most only a few other tool-using skills, whereas apprentice human adze-makers, for example, are simultaneously mastering numerous other tool uses.

Collard, 2001). Starting in their first months infants learn about object *affordances* (Gibson, 1979; see below) through exploratory activity and observation.

2.1. Sensorimotor Development and Exploration of Affordances

Object functions are based on the physical layout and properties of objects: their material, parts and part configuration, and markings. To characterize how such properties relate to tool-use, we invoke the concept of *affordances* (Gibson, 1979). An affordance is an object's potential to allow some sort of interaction with an organism (Gibson, 1982). For example, a chair affords sitting, standing-upon, or propping open a door. To humans, a cup affords containment of liquids or solids smaller than the mouth of the cup (e.g., flour, pens), tracing circles on paper, or weighting down papers. Affordances are defined by multiple properties (e.g., a paper cup, unlike a mug, cannot weigh down papers). Because affordances are defined by a specific organism's potential for interacting with those properties, they are inherent to the object-organism interaction rather than to the object alone. For example, plaster walls afford walking for flies but not humans, whereas they afford picture hanging for humans but not flies. Individual humans can exploit different affordances too, of course; a guitar affords more actions to a skilled player than to a rank novice. This is relevant when considering the early development of tool-use, because most artifacts have properties designed to afford certain actions to adults but not to infants and young children. These properties encompass everything from the size of handles to distances between controls (e.g., in an automobile) and the strength or dexterity to operate the tool (e.g., can opener, keyboard). Consequently, infants must learn to use tools in a world engineered for adults.

Infants and young children are restricted from exploring object affordances not only by their physical limitations but also by the limited accessibility of artifacts. Proximity of tool and goal objects promotes children's detection of an affordance (Bates, Carlson-Luden, & Bretherton, 1980). Opportunities to interact with objects are constrained by adults' design of children's environments. This design determines, for example, where objects are located and what sorts of interactions are permitted. Below we will consider issues of social input and social structure in children's acquisition of tool-using skills. First, though, we must consider how the development of sensorimotor abilities affects the development of tool-use (see also

Guerin, Krüger, & Kraft, 2013 and Lockman, 2000, for reviews of this topic).

Six- to 12-month-olds readily manipulate novel objects to explore their visible or haptic properties (e.g., squeezing soft objects or banging hard objects; Bourgeois, Khawar, Neal, & Lockman, 2005; Palmer, 1989). Through these interactions infants even become sensitive to the affordances of objects and how the affordances of multiple objects interact (e.g., the hardness of a graspable object and that of surface it is resting on, for banging). Exploration is a progressive, embodied, multimodal process. When infants first encounter an object they will visually explore its surfaces, boundaries, textures, and markings. This "active vision" (Ballard, 1991) guides infants' manual exploration so that by 5 months of age they adapt their reaching to object properties (e.g., Von Hofsten, 1991). As infants reach for, contact, and manipulate (and orally explore) objects, multimodal information becomes available so that infants refine their ability to interact with those and similar objects, and detect new affordances. Refinement can be gradual: younger infants learn to use a type of tool (e.g., spoon) over weeks and months of daily experience (Connolly & Dalgleish, 1989). This protracted development is partly due to their consolidation of motor synergies and motor control processes (e.g., Corbetta, Thelen, & Johnson, 2000).

Multiple neurodevelopmental factors contribute to the protracted acquisition of fluid tool-using skills. For example, the corticospinal tract, which is critical for deliberate object manipulation, is fairly late maturing (e.g., Gilmore et al., 2007). Cortical visual control, another critical factor in object exploration, also develops in the first few postnatal months (Johnson, 1990). Furthermore, some cortical and subcortical networks for integrating intermodal information appear to be relatively late-developing in infancy (Wallace, Carriere, Perrault, Vaughan, & Stein, 2006). Finally, development of certain cerebellar nuclei and cerebrocerebellar connections (e.g., cortico-ponto-cerebellar pathway) very likely contribute to skilled multimodal object exploration in the first year (e.g., Hans, Lammens, Wesseling, & Hori, 2006; Limperopoulos et al., 2005; Stoodley & Schmahmann, 2010).

Despite the immaturity of some crucial neurological resources, infants younger than 12 months will sometimes learn and rapidly generalize novel, nonobvious object affordances (Baldwin, Markman, & Melartin, 1993). For example, an infant interacting with spoons over days and weeks will eventually encode from these multimodal embodied experiences a more

generalized spoon–using action pattern.[3] This representation can be con-ceived as a contextually dependent, probabilistic neural network vector state that is activated in a graded manner by ongoing dynamic perceptual–motor states.

Simple function-types thus emerge late in the first year. For example, 6- to 11-month-old infants can classify object events using the generalized affordance of containment (Casasola & Cohen, 2002; Casasola, Cohen, & Chiarello, 2003). By 10–14 months, infants rapidly learn novel and abstract form-function associations (Horst, Oakes, & Madole, 2005). That is, they classify novel dissimilar-looking objects as similar based on a shared affordance (Madole, Oakes, & Cohen, 1993). Infants' object categories show graded prototypicality effects around learned affordances: Barrett, Davis, and Needham (2007) found that 12- to 18-month-olds generalized familiar but task-inappropriate actions to a prototypical spoon but not to a modified atypical spoon-like object. This suggests that infants do not promiscuously generalize any possible action or affordance to any object. In that study, however, the objects differed in both affordances and irrele-vant properties, and this combination of differences might have reduced generalization. Nevertheless, 1-year-olds can learn object actions and gen-eralize them to novel objects with similar affordances even after a delay (e.g., Baldwin et al., 1993; Bauer & Dow, 1994; Bauer & Fivush, 1994). Although various studies show a complex picture of the kinds of properties that infants generalize, relative to infant age and delay interval (e.g., Hartshorn et al., 1998), infants' ability to generalize and remember affordances certainly emerges before the first birthday. This ability is a critical cognitive element of human tool-use.

Tool-using skill depends on infants' and preschoolers' experiences with objects. Practice with an object's affordance helps infants reenact object-appropriate actions (e.g., Barrett et al., 2007), indicating a change in the infant's underlying sensorimotor representation. Reminders—even just seeing the object—further prolong infants' memory of affordances (Barr, Dowden, & Hayne, 1996; Bauer, Hertsgaard, & Wewerka, 1995). The parameters of experience-based learning are not fully known, but it is clear that they are constrained by infants' exploratory and intersensory abilities.

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[3] Infants can somehow learn generalized dynamic representations from separate events: by 2 months they can generalize event-elements from prior separate experiences with some distinct details, and they can learn and remember associations between their actions and different outcomes (Rovee-Collier, 1999). Also, by 2 months infants can form expectations about simple two-object events (Hespos & Baillargeon, 2001).

For example, the development of bimanual exploration skills after the first year (Fagard & Lockman, 2005) expands infants' ability to explore new object–object properties. This development probably involves, among other factors, the development of bimanually responsive cells in primary supplementary motor areas (M1, SMA) of cortex. It is less well understood how other physical factors, such as hand and arm strength, and cognitive factors, such as the ability to divide attention between objects in two hands (de Barbaro, Johnson, & Deák, 2013), contribute to this development. The relation between bimanual coordination and the development of tool-use is a conspicuously under-studied topic.

Sensorimotor development and tool-using skills do not end their intimate association after infancy. Like infants, preschool children's exploration and skilled use of objects are closely tied to practice and experience. For example, Greer and Lockman (1998) found that 3-year-olds gradually restricted the ways that they grasped writing tools over a 6-month period, presumably as a result of experience using crayons and markers. However, the study highlights the difficulty of dissociating sensorimotor development from other factors. For example, as 3-year-olds become more experienced using crayons and markers, they might increasingly attend to how adults hold pens and pencils. Thus, social learning could interact with sensorimotor development. It is also possible that adults increasingly encourage 3-year-olds to use more conventional grasping actions, and thereby directly shape children's tool-using skill. This would be a manifestation of Vygotsky's (1978) idea of scaffolding. Parents and teachers can facilitate children's success in learning new tool-uses that are within their grasp (so to speak)—that is, tool-uses in the "zone of proximal development." Such scaffolding has been documented in infants-parent dyads (Zukow-Goldring & Arbib, 2007) and in child–parent dyads (Radziszewska & Rogoff, 1988). Unfortunately, however, there is no comprehensive framework that can explain how this process works (e.g., what social-cognitive skills allow children to benefit from scaffolding), or predict when it will work, or describe how scaffolding processes change systematically from infancy to later childhood. For example, there will certainly be increasingly effective use of verbal instructions, suggestions, and hints in scaffolding interaction as toddlers and preschoolers build receptive language skills. However, parents probably also adapt to their child's changing motor and cognitive capacities (e.g., fine motor control skills, sustained attention, self-regulation). This has not been studied systematically as a factor in children's acquisition of tool-using skills.

In addition to practice, later development of tool–use is influenced by children's emerging implicit knowledge of the physical principles that underlie object affordances. This knowledge need not entail any conceptual understandings, but could be very rudimentary, pre-verbal, embodied, associations that guide or constrain children's expectancies about events. For example, Hood (1995) showed that toddlers infer that a ball would drop down a tube to a location immediately below, rather than following the path of a visible tube that curves to an opening not directly beneath the tube's entrance. Older preschoolers, by contrast, inferred the exit location based on the boundaries and path of the relevant tube. Another study demonstrated that children's expectations about object mass distribution and torque influences how they build block structures (Karmiloff-Smith & Inhelder, 1975). With increasing age, these expectations became more systematic and more accessible for controlled exploration. Eventually, older children can reflect on the detailed affordances of a novel tool based solely on visual examination (Klatzky, Lederman, & Mankinen, 2005). In sum, children's growing knowledge of physical properties impacts their sensorimotor exploration of object affordances and an eventual "distancing" of affordance-detection from intensive multimodal exploration. That distancing, along with the generalization over time and objects described previously, are critical for acquiring function-types, as will be described in Section 3.1.

It is difficult to dissociate sensorimotor development from cognitive factors. For example, in Koslowski and Bruner's (1972) historic study, 12- to 24-month–olds learned to use a lever to retrieve a toy. Toddlers in this task produced a variety of mostly ineffective behaviors. Not surprisingly, the oldest toddlers were more likely to discover how to use the lever effectively. However, this discovery was often preceded by other exploratory actions (e.g., oscillating the lever over short distances) that revealed the tool's affordances. Younger toddlers' exploratory behaviors were less effective. One possible reason is that older toddlers could modify their actions in a controlled way relative to a goal. The difficulty of keeping the goal in mind was evident in toddlers' tendency to move the lever while fixating their gaze on it and ignoring (perhaps forgetting?) the toy. Thus cognitive control (e.g., maintaining a goal representation) plays a role in toddlers' sensorimoter exploration. Cox and Smitsman (2006) note that children's object exploration depends on a complex relationship among object properties, sensorimotor traits of the child, and the child's exploratory goal, which itself is determined by the relation of the child and the context of action. Children's skill in negotiating this interaction improves with age: Bongers, Smitsman,

and Michaels (2004) found that between 2 and 3 years children improved in adapting their posture and movement patterns to carry rods of different lengths and weights to a target. Thus, children continually learn how to move their bodies to manipulate objects *for particular purposes*.

In sum, changes in tool-using skill from infancy to early childhood rest on active, motivated sensorimotor development. These changes continually interact with social and cognitive factors, some of which are described below. The changes occur in the context of the child's history of exploratory activity. Although different theoretical traditions emphasize the importance of exploration (e.g., Gibson, 1982; Piaget, 1954; Sutton & Barto, 1998) little is known about how practice affects children's acquisition of mature tool-using behaviors.

2.2. Social Structures and the Development of Tool-Use

2.2.1 Social Factors in Early Tool-Use

Social factors profoundly affect infants' and toddlers' acquisition of new function-types (Gauvain, de la Ossa, & Hurtado-Ortiz, 2001; Greenfield & Lave, 1982; Want & Harris, 2002). Some social factors compel infants to shift from general exploration of all affordances of objects to focus on the intended or conventional functions of objects. A propensity to watch other people using objects promotes infants' acquisition of typical or intended functions. For example, infants in face-to-face play interactions with a parent are far more interested in their parent's object-handling than in their parent's face, empty hands, or static objects (Deák, Krasno, Triesch, Lewis, & Sepeda, 2014). In an experimental setting, infants also attend to how hands are manipulating objects (Perone, Madole, Ross-Sheehy, Carey, & Oakes, 2008).

Older infants are further primed to learn tool-uses by watching other people. In experimental settings, children as young as 2 or 3 years learn and remember how an adult used an object from just a single demonstration (Casler & Kelemen, 2005; Deák, Ray, & Pick, 2002; Whiten, Custance, Gomez, Teixidor, & Bard, 1996). Even 1-year-olds can learn and remember an object's affordances by watching an adult (Bauer & Hertsgaard, 1993). Although infants remember adult's actions better if the actions are repeated or are causally expectable, these conditions are not *necessary* for infants to remember sequences of actions with objects for days or weeks (Barr et al., 1996; Bauer, 1992; Rakoczy, Tomasello, & Striano, 2005). Thus, infants' attentiveness to others' actions on objects facilitates memory for those actions.

Adults, for their part, craft a wide range of behaviors to guide infants' attention and actions on objects. Parents' verbal bids can draw infants' attention to distal objects (Deák, Walden, Yale, & Lewis, 2008). Verbalizations can draw older toddlers' attention to particular functions of objects, thereby influencing how toddlers classify those objects (Corrigan & Schommer, 1984). Parents also structure infants' interactions with objects using nonverbal communicative strategies. For example, parents will hold and move their infants' hands to get them to manipulate objects "properly" (Zukow-Goldring & Arbib, 2007). Adults' facilitative messages are of course constrained by an infant's sensorimotor and communicative abilities. For example, 2-year-olds are better than 1-year-olds at using adults' suggestions to modify their attempts at object-use (Chen & Siegler, 2000).

Turning to broader, "macro-level" social practices, parents in technologically developed cultures invest resources to create environments that allow infants to interact with a wide variety of toy objects. Modifying physical environments to promote infants' discovery of object affordances (e.g., toy tools, play kitchens, etc.) may facilitate the acquisition of tool-using skills and activities. This can be considered a broader form of cultural scaffolding (Vygotsky, 1978) that involves individual parents but extends to larger societal practices and structures. This topic merits further consideration.

2.2.2 Social Ecology and Learning of Tool-Using Skills

The social environment strongly constrains which affordances children learn to exploit. In the last decade there has been a great deal of research and discussion of infants' and preschoolers' propensity to imitate adults' actions upon objects and even to "over-emulate" (i.e., reproduce useless or inefficient movements) observed behaviors (e.g., Brugger, Lariviere, Mumme, & Bushnell, 2007; Gergely, Bekkering, & Király, 2002; Horner & Whiten, 2005; Schulz, Hooppell, & Jenkins, 2008). Rather than reiterating arguments about imitation that have been extensively articulated elsewhere, the remainder of this section will address far less frequently discussed but arguably no less fundamental questions about social structures that facilitate the development of tool-use in children.

People exploit some but not all affordances of objects (e.g., expensive crystal glasses *can* be thrown, but usually are not). No doubt this is partly due to practical and motivational reasons (e.g., we would only use a brick to pound a nail if it was important to hang the nail quickly and no hammer was available). Humans also, however, tend to limit the affordances that we

exploit to those that are designated as conventional, habitual, or intention-ally designed (Birch, 1945; Düncker, 1945). Vacuum cleaners, for example, are intended to suck dirt, not make noise, even though they do both. Children must sometimes work out this sort of distinction (Matan & Carey, 2001). Fortunately, the social environment offers ample information about intended or conventional object functions, and this information con-strains children's affordance–exploration in various ways. For example, an object's intended function is typically how it is most commonly used (and therefore that which is most commonly seen–in–use). Social agents also provide directive or corrective input about intended uses. For example, a toddler who is using her toothbrush to groom a dog might hear a parent exclaim, "Don't use your toothbrush for that!" Also an artifact may be designed in such a way to highlight the affordances related to its intended use (e.g., making buttons or handles a salient color, or using labels or markings to suggest relevant actions). That is, intended affordances of objects are sometimes engineered for easy discovery and learning (but see Norman, 1988).

The social information structures that indicate intended or conventional object functions may be very diverse. One category of these structures is the set of practices that cultures use to limit children's exploration of object affordances. For example, schools might limit access to sports equipment or craft supplies by putting them in restricted locations, imposing a "gate-keeper" (e.g., an adult who controls access), and implementing explicit rules for usage—where, when, who, and how. This sort of structuring can be so elaborate that a child's exploration of the object's affordances is tightly con-strained. For example, microscopes in a school biology lab might be kept in a special cabinet and made accessible only during certain periods by certain students, and only under the supervision of a designated teacher who tells students how, where, and when to use the tool. Thus, whether or not a nov-ice user (student) notices that a cylindrical end (eye-piece) affords looking-through, or knob-parts afford twisting, that student's exploration of those affordances is tightly constrained. Yet this elaborate system of social con-straints has purposes: not only does it communicate to the novice the value of the tool (nothing is known about how children learn this) but also it primes and accelerates the student's exploration and mastery of the tool's most specific, powerful functions. The teacher's verbal explanation and demonstration, and ongoing monitoring and feedback, is designed to limit *and* accelerate the student's learning of the most special but non-obvious affordances of the object. Naïve exploration would be less

efficient, and the gap between naïve exploration and instructed learning will be greater and greater as object functions become less obvious and more specialized and complex.

Given the ubiquity of this sort of social structuring of tool–using and tool–learning, there is surprisingly little research on *how* children are taught how to use new tools (but see Williams, 2012). Of course these sorts of elaborate social–input practices are not restricted to school settings: children in informal educational settings also receive elaborate social information about intended tool–uses. Experienced weavers in Guatemala, for example, give young girls progressively more difficult tasks to ensure the students' gradual mastery of the varied tools and materials used for weaving (Greenfield & Lave, 1982).

In summary, although there is much active research on the imitative (i.e., social–cognitive) basis of children's acquisition of new tool–uses, virtually nothing is known about the social structures that contribute to children's knowledge of tool–uses. Although there is a large literature on how adults teach children language, there is very little research on how adults—parents, teachers, or coaches—teach children to use objects, and how these practices impact children's tool use. The sizeable literature on child safety, for example, seldom addresses how children learn to use protective equipment or potentially dangerous tools, or how adults teach (or should teach) these crucial tool–using skills (e.g., McLaughlin & Glang, 2010). Similarly, the extensive literature on parenting contains few studies describing how parents teach children tool–using skills, even though this is a crucial, universal, and species–specific aspect of parenting. Some relevant research investigates how parents socialize children to prefer sex–typed toys (e.g., Caldera, Huston, & O'Brien, 1989; Langlois & Downs, 1980), but does not focus on how parents socialize the particular uses of sex–typed toys. A few other relevant and fascinating studies have investigated how parents help their preschool and school–aged children learn complex symbolic tools like pictorial instructions and maps, and how parents' scaffolding strategies differ based on the age and experience of the child (e.g., Gauvain et al., 2001; Radziszewska & Rogoff, 1988; Wood, Bruner, & Ross, 1976). In general, though, a universal, complex, crucial aspect of social knowledge that develops extensively in childhood—namely, tool–use and understanding object functions—remains almost entirely unstudied. I believe we would learn a great deal about human tool–use through vigorous, sophisticated investigation of this topic. However, any number of ethnographic studies and training experiments would not be fully

interpretable without simultaneous investigation of the cognitive and conceptual resources that shape and give rise to social practices and structures for teaching tool-use. It is these cognitive and conceptual resources to which we now turn.
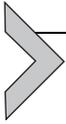
3. THE CONCEPTUAL BASIS OF HUMAN TOOL-USE

Two ideas dominate research on the development of function cognition and tool-using skills. One is that human teaching and learning are species-specialized sociocognitive skills that depend on the capacity to represent others' intentions; including others' intentions when using a tool (Rakoczy et al., 2005; Tomasello, 1999). The second idea is that children acquire a teleological bias or *design stance*: a tendency to ascribe object properties to some designer's intentions. This is thought to influence how children classify and name objects (Diesendruck, Markson, & Bloom, 2003; Kelemen, 1999), and possibly to interfere with creative discovery of unconventional object-uses (Defeyter & German, 2003; Düncker, 1945).

Without discounting the importance of these ideas, I will argue that other cognitive factors also contribute to children's ability to represent, infer, and think about functions. The current hypothesis is that specialization for tool-use begins with a capacity to *notice*, *remember*, and *abstractly generalize* different types of object functions. This capacity leads to the accrual of *function-type* concepts, referred to here as *FT*s. Eventually preschool children develop and refine an additional higher-order *abstract concept of function*—that is, a concept of function in-itself. For convenience, this will be called the *ACF*. The working hypothesis is that development progresses from active, motivated sensorimotor object exploration, to the accrual of a set of FTs, to the eventual emergence of an ACF that is not tied to any particular object, affordance, or function.[4]

To clarify this hypothesis, *function* refers to an object's potential to produce an effect through the deliberate application of nonrandom actions.

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[4] This framework does not imply any hard claims about causal relations between any earlier-emerging specialization and later, more abstract adaptations. It is *possible* that, for example, the early capacity to remember details of tool-using events is critical for learning function-types. However, evidence for such causal relations does not exist. Thus I am only describing evidence-supported adaptations that emerge in gradual, overlapping age-related waves, each of which might be critical for the development of mature tool-using skills. Whether there are strong causal relations among the adaptations is currently a matter of speculation.

Function is somewhat more specific than "affordance": it implies an instrumental object-use that is codified by culture or habit, and typically is supported by design (i.e., engineering to optimize that function).

A further ancillary hypothesis based on research described below is that the ACF emerges gradually between 3 and 5 years of age. Perhaps relatedly, there is no evidence of an ACF in nonhuman apes, although enculturated apes might have an incipient, transitional ACF an expectation that novel objects will have discrete functions, similar to an incipient form in a human 2- or 3-year-old. This ancillary hypothesis could be disconfirmed by evidence that 1- or 2-year-olds have an ACF, or that monkeys have a human–like ACF. It is not, however, disconfirmed by evidence that toddlers and nonhuman primates develop abstract FTs. The model makes no claims about the origins of an ACF in human children, due to a paucity of related evidence, although some tantalizing clues are found in the neuroscience literature, as described in Section 3.1.

3.1. Acquiring Function-Types

Children's ability to remember and generalize episodes of tool-use (witnessed or personally enacted) generates a "vocabulary" of types of functions. As FTs become more robust (i.e., readily evoked; less reliant on item-specific, familiar properties), they support *function-simulation* (i.e., imagined tool-use; Klatzky et al., 2005). These simulations permit creative planning and problem solving and might facilitate a higher-level ACF as described later (Section 3.2). First, however, we consider how children generate an initial set of FTs. What sort of experience—exploratory and socially constrained—could serve as input? What cognitive capacities allow children to acquire FTs?

3.1.1 Acquiring Generalized Function-Types

As outlined in Section 2.1, infants in the first year are learning simple physical affordances of objects, for example, graspability, containment, and noise making. The capacity to rapidly infer, remember, and generalize affordances improves considerably after 6–8 months.

By their second birthday, toddlers can more readily activate context-general, or abstracted, function-types. For example, they will reenact action sequences on objects following observation only, and little or no active haptic exploration of the objects. Moreover, toddlers will act upon toys based on their *depicted* or represented functions, even if the affordances of those

functions are disabled (e.g., toddlers will "cook" plastic food in a toy oven). In fact, 18- to 30-month-old infants occasionally attempt to use a toy object as if it were the functional object it represented, even though the relevant affordances are disabled by the toy's reduced size (DeLoache et al., 2004). As infants get older, they allow greater abstraction of functions away from the specific properties of familiar tools. For example, 28-month-olds are better than 24-month-olds at using a "neutral" object (e.g., stick) to play-act a specific function (e.g., brushing teeth; Harris & Kavanaugh, 1993; see also Johnson, Younger, & Furrer, 2005). Also, toddlers improve from 18 to 30 months at inferring objects' functions from drawings of events (Simcock & DeLoache, 2006). Thus, generalized function representations become more robust and less context dependent from 24 to 36 months.

3.1.2 From Function-Types for Function-Simulations: Transitioning to an ACF?

By 24–26 months, if not earlier, toddlers can do representational "filling in" of event sequences involving object functions. These representations are multimodal and perceptual-motor (see Hommel, Müsseler, Aschersleben, & Prinz, 2001). I will call these event representations *function-simulations*: imagined representations of sequences of actions by a sentient agent, involving causal relations between those actions and objects (i.e., tools). For example, Harris and Kavanaugh (1993) found that from 24 to 30 months toddlers improve in inferring the outcomes of pretended actions with object, with minimal perceptual support. For example, older toddlers can infer that overturning an (empty) container (pretended to contain milk) over a plush toy would result in the toy being wet. Thus, partial perceptual support allows 2-year-olds to "fill in" imagined sequence of actions. This requires abstract knowledge of, for example, containment affordances and pouring actions (as well as physical constrains such as gravity and fluid dynamics).

Elegant evidence that function-simulation develops during early childhood is described by Van Leeuwen, Smitsman, and van Leeuwen (1994). The authors showed that infants and children from 9 months to 4 years improved at using a hook to retrieve a cookie. However, what most determined whether a child succeeded was the ability to make multiple spatial transformations in order to orient and position the hook to pull in the cookie. This was not simply a matter of motor skill because all participants could manipulate the hook and pull in the cookie when the hook was already in position. Rather, difficulty was related to the number of spatial

transformations—like mental rotations—needed to imagine, and then realize, a close-fitting relation between the inward-curved end of the hook and the position of the cookie.

Additional indirect support for a function-simulation hypothesis comes from evidence that toddlers' planning of goal-oriented action sequences improves from 1½ to 3 years (e.g., Bullock & Lutkenhaus, 1988). This improvement occurs roughly during the same period as the ability to generalize FTs to novel objects (Corrigan & Schommer, 1984; Kemler Nelson, Frankenfield, Morris, & Blair, 2000; Kemler Nelson, Russell, Duke, & Jones, 2000). Perhaps this improvement results from children's growing capacity to produce elaborate function-simulations that support goal-directed plans for sequences of actions on objects. That is, the capacity for function-simulation is strongly related to toddlers' emerging FTs. In the next section, I postulate that such simulations might facilitate an ACF.

What is the neural basis of function-simulation? Hommel et al. (2001) outline the putative neural underpinnings of the representational system. Adults' representations have an embodied component—that is, they involve activation of the same resources as "real" tool-using behaviors (Johnson, 2000). Kellenbach, Brett, and Patterson (2003), for example, found PET evidence of a network for processing function- and action-specific properties of graspable objects, including left ventral premotor cortex (VPM), posterior middle temporal gyrus (MTG), and intraparietal sulcus (IPS). These areas are also involved in various ways with processes of action planning, object representations, and sensorimotor integration.

Other related evidence concerns so-called "mirroring" systems in the brain. Some cells in Macaques' premotor cortex, for example, increase firing when the animal produces a specific instrumental action, or when it sees another animal produce the action (Rizzolatti & Craighero, 2004). Many of the same cells are tuned to functionally specific manual actions, suggesting that FTs are related to generalized (e.g., not actor-specific) neural representations. For example, Oberman, McCleery, Ramachandran, and Pineda (2007) found that mirroring effects are elicited by seeing either a human hand or a hand-like tool performing an action. Thus the system seems to represent abstract categories of humanoid-embodied tool-using actions. In adult humans, visual or semantic representations of tools selectively activate a part of rostral-VPM (BA6; Chao & Martin, 2000). This region is an analog of a region in monkeys with significant populations of cells with mirroring properties, suggesting some degree of evolutionary continuity in this representational mechanism. Although currently there is minimal

evidence of the development of action mirroring networks in children, recent evidence shows unambiguously adult-like EEG phenomena related to somatomotor mirroring in 3-year-old children (Liao, Makeig, Acar, & Deák, under review). This suggests that preschool children's FTs are general enough to be elicited by watching an adult enact a deliberate action.

Currently the relation between behavioral evidence of FTs and function-simulations, and neurological evidence of functional action representations, is merely associative. Little is known about the normal human development of brain networks and pathways related to multimodal action representations (e.g., IPS, PMTG, VPM). The relation of input to developmental specialization is a matter of speculation, although Triesch, Jasso, and Deák (2007) presented evidence from a computational simulation suggesting one mechanism through which mirror neurons could develop. In the interest of generating further hypotheses about this process, I will briefly consider input factors in the acquisition of FTs.

3.1.3 Input and Acquisition

Each object-using episode that a child witnesses or enacts can provide dynamic input to a multimodal associative network that can later factor into the reactivation of motor network in response to new objects.

Amount of exposure to tool-use matters. In some cases, brief exposure to a particular function of a multifunctional object can prime young children's generalization of that specific function (Kemler Nelson, 1995). However, repeated experience facilitates toddlers' learning and generalization of function-types (Barr et al., 1996). For example, 2-year-olds' memory for object-action sequences is improved by seeing the sequences enacted several times. Repeated viewing also increases toddlers' propensity to generalize the actions to new test objects (Bauer & Fivush, 1994). Thus even repeated exposure to the same objects does not "entrench" the specifics of that object's function; rather it promotes a more generalized FT representation. Older children also respond to repetition: 4-year-olds classified objects by function more if functions were demonstrated twice rather than once (Deák et al., 2002). The second demonstration did not just ensure that children could remember the function, because even 3-year-olds could remember the functions. Rather, repetition seemed to indicate the importance of the FT—perhaps by underscoring the relevance of object function for the experimenter. What are the neural correlates of these practice effects? There is evidence that tool-use training induces somatomotor representational changes in connections between IPS and frontal cortex (Hihara et al., 2006). This suggests at least one cortical locus

of FT learning effects. It is also likely that repeated experience induces rapid specialization of specific zones or microzones in cerebellum (Imamizu, Kuroda, Miyauchi, Yoshioka, & Kawato, 2003). However, there are no developmental data from children to confirm this prediction.

In sum, before 2 years of age children are acquiring abstract function-types. The acquisition or accessibility of FTs seems to accelerate around 24–26 months, and is influenced by input factors including repetition and the "transparency" of object affordances. FTs eventually become robust enough to support representational simulations of tool-uses, even when there is a paucity of contextual support. This achievement may be a springboard to the next phase of development: The emergence of an ACF.

3.2. Acquiring an ACF

More than a year after infants begin showing knowledge of FTs, perhaps around 4 years of age, children show evidence of a higher-order concept of function. This ACF allows adults and children to more readily organize, select, and communicate about hypothetical functions. The ACF is there-fore a conceptual requisite of humans' artifact culture, allowing us to reflect upon, promulgate, and build upon tool-using innovations. This encom-passes Tomasello's (1999) construct of "ratcheting." To clarify by way of counterexample the nature of the hypothesized ACF: 2- and 3-year-old children can sometimes use tools in adaptive ways, and induce and generalize nonobvious functions of objects, and shift rapidly between FTs (e.g., in the context of pretend play). But these behaviors do not necessarily indicate explicit knowledge that any given artifact—or manufactured or modified material—has *some* intended, conventional, or optimal function, and this function determines other properties of the object, such as its label.

Deák et al. (2002) investigated the development of an ACF by studying how 3- and 4-year-olds choose to sort objects by shape or by function. Chil-dren were first instructed to sort two practice objects by function or by shape. They then sorted eight additional distinct test objects by shape or by function, with no further instructions, reminders, or feedback. Almost all 4-year-olds spontaneously and consistently generalized the practice instruction to the test objects. Thus, a child asked during warm-up trials to put objects "with the one that does the same thing. . .the one that works the same" continued to sort other objects with different functions according to an imputed function rule, though there was no further mention of function. Notably, children did not thoughtlessly sort by function: another

group of children instructed to sort the practice objects by shape spontaneously generalized a shape-sorting rule to the test objects. Also, 4-year-olds who heard no specific practice instruction also spontaneously and consistently used a sorting rule, but some children chose to sort consistently by shape and others sorted consistently by function. Thus, function-based sorting was readily adopted in response to a modest social suggestion. Follow-up studies (Deák, Ray, & Pick, 2004) replicated the finding that 4-year-olds readily generalize an abstract function rule without further suggestion or prompting.

Why does this behavior demonstrate an ACF? Consider by analogy a child in math class completing an arithmetic worksheet. The child might see one or two examples that illustrate one operation (e.g., subtraction) at the top of a page, and then consistently generalize that operation to the remaining problems, even with no explicit instruction to do so. We would then assume that the child has an abstract concept of subtraction. By the same token 4-year-olds in Deák et al. (2002, 2004) demonstrated an ACF.

What about 3-year-olds? In Deák et al. (2002) only 19% of 3-year-olds spontaneously generalized practice instructions to sort by function. One interpretation is that 3-year-olds simply are not consistent. However, 75% of 3-year-olds in a shape-sorting practice group consistently generalized the shape instruction, more than 3-year-olds in a no-instruction group. Thus, 3-year-olds were neither insensitive to instructions nor unable to apply a consistent sorting principle to a series of dissimilar test objects. They just did not generalize a *function* rule. However, in a follow-up study, when 3-year-olds began with four warm-up trials instead of two and were periodically reminded to think about the warm-up trials, 37% of 3-year-olds continued to consistently sort by function. Thus, with added social support (i.e., scaffolding) some 3-year-olds could show an accessible abstract principle of function, but most 4-year-olds did so more readily.

Other relevant evidence of a developing ACF comes from labeling studies. Following a long debate about whether children name artifacts by shape or by function (e.g., Graham, Williams, & Huber, 1999; Kemler Nelson, Frankenfield, et al., 2000; Smith, Jones, & Landau, 1996), there is now converging evidence that children, like adults, label artifacts according to their function (Bloom, 1996; Hughes, Woodcock, & Funnell, 2005; Miller & Johnson-Laird, 1976; Myung, Blumstein, & Sedivy, 2006). Even if external appearances conflict with function, and objects and labels are novel,

4-year-olds often prefer to label by function (Kemler Nelson, 1999): Deák et al. (2002), for instance, found that regardless of how children sorted objects (by shape or function) 4-year-olds labeled them by function. This tendency increased from 3 to 5 years. Extending the age-related trend reported by Deák et al. (2004), other studies show that 2- and 3-year-olds consider function information when labeling objects (Kemler Nelson, 1995; Kemler Nelson, Russell et al., 2000), and infer that novel labels refer to function-defined categories (Kemler Nelson, 1999). These tendencies seem to be stronger in children 4 years and older than in children 3 years or younger (Smith et al., 1996). How are these results relevant to an ACF? *Consistent* patterns of label extension, particularly with novel objects and conflicting properties, imply some abstract principle. If children sometimes label by function and sometimes by other properties, perhaps on the basis of salience, it would not constitute evidence for an ACF. That pattern is in fact more common in 2- and 3-year-olds than in 4-year-olds. Thus, results support the claim that from 3 to 5 years of age, most neurologically healthy, middle-SES children are acquiring an accessible ACF.

3.2.1 Does the ACF Emerge from Social Understanding?

One question is how the ACF relates to the capacity to infer and imitate others' instrumental actions—a capacity that emerges as early as the second year (Tomasello, 1999). Human children imitate object-uses somewhat differently than nonhuman primates do, at least partly because they take into account an actor's intentions (e.g., Horner & Whiten, 2005; Whiten et al., 1996). The relation between children's inferences about intentions and inferences about object functions remains unclear (Gergely et al., 2002; Tomasello, 1999), but it is not obvious why the former would be necessary for the latter. Toddlers do not imitate tool-use the same way they imitate noninstrumental play (Rakoczy et al., 2005), and preschoolers can flexibly infer complex object functions without a basis for imitation (Deák & Boddupalli, under review; see below). For example, Thompson and Russell (2004) found that toddlers emulate a tool-use after seeing it animated with no human actor. Thus, the capacity for imitation cannot readily explain the developing ACF.

3.2.2 Later Developments

There is no reason to believe that the ACF develops precipitously in the fifth year, or that it undergoes no further refinement after 5 or 6 years.

Adults tend to conceptualize artifacts in terms of their *intended* functions (i.e., the function intended by the designer; Dennett, 1987), and this "design stance" can be conceived as a refinement of an ACF. Human children also acquire a design stance that guides certain of their inferences about objects and functions (Bloom, 1996; Gelman & Bloom, 2000; Matan & Carey, 2001), but this acquisition appears to be fairly protracted. Matan and Carey (2001), for example, found a design stance was stronger in 6-year-olds' than 4-year-olds' inferences about object functions (see also Defeyter, Hearing, & German, 2009). Moreover, Defeyter and German (2003) found that 5-year-olds readily enable both conventional and non-conventional affordances of a familiar object type, but 6- to 7-year-olds were more likely to identify artifacts only with their intended functions and ignore unconventional affordances. This suggests that a design stance constrains inferences of 6- and 7-year-olds, but not younger children. Also, Kelemen (1999) found that older children do not clearly differentiate between teleological (i.e., intentionally created) origins of artifacts from other (e.g., evolved) origins of natural kinds (e.g., animals or minerals). This suggests that inferences about design are refined slowly to guide children's inferences about functions. Evidence that the design stance follows a more rudimentary ACF can be inferred from the questions preschool-aged children ask adults about novel artifacts. Preschoolers sometimes ask, "What is it for?" or "What do you do with it?" (Greif, Kemler Nelson, Keil, & Gutierrez, 2006; Kemler Nelson, Egan, & Holt, 2004) but not "Who made it?" or "Why is it here?" suggesting that questions about origins and designs are secondary to questions about function. Of course, design and origin questions might simply be more difficult to articulate. Nonetheless, the hypothesis that the design stance is a later refinement remains plausible.

3.2.3 Why Do Humans Develop an ACF?

All of this begs the question of why we would require an ACF at all. On one hand this question is analogous to questions of why we are capable of metalinguistic conceptualization or reflection on high-order social structures (e.g., macroeconomics, political philosophy). Perhaps humans by middle childhood have developed a general capacity for higher-order meta-conceptual reflection, and this can be applied to any topic (see Sperber, 2000). The ACF would be a manifestation of this capacity as applied to functions and tool-uses. On the other hand, there might be some differentiation of these meta-conceptual tendencies: one can

imagine that in our evolutionary ancestral environment certain kinds of meta–representations were especially useful. These might include a capacity to reason about human motives and mental states, and a capacity to reason about general causal forces and processes in the physical world. This hypothesis is expounded by Tomasello (1999). The point, however speculative, is that expanding tool-use by our hominin ancestors might indicate a privileged role of the ACF in the human capacity for meta-representation.

Although that speculation is untestable, we can indeed investigate how the ACF allows modern humans to reason about, classify, plan, communicate about, and solve problems with tools. In other words, why does an ACF matter? In the following section, I will explore the development of a tool-using capacity that might rest, at least in part, on an ACF. This is the ability to think flexibly about possible functions.
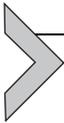
4. FLEXIBLE GENERALIZATION OF FUNCTION

The capacity to think flexibly about functions is central to some human specializations in thinking about tool-uses (e.g., engineering, design). An ACF that supports flexibility among individuals in a cooperative group is a prerequisite of cultural institutions such as manufacturing, architecture, and industrial design.

The capacity to think flexibly about function remains challenging throughout the lifespan (Birch, 1945; Düncker, 1945; Ye, Cardwell, & Mark, 2009). In childhood, there is converging evidence of substantial increases in cognitive flexibility from 2 to 4 years. Although 2-year-olds show some flexibility by substituting objects in pretend play, their fluidity in dissociating surface properties from pretended functions improves from 2 to 3 years (Harris & Kavanaugh, 1993). Moreover, there is growing evidence that this ability continues to improve from 3 to 5 years. For example, Deák et al. (2004) found that 4-year-olds could switch from using a shape-matching rule to using a function-matching rule, whereas 3-year-olds could not. However, the results could have been due to a simple increase in ability to sort objects according to their function, not necessarily due to any additional changes in flexibility.

More conclusive evidence comes from a more recent finding that from 3 to 5 years children become more flexible at inferring different functions in the same array of objects (Deák, 2006; Deák & Boddupalli, under review).

Children were asked to infer and generalize different functional affordances of different objects in a complex array. They were shown object sets several times. Each set included five objects, and each object had three parts that afforded three functions. One object in each set was a standard object. That object's three parts were each similar to one part from each of three other objects in the set. Thus, the standard shared one of the affordances of each of three other objects. Each time children saw a given set they learned that the standard could produce some function (e.g., sifting pebbles from sand). They did not see how this was done, so they had to infer which of the standard's parts afforded the function and then induce which of the other four objects had a part that afforded the same function. A different effect and affordance was featured on each trial, so every time children saw a set they had to infer and generalize a different part. This task tested children's flexibility in generalizing different functions shared by different subsets of objects within a set.

In this test, 3-year-olds were above chance in their first inferences about the sets; this finding, along with pretest results, indicates that they were capable of detecting the relevant affordances of the various parts. However, 3-year-olds' later inferences, which required shifting attention to different affordances/parts of previously seen objects, were less accurate than their first inferences, and less accurate and flexible than the inferences of 5-year-olds. Four-year-olds showed intermediate flexibility. One interpretation is that from 3 to 5 years children improve at rapidly inferring or imagining possible dynamic causal outcomes, and then shifting representational resources to make other inferences or to simulate other actions while ignoring previously attended objects or properties. This improved facility for representation, attention and action supports fluid reasoning about possible functions. The improvement might also relate to broader changes in representational and attentive skills from 3 to 5 years (e.g., Davis & Pratt, 1995; DeLoache, 1989; Jones, Rothbart, & Posner, 2003; Perner, 1991).

These results would appear to conflict with previous findings about functional fixedness (Düncker, 1945) in children. Defeyter and German (2003) reported that functional fixedness increases from 5 to 7 years. By contrast, Deák and Boddupalli (under review) found increasing flexibility from 3 to 5 years. It is difficult to interpret this apparent discrepancy because there are many differences between the methods, including the number of objects, number and kinds of functions, number of presentations, instructions, and participant ages. It is possible that in some cases the developing

ACF and an emerging design stance can reduce attention to alternate affordances, whereas in other cases the ACF facilitates a dissociation of affordances from conventional functions, and allows rapid or creative shifting among representations of different functions.
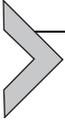
5. CONCLUSIONS AND QUESTIONS FOR FUTURE RESEARCH

A trenchant question in the behavioral and social sciences is how humans develop a prolific tool-using ability early in life, thus promulgating an "artifact culture." The answer includes protracted development of sensorimotor skills with active exploration, an intricately structured social environment that promotes culturally sanctioned tool-using skills, and crucial, species-specialized cognitive capacities. These capacities include the ability to infer other people's intentions and goals, currently a topic of intensive study (e.g., Gergely et al., 2002; Tomasello, 1999; Want & Harris, 2002). They also include the ability to form abstracted representations of function-types, and eventually a highly abstracted concept of function *per se*. These cognitive skills develop rapidly between 2 and 4 years, and seem to consolidate by 5 or 6 years of age.

These conclusions are supported by studies showing that children as young as 2 years notice, imitate, remember, and utilize kinds of object functions. By 4 years, children readily encode and remember novel functions for novel objects and they use that information to guide inductive inferences including object classification and selection, object naming, and action planning. Moreover, 4-year-olds spontaneously adopt an abstract function-based-matching rule with very little instruction. Four- and 5-year-olds also can flexibly induce multiple functions for the same object or object array, effectively "isolating" affordances from one another to reason about a variety of possible functions. Finally, from 4 to 7 years children show progressive development of an adult-like concept of design, relating objects' functions to their intended purposes and origins.

An outstanding question concerns the neural processes and structures that support this progression of tool-using skills and cognitions. This progression involves perceptual-motor development, social learning, causal knowledge, and meta-representational knowledge. The structures that become specialized to represent function-types for different activities (e.g., holding, using, naming, imagining) include regions of visual, parietal, and frontal cortex that are overlapping but partly differentiated. For

example, in nonhuman primates a dorso-dorsal stream (V6 to SPL to premotor F2) is involved in reaching for objects, whereas a more ventro-dorsal pathway (MT/V5 to IPL to ventral premotor areas F4–5) mediates hand shapes for grasping. In humans, other networks (possibly involving posterior parietal cortex and Broca's area) are involved in action knowledge for tool-use or in semantic knowledge of object functions (temporal cortex) (see reviews by Daprati & Sirigu, 2006; Johnson-Frey, 2004; Rizzolatti & Craighero, 2004). Yet we still know relatively little about the complexities of these networks in humans and virtually nothing about their development. In the future it will be useful to investigate the plasticity of regions that are relevant in adults, the anatomical and physiological development of pathways and networks, and effects of input. Also, we do not know how these specialized brain structures for tool-use interact with other relevant processes such as talking about functions, inferring and planning object-uses in light of social information, and interactions with executive cognitive processes such as creative problem solving. Although these questions would benefit from a well-specified theoretical framework, there is currently no explanatory model that can predict and explain the neurological, behavioral, and social-cognitive facts of functional thinking and tool-use in a realistic developmental model.

As little as we now know about these topics, the observation that acquisition of abstract function-types is followed by the emergence of an ACF might hold clues to the nature of our species-specialized abilities to reason about objects and to use tools. Yet a number of open questions remain. For example, I have focused on the development of tool-using skills from infancy through early childhood. Yet obviously tool-use expands tremendously from middle-childhood into adulthood. What further developmental changes might we see over this long span? Is later development simply a matter of refinement of skills and accrual of new function-types and subtypes? Children from 5 to 10 years can certainly acquire proficiency, even expertise, with tools (e.g., musical instrument, soccer ball, Rubik's Cube). Adults, just as certainly, may require years to acquire similar levels of proficiency. Whether or not there are any qualitative changes across these years in the cognitive bases of tool-using skills remains an unanswered question.

ACKNOWLEDGMENTS

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