Representing Object Functions: The Cognitive Basis of Tool-Use by Children

Gedeon O. Deák
University of California-San Diego, Dept. of Cognitive Science, 9500 Gilman Dr., La Jolla, CA 92093-0515, Email: deak@cogsci.ucsd.edu

Abstract

The cognitive basis of tool-use in humans is the capacity for conceptual abstraction of object affordances. These abstractions support dynamic flexible representations, or simulations, of agents using instruments to cause effects. This cognitive capacity is largely mature by 4 years of age. It requires high-level networks that take many sources of input, including events that are embedded in social interactions. The content of children's simulations is therefore dependent on social and exploratory experience, and on the capacities to acquire very abstract conceptualizations and to produce elaborate representations from minimal, or even distracting, perceptual information.

1. Where does tool-use come from?

Tool-using is a hallmark of human intelligence. In every culture studied, present and past, humans extensively manipulate available materials in a variety of ways for a variety of purposes. Other primates seldom use tools: Only very recently, for example, were instances of tool-use observed in wild gorillas [5]. It is not that apes lack intelligence, manual dexterity, or interest in objects [23]. Enculturated apes learn to use some human artifacts, and wild chimpanzees use tools in a few sophisticated ways [4]. What is different about how humans think about objects?

In the remainder of this paper I will consider the cognitive achievements necessary for humans' tool-use. I argue that the central cognitive achievement in human tool-use is the capacity to *remember* and *flexibly imagine* (i.e., simulate), different possible events in which an agent uses objects to cause effects. Remembering and generalizing episodes of tool-use results in a "vocabulary" of object uses. Imagining possible tool-uses allows creative problem solving with tools, and implies an abstract concept of function. The function concept also affects how we describe and classify objects. Imaginative simulation of function emerges around 2 years of age, and an abstract function concept is established by 4 years.

1.1. What is function?

The prolific use of artefacts by humans hinges on our conceptual representation of function. Function has at least two facets that are conceptually distinct but interdependent. The first is *affordance* [14], or an object's potential to support certain interactions with an organism [14]. For example, for adult humans a chair affords sitting, as well as standing-upon, wedging-between (e.g., door and doorway), lying-upon (when aligned with other chairs), etc. A cup affords containment of liquids (or solids smaller than the mouth of the cup), as well as weighting down papers, listening at a door, etc. In all cases affordances derive from physical features of an object *with respect to* the organism "using" it. Thus, walls afford walking for flies and ants, but not mammals. I will use the concept *affordance* as a gloss for physical object properties that support a specific use.[1] (Note that most objects afford the same uses to apes and humans, but only humans typically take advantage of, learn, and innovate a large number of tool uses.)

The second facet involves the social environment. People typically exploit some, but not all, affordances of objects. (e.g., Ming vase is throwable but this affordance is seldom explored). The most common function(s) of an object is its *intended use(s)*. Young children are able to quickly learn and remember how an adult uses an object, but, as described below, less able to simulate functions of novel or unfamiliar objects.

No theory has considered how physical affordances and social environment intersect as children learn to use tools and think flexibly about functions. There are many possible relations. For example, some affordances are more noticeable and easy-to-exploit than others, and some affordances are used more often than others in a social environment, but noticeability and conventionality do not

[1] This does not imply a strong position on Gibson's theory of direct perception, nor does it dismiss the difficulties of the concept. For example, does my car afford transportation? Does the affordance disappear if the battery dies? Does it return while I am connecting the new battery? Also, *affordance* is very broad: does a doorway "afford" moving-through in the same sense that an iPod affords information storage? Despite such challenging questions, the concept is suitable for considering specific uses of objects with fairly simple mechanics that are operated by gross or fine motor actions.

always correspond. For example, a toddler might notice that pot lids make terrific percussion instruments, but receive corrective feedback from noise-sensitive adults if she explores their acoustic properties at length. Nevertheless, because most artefacts are engineered for ease-of-use, the most accessible affordances are often the conventional ones. Also, conventionality will determine what tool-uses children see other people perform. It also might determine the social feedback children receive for exploring unconventional affordances. Thus, the social environment determines children's opportunities for exploring affordances and the models of conventional uses they see, as well as some feedback for their object exploration.

It is not clear whether or how these experiential factors influence the emergence of an abstract concept of function, or the development of the capacity to flexibly simulate possible functions. One hypothesis that experience with particular object uses feeds a growing "vocabulary" of abstract function "types." It seems likely that as this vocabulary expands, children become better at imagining possible functions of novel (or imagined) objects, and at using function information for other purposes such as object naming.

The next section describes what is known about how infants and toddlers learn affordances and conventional uses, as well as hypothetical implications of this evidence.

1.2. Infants' experience with functions: Exploration and socialization

Two ideas currently dominate research on the development of function knowledge and tool-using skills. One is that human teaching and learning ("demonstrating-for" and "imitating-from") are reciprocal socio-cognitive skills that require a unique imitative capacity, which hinges on the ability to represent others' intentions (Tomasello, 1999). In this view, tool-use is closely related to imitation because both require representing others' intentions for tool uses [26].

Another idea is that children acquire a teleological bias or *design stance:* a tendency to ascribe object properties to the designer's intentions. The design stance is thought to influence how children classify and name objects [12][17], and that it imposes a cost in cognitive flexibility: *functional fixedness*, or difficulty inferring unconventional uses for objects [11][13].

These ideas are intriguing and they have far-reaching implications. It is not clear, however, that either one captures the central *conceptual* achievement of thinking abstractly and flexibly about object functions. To better understand this achievement, let us consider research about infants' and children's knowledge and inferences about function. That research supports a coherent view of how thinking about function develops, and the role of social information, though many questions remain.

Infants acquire information about affordances of objects through exploration. Six- to 12-month-olds use exploratory actions to manipulate novel objects [28]. Yet even at 6 months of age infants do not explore objects at random but tailor their action to objects' visible distinct properties (e.g., squeezing soft objects; bang hard objects). Exploration is thus a progressive, embodied, multimodal process. When infants first see an object they will visually explore its surfaces, boundaries, textures and markings. This active vision guides infants' initial manual exploration: by about 5 months of age they adapt reaching gestures to properties of objects [37]. As infants reach for, contact, and manipulate objects, new multimodal information becomes available to update the object representation, and affordances are revealed or refined. Refinement can be quite gradual: infants' learn to use a type of tool (e.g., spoon) over weeks and months of daily experience [7]. (The same is true of young chimpanzees [3]). What infants learn in this manner is a *function-type*. For example, if an infant is given various spoons when fed in a high-chair, her encoding of these multimodal, embodied experiences (including her own actions and the resulting outcomes) will yield a generalized 'spoon-use' concept stripped of irrelevant details.[2]

Several studies show that some simple function-types are learned by the middle of the first year; for example, affordances, like containment [6]. By 9 months infants perceive different-looking objects with the same function as similar [24]. This focusing on abstract functional similarity is the first sign of a critical human cognitive basis of tool-use, the abstract concept of function.

Although it is unknown exactly how abstract function-types are acquired through experience with objects, several hypotheses can be drawn from available evidence (Section 2). Beside repetitive trial-and-error exploration [29], social information is important. Solitary exploration might reveal some object affordances, but not necessarily intended function. However, the propensity to watch how other people use objects might promote infants' exploration of intended functions. One- and 2-year-olds learn about specific object uses from other people: at an extreme, for example, caregivers sometimes take and move infants' hands to get them to manipulate objects

[2] Are infants capable of learning generalized dynamic representations from separate events in this fashion? It seems likely. By 2 months infants can generalize event-elements from prior experiences (the details that are retained change with age), and can learn and remember associations between their own actions and different outcomes [31]. By 3 months infants can recognize abstract categories of human action [34] from impoverished displays. Finally, by 2 months infants can form expectations about a kind of simple 2-object events [16].

"properly" [38]. This is a clear case of the social environment "boosting" infants' discovery of affordances. Notably, there are only *two* documented observations of chimpanzee mothers guiding their infants' tool-using attempts [4]. Thus, it is currently impossible to separate the roles of social input and the capacity to represent abstract function-types in the development of advanced tool-using cognition in human children.

In this account I am treating teaching events such as those observed by Zukow-Goldring and Arbib as labelled examples (or error feedback, depending on the circumstances) in training high-level associative cortical networks to recognize and generate patterns for abstract function-types. Imitation also is considered specialized input, akin to self-supervision with a degraded teaching signal. Both should boost function-learning. However, it is not clear that either one is crucial for cognition of function. Simply *noticing* and retaining some trace representation of how people use specific tools, and exploring the same tools under similar goal state, should allow children to learn conventional uses.

Summary: Infants' and children's tendency to explore object affordances, boosted by social input and feedback, provides input to function-learning networks (supported by robust attention, memory, and generalization processes). These networks learn categories of causal tool-using events from observed and experienced events. These abstractions are function-types.

1.3. Emergence of an abstract concept *function*

Learning of function-types begins in late infancy. From this gradual process, and possibly other unknown processes, a higher-order conceptualization emerges. This is an abstracted concept of function, independent of other object properties, even those correlated with function (e.g., shape). The concept allows adults and even children [33] to organize new information about objects and tool-using events. Its development was shown by [10]: 3- and 4-year-old children were instructed to sort two practice objects by function or by shape. They then sorted eight more objects (either by shape or by function) without any further instruction, reminder, feedback, or other guidance. Almost all 4-year-olds spontaneously and consistently generalized the practice instruction to test objects. Thus, children who were initially asked to put training items "with the one that does the same thing—the one that works the same" kept doing so, though on every trial the shapes and functions differed. Thus, 4-year-old readily use an *abstract* principle of function to reason about diverse objects. This was not just because the function information was especially salient: children who were initially told to sort by shape spontaneously, consistently generalized *that* rule; also, without any initial instruction 4-year-olds tended to sort the items by shape.

What about 3-year-olds? Only 19% spontaneously, consistently generalized an initial function instruction, whereas 75% generalized a shape instruction. In a group of 3-year-olds instructed to sort by function for four practice trials and then given explicit reminders to use the instruction, 37% of children consistently sorted by function. This shows gradual acquisition of the function-concept between 3 and 4 years. A working hypothesis is that this concept supports flexible reasoning about possible functions ([9]; see section 2).

2. How children acquire function-types and a concept of *function*: Specific claims

Experimental studies of children's use of function information suggest several more elaborate hypotheses and predictions about how tool-using cognition develops.

2.1. Quality of experience matters

Understanding functions as abstract potentials of objects requires induction from observed, imitated, and exploratory object-using events. Each experience with an object provides input to multimodal associative cortical networks. Specific dynamic affordances children see as input tend to be encoded and repeated in children's responses. For example, Kemler-Nelson [18] familiarized preschoolers with one of two possible functions of an object. Children then made more accurate generalizations about the affordance they had experienced. Even 2-year-olds use adults' input to select which affordance they use to sort novel objects [8].

Not all affordances are created equal: some are more learnable than others, all else being equal. Kemler-Nelson [18][19][20] has shown that 2- to 4-year-olds' inductive inferences about functional properties depend on [a] physical parts with specific affordances, [b] modifications that may disable functions; and [c] other function-irrelevant properties. For example, preschoolers are more likely to classify objects by function if the intended function is causally well-designed than if it is dysfunctional [21]. Even when artefacts are disabled (and thus children cannot have seen the function), 2- and 3-year-olds are sensitive to whether the function-loss seems accidental or intentional.

The quality of experience that matters includes social factors. For example, 1-year-olds are more likely to recall (after one week) a series of actions with objects (e.g., making a rattle) if they had initially gotten to imitate the series than if they merely watched it [2]. Perhaps it is particularly effective input for learning functions to see someone else perform a function, and then try to perform it yourself, when the memory trace of the observed action remains active. There is no direct test of this claim, but some intriguing findings concern the so-called "mirror neuron" system identified with cortical area F5 (and STS, PF, and perhaps others) [30]. Some cells seem to respond best to seeing a specific type of instrumental action produced, or to producing that action. Many cells are tuned to certain outcomes of actions, or functions.[3] Consistent with the current proposal, some action-selective cells in F5 respond in a graded way to function events: strongest to seeing an full action and result; less to the sound of the action or sight of part of the action [22][36]. Thus, verisimilitude of function input is reflected in the strength of the resulting neural vectors. Some approximation of that neural vector will also be evoked when the observing animal performs the same function-specific actions.

Thus, content and quality of experience affects children's generalizations about function-types, and their use of function to classify or name objects. Some kinds of social experience are especially effective for learning.

2.2. Quantity of experience matters

Though it might seem obvious, there is evidence of a relation between the extent of children's experience with tools and functions, and their readiness to make inferences about function. For example, 4-year-olds more often classify objects by function (when a shape-sorting alternative also is available) if the test object's function is demonstrated a second time just before they sort it [10]. The second demonstration seems to consolidate children's attention to the relevant function-type, as opposed to merely consolidating their memory of the specific object's funtion (3-year-olds remember virtually all functions of 28 unique objects after only demonstration each, for at least 20-30 minutes after their sorting response). Thus, toddlers are interested in, and quick to encode, function, and repeated experience increases their use of function information for inferences about objects.

Effects of repeated experience also are documented in infants' learning *and* generalization of function-types: 2-year-olds who see object-use sequences over several sessions demonstrate not only progressively better memory for the actions in those sequences, but a greater propensity to extend the actions to substitute "props" [1].

Thus, repeated experience with a specific affordance, especially with some variation across instances, consolidates memory trace for that function-type, making it more accessible for future reasoning about object properties.

2.3. Flexible generalization of function

Around the age (3-4 years) when children acquire an abstract concept of function as a *kind* of object property. They also gain skill in flexibly thinking about possible object functions. I tentatively propose that the former supports the latter, but for now this is based only on a developmental correlation: 4-year-olds readily adopt an abstract function-based classification rule; 4-year-olds also are flexible in reasoning about different functions of the same object (compared to 3-year-olds in both cases). The latter was shown by Deák [9], who tested 3- to 5-year-olds' ability to flexibly induce different functions for different subsets of objects within a complex array. This entailed processing 15 object parts with different affordances, on five objects in each of 5 object sets (shown three times each). Children were shown on each trial that a standard object (with three parts) could somehow produce an unobserved function (e.g., removing pebbles from sand) but not *how* this was done. They had to infer which of the parts afforded the function (e.g., sieve-like arm), and look for another object in the set "that could do that [effect], too" (i.e., a similar part). Importantly, a different effect was shown on each trial, requiring children to choose a different part and generalize to a different object. This tests flexibility in inducing functions. Trials were timed so that through the first, second and third trials with a set, children had visually examined the objects for 25, 35, and 45 sec. No other input was given (i.e., children did not manipulate or see the objects used). Notably, 3-year-olds are above chance (about 50% correct; chance = 25%) in their *first* inferences about the five sets. However, their later inferences, when they must reason about different affordances to form a new ad hoc function category, 3-year-olds are no more accurate than chance. By contrast, 4-year-olds also make about 50% correct first inferences, but then are slightly *more* accurate in later trials despite proactive interference from their previous choices.[4] Apparently, a few more seconds of time spent visually examining a complex array of objects allows 4-year-olds to imagine and infer new affordances and functional categories, whereas this is difficult for 3-year-olds, who sometimes perseverate in their inferences about shared affordances. This is a significant age-related change in cognitive flexibility.

[3] Little is known about how tool-use is represented in the system. However, a recent study [27] suggests that in humans, some of the system is activated by either seeing a human hand or a non-human hand-like tool performing an action, suggesting that the system might represent tool uses as well as body actions.

[4] Control studies show that children do in fact remember their first responses, and therefore are susceptible to proactive interference during later inferences about the sets.

2.4. Function concept, flexible thinking about function, and socio-cultural practices

Once children acquire a repertoire of shared function-types, an abstract function-concept, and accompanying gains in thinking flexibly about function, how does this new level of sophistication intersect with their socio-cultural practices and environment?

Children acquire conventional principles for labelling objects in their culture. In [10] described bove, in addition to sorting objects 3- and 4-year-olds were asked to label them. Their labels could highlight shape similarity, function similarity, both (e.g., "pen-light"), or neither. No matter how the child previously sorted objects, the dominance of function-based labels increased by a linear function from 3 to 5 years, such that older 4-year-olds label most objects by function, as do adults (in most cases; see also [32]).

Children also seem to acquire a "design stance" whereby the *intended* function of an object receives more psychological weight. The design stance might emerge after 4 years of age, later than the abstract concept of function [25], but the matter is not settled. The importance of intended function in adults' tool-using cognition can be seen in functional fixedness problems [13], wherein knowing an object's intended or typical function impedes adults from perceiving other affordances. The traditional functional fixedness problems are mostly very difficult, however, and the *reasons* for functional fixedness are not well understood. A new approach is to examine how developing knowledge of function relates to functional fixedness. Here an intriguing discrepancy has been reported: Defeyter and German [11] argue that fixedness is acquired as children learn the conventional uses of objects, based on evidence that older children actually are *less* likely to notice an unconventional object function than younger children. In contrast, Deák [9] found increasing flexibility from 3 to 5 years of age in children's induction of different functions for the same object. Clearly questions remain about how the design stance and teleological thinking influences children's thinking about object functions (but see [12]).

3. Future directions and questions

A major outstanding question concerns the perceptual and neural processes by which event information is encoded, remembered and abstracted. This process likely results in secondary cortical networks becoming specialized, between infancy and age 4 years, to represent coherent function-types. This probably requires multimodal integration of protracted, complex patterns of information (in, e.g., observed tool-using events), as well as some tendency to parse events into conceptually meaningful units (e.g., an actor's action-steps towards a completed tool-using attempt).

A related question is how these networks interact with other executive cognitive processes to permit, for example, thinking flexibly and creatively about new uses of objects or new (invented) tools, or focusing attention on certain (e.g., conventional) affordances.

A third question concerns social experience. It seems function representations are graded and generalizable, but we lack good ethnographic descriptions of how, and how much, infants and children first interact with various objects with various functions. In other words, what exactly are the opportunities, observed experiences, and feedback in infants' social environment that lead them to acquire certain function-types?

Another question concerns the interaction of learning about function-types, acquiring higher-order concepts and uses of function, and brain development. The fact that an abstract concept of function, and more flexible thinking about function, and perhaps the first signs of a design stance, all become apparent around 4 years of age, suggests that some experience-dependent neural processes (e.g., synaptic pruning in higher association areas and frontal cortex; myelination of certain regions, changes in white-matter pathways) signal the species-specialized capacity to think about ways to do things with objects.

Finally, is it possible to simulate abstract knowledge of function in artificial agents such as robots? Although robots can learn to use certain narrow classes of objects in very narrow ways, the claims made here suggest that human-like tool use would require the capacity to internally simulate different possible interactions with object properties. It would require abstractions of many specific affordances, and possibly a meta-concept of function that organizes innovative, active attempts to do things with objects.

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