On the psychological origins of tool use

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ABSTRACT

The ubiquity of tool use in human life has generated multiple lines of scientific and philosophical investigation to understand the development and expression of humans’ engagement with tools and its relation to other dimensions of human experience. However, existing literature on tool use faces several epistemological challenges in which the same set of questions generate many different answers. At least four critical questions can be identified, which are intimately intertwined—(1) What constitutes tool use? (2) What psychological processes underlie tool use in humans and nonhuman animals? (3) Which of these psychological processes are exclusive to tool use? (4) Which psychological processes involved in tool use are exclusive to Homo sapiens? To help advance a multidisciplinary scientific understanding of tool use, six author groups representing different academic disciplines (e.g., anthropology, psychology, neuroscience) and different theoretical perspectives respond to each of these questions, and then point to the direction of future work on tool use. We find that while there are marked differences among the responses of the respective author groups to each question, there is a surprising degree of agreement about many essential concepts and questions. We believe that this interdisciplinary and intertheoretical discussion will foster a more comprehensive understanding of tool use than any one of these perspectives (or any one of these author groups) would (or could) on their own.

1. Introduction

The ubiquity of tools in human cultures since the origin of the genus Homo has provoked enduring philosophical inquiries into humans’ engagement with tools (Gibson and Ingold, 1994), in part because tool use is often considered to reflect a unique dimension of technical engagement with tools (Gibson and Ingold, 1994), in part because tool use is often considered to reflect a unique dimension of technical engagement with tools (Gibson and Ingold, 1994). Aristotle wrote more than 2000 years ago, “The hand can become a claw, a fist, a horn or spear or sword or any other weapon or tool. It can be everything because it can grasp anything or hold anything” (Aristotle, The Animal Parts (IV, 10)). Today, anthropologists, ethologists, psychologists, and neuroscientists investigate the development and expression of humans’ engagement with tools in relation to other dimensions of human experience, and the increased efficiency and complexity of tool use in human populations over generations (Boyd and Richerson, 1996; Osiurak and Reynaud, 2020a; Tomasello et al., 1993). The origin of this phenomenon, called cumulative technological culture, was judged in 2005 by the journal Science as one of the 125 big scientific questions of the millennium. It appears that deepening our understanding of the psychological bases of tool use is fundamental to understanding the origins of tool technological culture. One might conjecture at first glance that the answers would be within easy reach. After all, they only require conceiving experiments in which individuals use tools, with researchers manipulating different variables to reveal the underlying psychological processes. However, behind this apparent simplicity, research on tool use faces several epistemological challenges in which the same set of questions generate...
many different answers. In the present target article, six research groups answer four critical questions about tool use, which are intimately intertwined, and suggest what should be the direction of future research on tool use. We provide a brief overview of the four questions and introduce how each author group approaches tool use before presenting each group’s answers.

**What constitutes tool use?** This question may appear trivial yet it is not. The process of defining any psychological concept is neither neutral nor viewpoint-free—any definition is necessarily limited and oriented toward the theoretical solutions provided to account for the phenomenon studied (Osiurak and Heinke, 2018). We have often posed this question to our academic friends, and responses have been quite varied. Those initiated in biomechanics, human movement science, or even neuroscience, such as Mangalam, Fragsaz, and Bongers, exclusively reserve the term ‘tool use’ for using objects to solve a mechanical problem (e.g., a hammer to drive a nail). Cognitive archaeologists such as Stout and cognitive psychologists such as Osiurak classify any implement (e.g., a calculator and a smartphone) under the umbrella term of tool use or an even broader term of technology. Ecological psychologists such as Wagman and Day consider any use of an object as tool use, irrespective of its use so long as that object changes the perceptual or behavioral capabilities of the user. Complexity scientists like Kelty-Stephen consider any behavior that changes the boundary between the organism as its environment as tool use and hence thus highly divergent. The same difficulties arise in the scientific study of tool use because there is no consensus on what tool use is (Fragaszy and Mangalam, 2018; Osiurak et al., 2010). The definitions given by Beck (1980), and updated by Shumaker et al. (2011; see Table 1) are perhaps the most thoroughgoing and influential attempt to define tool use (at least in the comparative literature), although Beck (1980; also see Hansell and Ruxton, 2008) warned that his definition only reflects a behavioral description and does not imply any biological or psychological distinction. Beck’s and Shumaker et al.’s definitions have two significant merits. The first feature is that these authors did not merely define ‘tool use’, but also concepts that are related to tool use, such as tool making and construction (Table 1). Thus, their definition of tool use is also a definition by exclusion (e.g., excluding tool making and construction). The second merit is that their definition is derived from the animal behavior literature, which facilitates discussions of the specificity of tool use to particular species.

**What psychological processes underlie tool use in humans and nonhuman animals?** The emphasis placed by Beck (1980) and Shumaker et al. (2011) on object manipulation is consistent with the literature on tool use that has repeatedly stressed the critical role of manipulation-related psychological processes or, more generally, of embodied cognitive processes. However, the embodied cognition approach is not unitary—there are several different versions. The first version is in direct line with the ecological approach to perception and action initially developed by Gibson (Gibson, 1966, 1979), in assuming that tool use can be fully understood as perception-action processes required for effective execution (Biryukova and Bril, 2012; Bril et al., 2009, 2012; Fragsaz and Mangalam, 2018; Kahrs and Lockman, 2014; Lockman, 2005; Mangalam, 2016; Mangalam and Fragsaz, 2016; Pagano and Day, 2020; Smitsman, 1997; Smitsman et al., 2005; Wagman and Carello, 2003). In this perspective, the emphasis is on the lawfully structured patterns of energy in the environment available to the perceiver as information. Tool users exploit this information when manipulating a tool. For instance, as mass increases and the center of mass is located farther from the point of rotation, objects are perceived to be more appropriate for power tasks (e.g., striking a nail or throwing for distance), and as mass decreases and the center of mass is located closer to the point of rotation, objects are perceived to be more appropriate for precision tasks (e.g., striking a small nail or throwing for precision) (Michaels et al., 2007; Wagman et al., 2016; Wagman and Carello, 2001). For example, another version of embodied approaches to tool use has been developed in parallel, mainly from the neuropsychological literature (Buxbaum, 2001; Heilman et al., 1982; Rothi et al., 1991; van Els et al., 2014). Contrary to the aforementioned (ecological) perceptuomotor approach, this version assumes that conceptual knowledge is directly extracted from the sensorimotor experience with familiar tools (e.g., hammer, knife). This knowledge about manipulation offers an advantage in any required information processing by avoiding the reconstruction de novo of each step of the process. A third approach has been formulated mainly from the idea that tools help modify the physical environment. Here, the emphasis is on the physical (or technical) reasoning involved to understand and perform these modifications (Goldenberg and Spatt, 2009; Johnson-Frey, 2004, 2003; Osiurak et al., 2020b; Vaesen, 2012). This approach can be viewed as ‘deseembodied’, considering that manipulative aspects are secondary and not the critical component of tool use.

**Which of these psychological processes are exclusive to tool use?** As defined by Beck (1980; see Fragsaz and Mangalam, 2018; Shumaker et al., 2011), tool use is notably characterized by the fact that it implies manipulating an external object to modify the state of the physical environment. Humans and a number of nonhuman species manipulate objects. Tool use concerns not just manipulating the tool but also acting with the tool on something in the environment – another object or a surface. This supposes the existence of an attentional shift from the effector on the body (e.g., hand, beak) to that on the tool (e.g., hammer’s head, screwdriver’s tip) (Fragaszy and Mangalam, 2018; Mangalam and Fragsaz, 2016; Osiurak and Federico, 2020), a phenomenon called “distalization of the end effector” (Arbib et al., 2009). A critical question is whether distalization of the end effector is exclusive to tool use. Construction behavior, like tool use, also results of modification in the physical environment, raising the question whether the same psychological processes underlie tool use and construction behavior (Arbib, 2012; Walsh et al., 2011). The question of the exclusivity of psychological processes to tool-use behavior can be extended to other aspects of tool use, such as the ability to combine several tool-use actions in sequence (meta-tool-use, such as using a tool to acquire another one or to use one tool to create another one).

**Which psychological processes involved in tool use are exclusive to Homo sapiens?** Humans, we now know, are not the only species that use tools. Thus, our fascination with human tool use behavior extended to other tool-using species in which tool use takes on a different character (Fragaszy and Mangalam, 2018; Mangalam and Fragsaz, 2016). Often observation of a member of nonhuman species using a tool prompts discussions about the potential advanced technical intelligence in that species compared to other, non-tool-using species (Chevalier-Skolnikoff, 1989; Huber and Gajdson, 2006; Mather, 1994; Matsuzawa, 2001; Osiurak and Reynaud, 2020a; Parker and Gibson, 1977; Seed et al., 2009; Vaesen, 2012; van Schaik and Burkart, 2011). This perspective has been criticized (Emery and Clayton, 2009; Haslam,
M. Mangalam et al. 2013; Wagman et al., 2019). Thus, an outstanding question is whether at least some psychological processes involved in tool use are unique to the human lineage.

Mangalam and Fragaszy integrate concepts from ecological psychology and movement science to formulate an embodied theory of tooling. They specifically use ‘tool’ as a verb, meaning to act with an object to achieve a mechanical goal in the service of a functional goal, and ‘tooling’ as a noun to label these actions. Mangalam and Fragaszy’s embodied theory makes testable predictions about the development, form, or effectiveness of tool use in humans and nonhuman animals, many of which have been confirmed by neurocognitive findings (Colbourne et al., 2021).

Wagman and Day, who also approach tool use from the perspective of ecological psychology, emphasize that tool use is associated with changes in lawfully structured patterned energy arrays that provide information about the animal-environment relationship. Therefore, using a tool is the detection (and exploitation) of information about this changed relationship. Thus, any species capable of detecting and exploiting such information is capable of tool use.

Kelty-Stephen views tool use from Mandelbrot’s multifractal-geometrical lens and explains how tool use rests on nonlinear interactions across nested scales of activity that support scale-free flexibility in behavior. Tool use, in this view, occurs in an organism with porous and blurry boundaries between organism and environment. Kelty-Stephen deems tool use just another factor contributing to the intermittency (discontinuities) in behavior that characterizes the aptability of organisms, as tools blink in and out of existence as a separate entity from the body. He cites many of his own studies to make a case that the multifractal structure inherent to fluctuations in movements is a meaningful way to understand and model the perceptual control of tools.

Bongers takes a more functional approach grounded in the control of the body-plus-tool system. Much of his arguments stem from findings that a tool is integrated in movement synergies. Properties of the body-plus-tool system thus affect how the user perceives objects and surfaces in their surroundings.

Stout takes an evolutionary anthropological perspective on tool use. He discusses tool use in the context of the broader realm of technology, highlighting interactions among technological production, collaboration, and reproduction. Further, he emphasizes the key role played by internal models for action prediction and synchronization of movements of the user.

Osiurak focuses on the cognitive aspects of tool use. He specifically talks about the neural substrates of causal and analogical reasoning about physical principles of mechanical actions (e.g., force and leverage), which together constitute technical reasoning. Osiurak posits that technical reasoning is involved in all manifestations of human materiality.

In this way, this review exemplifies the richness of psychological research on tool use. Considering diverse investigative approaches is critical to identify productive ways forward to investigate this phenomenon. The present review aims to fill this gap. Its originality lies in presenting under the same umbrella responses to standardized questions concerning tool use from practicing scientists following different psychological approaches. In closing, we offer suggestions to help orient future work on this fascinating topic, which may afford synthesis of different approaches.

Our unconventional format for this article is intended to provide the reader in just a glance an overview of several different psychological approaches to tool use, the kinds of questions they ask, and how they contribute to understanding tool use. The psychological processes that each of these approaches posits to be involved in tool use influence the study design and analytical methods used (e.g., Kelty-Stephen may use nonlinear analytical methods to examine the role of movement fluctuations in the perception of tool properties; Bongers may use cross-correlation analysis to study joint-angle coordination; Osiurak may use double dissociation to study the neurocognitive mechanisms specifying tool-related technical knowledge in the brain). If one approach posits that no psychological process is exclusive to tool use, then it would also reject the idea of specific brain regions dedicated to tool use. If another approach posits that a given psychological process is exclusive to humans, it will immediately point towards some uniquely human neuronal correlates. The reader can contrast these approaches and decide what kinds of questions about tool use can be satisfactorily answered. Of course, none of these approaches can explain empirical results to life scientists at all levels of interest: development, phylogeny, function, and mechanism, such as neurocognitive processes. But, at the very least, they may shed light on some aspect of tool use that other approaches take for granted. The idea is not to settle a debate for now or forever but rather to showcase the epistemological diversity of the scientific study of tool use to readers unfamiliar with these approaches.

2. Embodied tooling — Madhur Mangalam & Dorothy M. Fragaszy

We approach the topic of engagement with tools (henceforth, tooling) from a comparative, evolutionary perspective to explain phylogenetic and developmental origins of these behaviors in diverse species. Unfortunately, in our field, nearly all published works describe observations of nonhuman animals using objects to achieve a goal as ‘tool use,’ but rarely do they use these observations to test theoretical predictions relevant to the development, form, or effectiveness of the behavior because there has been no theory generating testable hypotheses regarding this behavior.

A theory that supports prospective experimental work is essential for progress in this field. We have been developing an embodied theory of tooling (Fragaszy and Mangalam, 2018) that integrates concepts from ecological psychology and movement science. Ecological psychology provides the concept of affordances (Fig. 1), enabled by the perception of object properties and surface layouts (including spatial relations among objects and orientation of body segments and objects attached to the body as a unit to objects in the environment) through the use of proprioceptive information (Gibson, 1966; Shaw, 2001). In other words, ecological psychology is primarily concerned with perception-action coupling (e.g., what perceptual information an individual uses to a specific end and how). Movement science provides the concept of controlling the bodily degrees of freedom for functional coordination of movements (Bernstein, 1967; Bernstein et al., 1996) and the concept of situating an activity within the organism-task-environment system

![Fig. 1. Affordances. The surface of a loamy soil affords tunneling to a mole, probing in search of prey to a bird, and walking to a fox. Drawing courtesy of A. Osuna-Mascaró.](image-url)
Table 2

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Instrumental problem solving</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ants, <em>Aphaenogaster spp.</em></td>
<td>Carry soft foods on or in pieces of leaf, mud, and sand grains</td>
<td>Fellers and Fellers (1976)</td>
</tr>
<tr>
<td>Collector archipes, <em>Tripernesus grilloser</em></td>
<td>Camouflage by draping own body with objects</td>
<td>Ziegenhorn (2016)</td>
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<tr>
<td>Octopus, <em>Octopus vulgaris</em></td>
<td>Cover the entrance to their den with rocks</td>
<td>Mather (1994)</td>
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<tr>
<td>Octopuses, <em>Amphioctopus marginatus</em></td>
<td>Obtain shelter in coconut shell halves</td>
<td>Finn et al. (2009)</td>
</tr>
<tr>
<td>Archerfish, <em>Toxotes jaculator</em></td>
<td>Catch flying insects by spitting water droplets on them</td>
<td>Gerullis and Schuster (2014)</td>
</tr>
<tr>
<td>Crocodile, <em>Crocodylus porosus</em></td>
<td>Lure birds with twigs and sticks placed on body</td>
<td>Dinets et al. (2015)</td>
</tr>
<tr>
<td>Egyptian vultures, <em>Neophron percnopterus</em></td>
<td>Break open eggs by throwing and dropping stones on them</td>
<td>Lawick-Goodall (1971)</td>
</tr>
<tr>
<td>Northwestern crows, <em>Corvus caurinus</em></td>
<td>Raise rate water level in a container to reach floating worms by dropping pebbles</td>
<td>Zach (1978)</td>
</tr>
<tr>
<td>Rooks, <em>Corvus frugilegus</em></td>
<td>Block the entrance of the burrows of ground squirrels to assist in capturing them</td>
<td>Michener (2004)</td>
</tr>
<tr>
<td>North American badgers, <em>Taxidea taxus</em></td>
<td>Threaten humans by throwing stones</td>
<td>Hamilton et al. (1975)</td>
</tr>
<tr>
<td>Baboons, <em>Papio spp.</em></td>
<td>Modulate the frequency of their vocalizations with leaves</td>
<td>Hardus et al. (2009)</td>
</tr>
<tr>
<td>Bonobos, <em>Pan paniscus</em></td>
<td>Raise rate held in the mouth with branches held in the trunk</td>
<td>Ingrmann (1996)</td>
</tr>
<tr>
<td>Chimpanzees, <em>Pan troglodytes</em></td>
<td>Reach for a hanging banana by stepping on wooden boxes</td>
<td>Köhler (1925)</td>
</tr>
<tr>
<td>Chimpanzees, <em>Pan troglodytes</em></td>
<td>Drink water from tree hollows using leaves to sponge the water</td>
<td>Tonoooka (2001)</td>
</tr>
<tr>
<td>Hyacinth macaws, <em>Anodorhynchus hyacinthinus</em></td>
<td>Stabilize a nut in the beak with wood wedges</td>
<td>Bornari and Ottino (2005)</td>
</tr>
<tr>
<td>Lion, <em>Panthera leo</em></td>
<td>Rub a sore area of its paw with a thorn held in the mouth</td>
<td>Bauer (2001)</td>
</tr>
<tr>
<td>Elephants, <em>Elephas maximus</em></td>
<td>Brush flies off their body with branches held in the trunk</td>
<td>Hart et al. (2001)</td>
</tr>
<tr>
<td>Bearded capuchin monkeys, <em>Sapajus libidnus</em></td>
<td>Dig soil with stones to excavate tubers</td>
<td>Falotico and Ottino (2016)</td>
</tr>
<tr>
<td>Long-tailed macaques, <em>Macaca fascicularis</em></td>
<td>Floss their teeth with hair</td>
<td>Watanabe et al. (2007)</td>
</tr>
<tr>
<td>Sumatran orangutans, <em>Pongo abelii</em></td>
<td>Wipe body with leaves to remove substance</td>
<td>Fox et al. (1999)</td>
</tr>
<tr>
<td>Chimpanzees, <em>Pan troglodytes</em></td>
<td>Flush or disable vertebrate prey in tree hollow with stick</td>
<td>Pruett and Bertolani (2007)</td>
</tr>
<tr>
<td>Chimpanzees, <em>Pan troglodytes</em></td>
<td>Puncture soil with stick to reach underground termite nests</td>
<td>Sanz and Morgan (2007)</td>
</tr>
</tbody>
</table>

* Additional taxa have been reported to behave in similar ways.
action of a given individual with specific materials to accomplish a particular task in a particular setting (Bril et al., 2012; Mangalam and Fragaszy, 2016; Smitsman, 1997).

We suggest joint deployment of these three perceptuomotor processes distinguishes tooling from other instrumental problem-solving. Particular experiences accompany these processes in humans. We do not know if nonhuman animals experience tooling as humans do, but these same perceptuomotor processes must occur in some form.

- Establishing and managing spatial relation(s) between an object attached to the body and a target object or surface. Tooling requires establishing and managing at least one spatial relation between an object attached to the body and a target object or surface (see Fragaszy and Mangalam, 2018, for detailed explanation). Spatial relations in a tooling activity can vary in several dimensions. First, the number of relations can vary; tooling can involve managing more than one spatial relation between the body, the tool, and the target object or surface, sequentially, or concurrently. For instance, to join two planks, an individual might align the planks in a certain way (first spatial relation), then place a nail at a particular point on the top plank (second spatial relation), then strike the nail with the hammer (third spatial relation) to drive it through the planks. Spatial relations differ in their specificity: placement, orientation, and geometric alignment. Consider, for example, using a screwdriver to drive in a screw. The screwdriver’s distal end must be placed quite precisely on the screw’s head, and the screwdriver’s shaft must be oriented parallel to the screw’s long axis to enable the screwdriver’s head to fit into the screw’s head. Spatial relations can also vary in temporal dynamics, from static to dynamic. The relation between the two planks in the previous example is static because once they are placed in position, they are not moved relative to each other. Similarly, the nail is placed in a fixed location on the top plank. The relation between the hammer and the nail is dynamic because the hammer is moved relative to the nail.

- Distalization of the end-effector. Tooling requires the distalization of the end-effector—the locus of perceptuomotor control—from the body to the part on the tool that acts upon the target object or surface (Arbib et al., 2009). Studies have shown that in monkeys using pliers to grasp a food item, the grasp-related cortical regions encode for movements of the pliers’ jaws rather than movements of the fingers (Umiltà et al., 2008). A specific grip configuration may be imposed by the mass, shape, and size of the pliers, and movements are adapted to the pliers’ jointed feature (direct vs. reverse pliers). These findings have been replicated in humans (Gallivan et al., 2013). Tooling is also associated with remapping of somatic senses to perceive what is happening at the tool tip rather than at the fingertips (Miller et al., 2018; Takahashi and Watt, 2017). Some studies have also reported that the remapping of the space surrounding the body to perceive reaching affordances from the frame of reference of the handheld tool rather than the hand (Berti and Frassinetti, 2000; Farne et al., 2005; Maravita and Iriki, 2004), but these reports have remained questionable because of the small overall effect size and low statistical power (Holmes, 2012). Indeed, it has been suggested that the effects observed in these studies might simply reflect a shift of spatial attention from the hands to the tooltips—a hypothesis that has remained untested (Holmes et al., 2007, 2009).

- Coordinating the body-object system. The body-object system is coordinated differently than the body-only system, as manifest in different movements and postures. A simple example makes this point: different postures and movements are used when gripping a nail with the hand than when gripping it with pliers. Even when the task demands do not manifestly require different postures and movements, moving with a grasped object alters movement coordination. For example, people move their arms differently to stabilize the end-point trajectory when using the arm and hand to point at a target than when pointing at the same target with a stick (Valk et al., 2016; van der Steen and Bongers, 2011).

Which of these psychological processes are exclusive to tool use? None of the above perceptuomotor processes is exclusive to tooling. The acts of establishing and managing spatial relation(s) between an object attached to the body and a target object or surface are part of several non-tooling activities and are observed in both humans and nonhuman species, such as chimpanzees and capuchin monkeys aligning a stick to a matching cut-out in an experimental task (Fragaszy et al., 2011, 2015; la Cour et al., 2014), or a weaver bird inserting grass or twigs into a partially completed nest (Walsh et al., 2011). The end-effector is distalized in many non-tooling contexts, such as when using a manipulandum to move a cursor on the screen, although this behavior has been classified by some as tool use (Heald et al., 2018; Ingram et al., 2010). (Using a manipulandum to move a cursor does not qualify as tooling according to our definition because the manipulandum does not directly and mechanically affect the screen.) We coordinate the body-object system all the time in non-tooling contexts, such as when passing through a doorway sideways when holding an object wider than the doorway (Higuchi et al., 2006), or when using assistive devices—from wheelchair to exoskeleton (Pazzaglia and Molinari, 2016). Transporting an object inevitably involves coordinating the body-object system, irrespective of the context. These examples clearly illustrate that each perceptuomotor process is involved in many activities beyond tooling.

Which psychological processes involved in tool use are exclusive to Homo sapiens? We do not suppose that tooling is exclusive to humans in a holistic way, although we have no doubt that there are large differences among species in the elaboration and efficiency of the perceptuomotor processes involved in tool use: (i) Establishing and managing spatial relation(s) between an object attached to the body and a target object or surface; (ii) distalization of the end-effector; and (iii) coordinating the body-object system. Unfortunately, few comparative studies isolate each one of the three processes. We have suggested differences across species in two of the three processes but some commonality between humans and other species in the third. With respect to perceiving and managing spatial relations between a grasped object and another object, by two years of age, humans readily align a straight stick to a matching cutout in a platform surface, whereas adult chimpanzees and capuchin monkeys do so imprecisely (Fig. 2) (Fragaszy et al., 2011, 2015; la Cour et al., 2014), suggesting a deep difference between humans and nonhuman primates in this domain. With respect to coordinating the body-object system when tooling, some evidence indicates that nonhuman species can do this modestly, but not as effectively as humans. For example, when cracking nuts using stone hammers,
Gibson (1966) arrived at a convergent conclusion. There is an on the distinctive perceptuomotor processes of tooling noted above. To tooling could be investigated more productively by setting aside the notion that tooling is an index of ‘complexity and function of the nervous system. Findings from studies on reach-to-grasp movements using the hand or using the hand with a tool (e.g., grasping with fingers or with a tong) suggest an effector-independent neural encoding of movements (Gallivan et al., 2013, 2011; Umiltà et al., 2008). The interpretational nuances added by comparing actions with different effectors to achieve the same goal would yield a more reliable neurophysiological understanding of tooling than the currently available explanations based on comparisons of actual tooling with gesturing with an object (Hermsdörfer et al., 2012, 2007).

**What must be the direction for future work on tool use?** We suggest that expanding our understanding of each of the three component perceptuomotor processes we have highlighted above, and our understanding of their integration in tooling and other instrumental actions with objects, will be particularly useful. Ethologists may most naturally consider these processes in diverse species and developmental, ecological, and evolutionary perspectives. Psychologists may most naturally consider them in relation to attentional and related cognitive demands, particularly affordance learning and skill learning. Neuroscientists may most naturally consider them in relation to the organization and function of the nervous system. Findings from studies on reach-to-grasp movements using the hand or using the hand with a tool (e.g., grasping with fingers or with a tong) suggest an effector-independent neural encoding of movements (Gallivan et al., 2013, 2011; Umiltà et al., 2008). The interpretational nuances added by comparing actions with different effectors to achieve the same goal would yield a more reliable neurophysiological understanding of tooling than the currently available explanations based on comparisons of actual tooling with gesturing with an object (Hermsdörfer et al., 2012, 2007).

**Pantomimic** is the principal paradigm used to investigate the neural basis of tooling particularly in relation to cognitive and sensorimotor deficits in neurological patients (Buxbaum et al., 2005; Królczak and Frey, 2009; Martin et al., 2016b). Several interesting findings of how brain-damaged individuals move objects gesturally paint an optimistic picture of what we understand about the neural correlates of tooling (Goldenberg and Spatt, 2009; Johnson-Frey, 2004; Renfrew et al., 2008). However, pantomiming with objects is not comparable to tooling in any biologically relevant way (a detailed discussion is beyond the scope of this essay; we hope to address this issue in greater detail in a future piece). Tooling could be investigated more productively by setting aside the notion that tooling is an index of ‘complexity’ to focus on the distinctive perceptuomotor processes of tooling noted above.

Bernstein (1967; et al., 1996) stressed the importance of the senses to the coordination of actions. From a different theoretical orientation, Gibson (1966) arrived at a convergent conclusion. There is an untapped opportunity to study how the sensorimotor apparatus of species and individuals constrains their engagement in specific forms of tooling (Martinho et al., 2014; Troschanko et al., 2012). Accounting for the anatomy, physiology, and sensory processes of the user is critical to situate ‘tooling’ within the realm of biological inquiry.

### 3. Tool use as detection and exploitation of information in an ecological niche — Jeffrey B. Wagman & Brian M. Day

In the ecological approach to perception-action, surrounding energy distributions such as reflected light are lawfully (unambiguously, uniquely, invariantly) structured by substance and surface properties of the surrounding environment. This lawful structuring creates a unique pattern of energy at each point of observation in that distribution. The point of observation at which a given animal actively encounters this structured energy distribution and how this point of observation changes over time is lawfully (unambiguously, uniquely, invariantly) determined by that animal’s size, shape, mass, and how it moves through the world. Therefore, the structured energy patterns actively encountered by a given animal are lawfully determined by the relationship or fit between the animal’s various action capabilities and the substance and surface properties. In other words, the structured energy patterns actively encountered at a point of observation are informative about the behaviors that the animal can perform with respect to these substances and surfaces—they are informative about affordances for that animal.

The inherent lawfulness of this process means that the (changing) patterns of structured energy encountered by a given animal do not need to be ‘processed’. They need only be detected to be informative about affordances for that animal (Wagman, 2020). Thus, perceiving and actualizing affordances for a given behavior requires detecting and exploiting such information—no more and no less. The inherent lawfulness of this process also means that the same (or analogous) patterns are informative to a given animal about a given affordance regardless of (1) whether a tool alters the fit between animal and environment and (2) the sophistication of the brain and nervous system of that animal.

Therefore, perceiving and actualizing affordances for performing a behavior with or by means of a tool requires detecting and exploiting such information—no more and no less. Moreover, any animal species capable of detecting and exploiting such information is capable of tool use. And while tool use itself does not seem to depend on the sophistication of the brain and nervous system of a given species, the sophistication and proliferation of tool use may depend on the sophistication of the niche of a particular species. Consequently, investigating how to provide information about affordances by means of tools that are unique to the human niche (such as technological interfaces or virtual tools) is an important area for future research.

![Image](https://via.placeholder.com/150)

**Fig. 3.** When cracking nuts using stone hammers, wild bearded capuchin monkeys (Sapajus libidinosus) alter their strikes to strike a nut with less or more force based on the type and condition of the nut; they do so by adjusting the amplitude and velocity of the strike but do not adjust the hammer’s kinetic energy at impact. (a) An adult monkey is striking an intact piaçava nut (inset)—placed in a pit on a log anvil—with a quartzite stone hammer. Photo courtesy of Barth A. Wright. (b) Hammer’s kinetic energy at impact. (c) Strike’s amplitude. (d) Hammer’s velocity at impact. Adapted from Mangalam et al. (2018a).
What constitutes tool use? The ecological approach to perceiving and acting focuses on a scientific understanding of the lawful control of everyday goal-directed behavior. In this approach, the fundamental unit of analysis is the animal-environment system, not the animal or the environment in isolation (Gibson, 1979; Turvey, 2018). In the ecological approach, it is (only) at this level that all psychological processes—including tool use—occur. A key reason for this focus is that the relationship or the fit between the animal and environment determines what possibilities for behaviors—what affordances—are available to that animal (Wagman, 2020). It is also at this level that these possibilities become actualized in the performance of a given behavior.

A tool alters the fit between animal and environment by changing the ability of that animal to perceive or actualize affordances. Therefore, tool use is the exploitation of this altered animal-environment fit in the context of performing a given goal-directed behavior. By this definition, using a hammer to drive a nail qualifies as tool use. The hammer changes the ability to actualize many affordances, including the ability to forcefully strike another object. It is this change that is exploited in achieving the goal.

Alternatively, merely carrying a hammer does not qualify as tool use. This is tool transport rather than tool use. Stacking stones to build a barrier also does not qualify as tool use. This is construct behavior rather than tool use. In both cases, affordances are actualized in the context of a goal-directed behavior. However, in neither case does the object (the hammer or the stones) change the animal’s ability to perceive or actualize affordances. Actualizing affordances is not the same as tool use. Bending a straight wire into a hook also does not qualify as tool use. Before and after it is bent, the wire alters the fit between animal and environment. Though bending the wire is likely to be goal-directed, doing so does not—in and of itself—exploit how it alters the fit between animal and environment. Changing the affordances of a given object is not the same as tool use. Instead, this is tool making or tool modification.

However, throwing stones at an aggressor, using a wheelbarrow to transport stones, and using a bent wire to retrieve a food item each qualify as tool use. Similarly, using a flashlight, a long cane, or a guide dog to safely navigate a cluttered environment also qualify as tool use. In each case, these objects change the ability to perceive and actualize affordances in ways that are exploited in achieving the goal.

What psychological processes underlie tool use in humans and nonhuman animals? In the ecological approach to perceiving and acting, the relationship between animal and environment lawfully structures patterned energy distributions. The structure actively encountered at a point of observation in such distributions provides information about this relationship (Fig. 4, bottom). That is, it provides information about affordances—whether, when, and how to move to achieve a goal. Thus, perceiving and actualizing affordances for performing a goal-directed behavior requires the psychological processes of detecting and exploiting information—no more and no less (Wagman et al., 2019). These processes stand in contrast to more traditional psychological processes proposed to underlie perceiving and acting, such as remembering, computing, and inferring, among others.

When the fit between animal and environment is altered by means of a tool, the structure encountered at a point of observation provides information about this altered relationship (see Fig. 4, middle). That is, it provides information about affordances for tool use—whether, when, and how to use the tool to achieve a given goal. Consequently, perceiving and actualizing affordances for performing a goal-directed behavior with or by means of a tool similarly requires the psychological processes of detecting and exploiting information—no more and no less. These processes stand in contrast to the more traditional psychological processes proposed to underlie tool use, such as imagining, reasoning, and problem solving, among others.

The lawful structuring of energy distributions guarantees that the same (or analogous) patterns provide information about a given affordance regardless of details of the particular energy distribution being structured and the particular anatomical component(s) used to detect such structure. This is readily demonstrated in a context common to tool use—the hefting, wielding, or manipulating of objects by muscular effort (see Carello and Turvey, 2016). When wielding an occluded object, people can perceive many different affordances of that object, and they can perceive a given affordance of that object under many different wielding circumstances (Hajnal et al., 2007; Mangalam et al., 2017; Wagman et al., 2017). By the same token, when people probe a surface with an object, they can perceive many different affordances of that surface, and they can perceive a given affordance of that surface under many different probing circumstances (Wagman and Hajnal, 2016, 2014a,b).

Perceiving affordances of, and by means of, a tool requires spontaneously and temporarily assembling task-specific detection units from potentially independent components—across both body and tool. Actualizing affordances of a tool requires an analogous process of spontaneously and temporarily assembling task-specific control units from potentially independent components—again, across both body and tool. The detection and exploitation of lawfully structured energy distributions likely underwrites both phenomena (Carello and Wagman, 2009; Profeta et al., 2020).

Which of these psychological processes are exclusive to tool use? As described above, in the ecological approach, lawfully structured patterned energy distributions provide information about whether, when, and how to move to achieve a goal. The lawful structuring of energy distributions guarantees that the same (or analogous) patterns provide information about a given affordance across circumstances. This includes whether or not an animal exploits an altered animal-environment fit in the context of achieving a goal (i.e., whether or not an animal engages in tool use).

When an animal moves from place to place in a cluttered environment, it encounters a lawfully generated pattern of optical structure that is informative about the animal-environment relationship—specifically...
about how, when, and where it is moving. Moreover, such patterns are informative about whether, when, and how a person must move to achieve a goal (e.g., catching a ball, see Fink et al., 2009). Critically, such patterns are also informative as to whether, when, and how a person must move a tool such as a vehicle to achieve a goal (e.g., steering or stopping safely, Fajen, 2013, 2007; Fajen and Matthys, 2011; Kadar and Shaw, 2000).

Likewise, when an animal moves one of its limbs about a given joint, it encounters a lawfully generated pattern of resistance to rotational acceleration that is informative about the animal-environment relationship—specifically about how, when, and where the limb is moving. Moreover, such patterns are informative about whether, when, and how a person must move that limb to achieve a goal (e.g., pointing at a target, Pagano and Turvey, 1998). Critically, such patterns are also informative as to whether, when, and how a person should move a hand-held tool to achieve a goal (e.g., hammering or displacing another object) (Wagman et al., 2016; Wagman and Carello, 2001).

In both cases, it is irrelevant whether achieving the goal requires controlling the person’s movements or the person-plus-tool system. The lawful structuring of patterned energy distributions by the relationship between animal and environment entails that the information about how, where, and when to move to achieve the goal is the same (or analogous) across this transformation (see Fig. 3, middle). This likely explains why tools, be they vehicles or hand-held objects, are often ‘functionally transparent’ to skilled users. In both cases, tools are perceived as part of the body because they are perceived the same way as the body (Pagano and Turvey, 1998). In other words, perceiving the body and an object attached to it require identical psychological processes.

Which psychological processes involved in tool use are exclusive to Homo sapiens? The lawful structuring of energy distributions by the relationship between animal and environment guarantees that the same (or analogous) patterns provide information about a given affordance regardless of the specifics of the sensory apparatus, nervous system, and brain of the animal doing the perceiving. Such details are irrelevant so long as that animal can detect the structured energy patterns that are informative about whether, when, and how to move to achieve a given goal. Incontrovertibly, animals across all phyla perceive and actualize affordances. According to the ecological approach, these abilities result from the same lawful processes—psychological and otherwise—across species (Turvey, 2018; Wagman et al., 2019). Moreover, the abilities of animals to exploit how a tool alters the ability to perceive and actualize affordances are also the result of the same lawful processes—psychological or otherwise—across species.

Tool transport, construction behavior, and tool modification are widespread across the animal kingdom—even in so-called ‘lower animals’ such as crustaceans, insects, worms, and amoeba (Turvey, 2018; Wagman et al., 2019). Instances of tool use (as defined above in section 1), however, are less common—occurring mostly (but not exclusively) in birds and primates (Hunt et al., 2013). This observation begs the question as to why instances of tool use proper are not more common across the animal kingdom—especially, if we suggest, the information about a given affordance is the same (or analogous) regardless of differences in sensory apparatus, nervous system, and brain across species.

We propose that this disparity is not due to differences in brain, nervous system, or intelligence across species. Rather, we propose that it is due to differences in the ecological niche occupied by those species. A niche is how a particular species lives, given the fit between animal and environment particular to that species. A niche is a way of life— it is a set of affordances for a particular species (Gibson, 1979; Turvey, 2018). Species occupying different niches necessarily encounter (and perceive and exploit) different affordances. The more complex the niche of a given species, the more diverse and complex the set of affordances available to that species’ members, and the more likely those members will (learn to) perceive and exploit affordances for tool use.

Accordingly, species other than primates and birds engage in tool use when their niche is modified to include the opportunity (to learn) to perceive and exploit these affordances. For example, rats perceive and exploit affordances for driving a vehicle when their niche is modified to include opportunities to (learn to) do so (Crawford et al., 2020). Moreover, the driving skills of rats raised in an enriched environment (i.e., an enriched niche) are superior to those raised in a standard environment.

What must be the direction for future work on tool use? Affordances for tool use are relative to the niche that an animal species occupies. Humans occupy a unique niche that includes a vast array of technological, communication, and representation systems. In this niche, affordances for tool use include teleoperation of search and rescue robots, the Mars rover, or surveillance drones; the manipulation and repair of internal bodily organs and tissue by means of laparoscopic surgical instruments; and even the (un)locking of the door to one’s home using a smart phone app. In all such cases, these devices change the ability to perceive and actualize affordances in ways that are exploited in achieving the goal.

In the general case, information about affordances for tool use is available in the structure in patterned energy encountered at a point of observation. However, in the situations described above occurring in the human socio-technological niche, information about affordances is available only by means of an interface (e.g., a computer-mediated visual display). This requires designing to preserve, enhance, or (in some cases) even generate the lawfully structured energy patterns that provide information about affordances (Pagano and Day, 2020; Fig. 3, top). Therefore, an important direction for future research is to determine precisely how to do so. In other words, future research should be directed at designing the interface that allows for perceiving and actualizing affordances of virtual tools to be the detection (and exploitation) of relevant information—no more and no less.

For example, researchers developed a laparoscopic surgery simulator interface that could provide haptic feedback to the user about how far simulated bodily tissue could be manipulated until it was accidentally torn (Altenhoff et al., 2017; Hartman et al., 2016; Long et al., 2016). The researchers based the haptic information about ‘distance to break’ on optical information about ‘time to contact’ with a surface (see above, Fink et al., 2009). They found that novice participants and experienced surgeons who used the device improved their performance in a simulated laparoscopic surgery task after only minimal practice. This suggests that only minimal practice using a tool may be required for that tool to become functionally transparent. However, it is unknown exactly what kind and how much tool use experience is necessary and sufficient for this to occur. Therefore, future research should also be directed at determining those experiences that are necessary and sufficient to facilitate the functional transparency of a virtual tool or a user-tool interface (Day et al., 2019, 2017).

4. Tools as intermittent properties of the fractal coastlines between organism and environment — Damian G. Kelty-Stephen

Tool use rests on the cascades underwriting organism-environment relationships. Cascade dynamics comprise nonlinear interactions across nested scales of activity that support scale-free flexibility resulting in an organism with porous and blurry boundaries. Organisms spread fluidly over contextual constraints, contacting the environment along intermittent coastlines where behavior ebbs and flows against the more stable land. The tool-using organism can be more adaptive as it is intermittent, avoiding lock-in, extending and retracting, wandering, and hovering. Tool use is just another intermittent function in the daily work of an organism. However, the more startling possibility is that tools are themselves intermittent participants in the organism-environment exchanges.

Tools are necessarily tuned to the scale of a task. So, the associated intermittency may require viewing Gibsonian ecological psychology through Mandelbrot’s multifractal-geometrical lens. For Gibson (1979),
organisms and the environment entail one another, and any coastline between them is porous and blurry. When studying the coastlines bounding Britain, Mandelbrot (1967) realized that such boundaries embody fractional (or ‘fractal’ for short) dimensions. Off-putting at first glance, fractal dimensionality aims to do the critical job of quantifying structure that fails to be integer-dimensional (e.g., zero-, one-, two-, or three-dimensional points, lines, surfaces, or Euclidean solids). Coastlines with varying fractionality can crucially originate from nonlinear interactions across scales. Indeed, the nonlinear interactions across scales—that is, the cascades—entail variation in these fractal dimensions. That is, they entail ‘multifractal’ dimensionality (Mandelbrot, 2013).

The multifractal structure is thus a meaningful way to understand and model tool use. Organisms’ exploration of tools and task context depends on multifractal fluctuations in organisms’ movement (Doyon et al., 2019; Hajnal et al., 2018; Kelty-Stephen and Dixon, 2014; Mangalam et al., 2019a,b,c; Mangalam et al., 2020a,b,c; Mangalam and Kelty-Stephen, 2020; Stephen et al., 2009, 2010; Stephen and Hajnal, 2011). This insight may lead to the startling idea that tools could be intermittent, blinking in and out of existence as a separate entity from the body. In this sense, the muddiness of ‘tool’ concepts noted by Fragaszy and Mangalam (2018) may be a defining feature rather than muddiness in the scholarship.

What constitutes tool use? Tools enact a subtle balance at the boundary between organism and environment. The boundary between organism and environment is a dynamic, sometimes blurry distinction, and tools themselves may appear or disappear intermittently. An organism uses a tool to take an object to engage in direct mechanical interaction with a target surface (Fragaszy and Mangalam, 2018). As such, tools are necessarily tuned to the scale of a task. The key for our front door only works because it has the specific shape and size that moves the tumblers of a lock just so. However, tool use does not live at any specific scale, and tool use relies on an organism’s ability to slip up and down a hierarchy of scales. In this sense, the muddiness of ‘tool’ concepts noted by Fragaszy and Mangalam (2018) may be a defining feature rather than muddiness in the scholarship.

The blurriness of the boundary between organism and environment is not a denial of scientific inquiry. On the contrary, it is just such a blurriness that demands a specific class of scientific mechanism, namely the interaction across scales in a cascade. Tool use rests on the cascades underwriting organism-and-environment relationships. By ‘cascades’, I only mean the nonlinear interactions across nested scales of activity. The cascades offer a theoretical modeling framework that has been embraced in geophysical domains (Lovejoy and Schertzer, 2018) and psychological domains (e.g., Oakes and Rakison, 2019). This modeling framework entails the use of specific kinds of hypotheses and specific kinds of data analysis. However, before introducing the further entailment of the cascades modeling framework, we first elaborate on cascades.

We can see the cascades implicated in using the tool of a key. Intentional tool-use events like “unlocking the door with a key” rest within a larger context like “arriving at the front door after an evening out.” Nested within the intentional tool use are smaller movements and submovements, such as riffling through pockets and purses, looking for the key, curling fingers about this way, and that to leave through coins and receipts. Nestcd again within those events are yet smaller movements. For example, neurons fire and tendons gradually stretch. Events at all these scales gradually percolate up across scales, from neurons to hands and body, and ultimately the key, from dawning understanding that the key is not in these pants pockets, not in this purse. The curl of the fingers and brush of the cloth weave against the skin, cueing memory of feeling the key in another pants pocket. These diffuse submovements and movements spill over into a new strategy altogether: we reach out back into the largest scales of the context, and we use the fact that the vast expanse of front-door-and-house contains a landscape of flower pots and garden stones. Under at least one of these landmarks, we have a spare key. So, then we cast about in among the flora of our front yard, and soon we have descended again into smaller scales of movements, submovements, fingers gripping and tapping against ceramics and stone in the dark.

The ability to slip from one scale to another and blend information at different scales is because organisms have porous and blurry boundaries. Organisms spread fluidly over contextual constraints, contacting the environment along intermittent coastlines where behavior ebbs and flows against the more stable land. The tool-using organism can be more adaptive as it is intermittent, avoiding lock-in, extending and retracting, wandering, and hovering. Tool use is just another intermittent function in the daily work of an organism. However, the more startling possibility is that tools are themselves intermittent participants in the organism-environment exchanges.

Tool use involves a mutual contingency between tool and user. Fragaszy and Mangalam (2018) acknowledge this mutuality as a ‘body-plus-object’ system, but they may have underspecified the issue by suggesting the mutuality is an addition. For Gibson (1979), organisms and environments entail one another. Though he saw the relationship so constructive as generative of perceptual experience, the relationship between organism and environment is not some polite addition of parallel and mutually well-wishing processes. On the contrary, organisms constantly exert their goals upon the environment, exploring, reshaping, and usually leaving environmental resources irretrievably disturbed. Furthermore, environments press their constraints upon the goalful organisms.

Organisms and environments branch outwards and into one another—this is no less a tenet of ecological psychology than it is a tenet of ecologically-focused developmental systems theories that seek to anchor intelligent behavior in the contextual structure at many scales beyond the cells of the organism (Griffiths and Gray, 2001; Japyassú and Laland, 2017; Lewontin, 1982). Ecological approaches to intelligent behavior like tool use thus focus on the coastlines between organism and environment. Organisms and environments are colliding and invading one another at very many scales: ambient energy deforms the extended tissues of the organism, and organisms chisel and carve into the ambient array for newer and deeper meanings (Gibson, 1979). Such coastlines are built according to cascades, with the small-scale roll of pebbles up and down the shore, the medium-scale pressure like tides and currents, and the long-scale pressures like the plate tectonics shifting the earth’s surface.

The ecological psychology of Gibson and its insights into tool use may thus benefit from the geophysical research that has sought to make sense of the cascades in actual coastlines. When studying the coastlines bounding Britain, Mandelbrot (1967) realized that such boundaries embody fractional (or ‘fractal’ for short) dimensions. Off-putting at first glance, fractal dimensionality aims to do the critical job of quantifying structure that fails to be integer-dimensional (e.g., zero-, one-, two-, or three-dimensional points, lines, surfaces, or Euclidean solids). Coastlines with varying fractionality can crucially originate from nonlinear interactions across scales. The nonlinear interactions across the scale—the cascade that blends information from multiple scales to generate dynamic, distributed, flexible behavior—entail variation in these fractal dimensions. That is, they entail ‘multifractal’ dimensionality (Mandelbrot, 2013). Abstract and upsetting as the notion of fractional dimensions may be, multifractal geometry affords us with a quantitative toolset that converts the notion of a cascade from a lyrical example into a falsifiable model. A given measurement (e.g., of organism tool use) offers a clear need to be measured to test how strong or weak the interactions are across the scale.

Because the organism-environment relationship is never adrift from long-scale contingencies, it is not crucial that the tool and skin remain in constant immediate contact (cf. Fragaszy and Mangalam, 2018). The tool may drift from the immediate grasp, but the multi-scaled organization of the organism-environment relationship leaves no gap where the tool is ‘gone.’ Rather than an empty expanse, environmental space is full of clutter whose integral flow supports organisms via contact.
through distributed-but-rarely-distinct modalities (e.g., optical, acoustic, and haptic; Gibson (1979); Stoffregen and Pittenger (1995), and Harrison et al. (2021), respectively). The specificity of localized sensor cells is physiologically real, but it distracts from the non-exclusivity and often mutuality of manipulation and, say, observation when mechanical contact is lost (Stoffregen et al., 2017). Cascades span cross-scale interactions through these ecological flows like a spiderweb of contingency that the organism then manipulates to extend its reach.

We can revisit our considerations of using a key to open the door. The seemingly obvious ‘tool’ is the key. However, according to Fragaszy and Mangalam’s (2018) definition, the narrowly defined ‘tool’ actually slips in and out of existence, and other tools flicker into existence to make up the difference. The key that we thought was in our pocket or pursued turns out only to be a tool in potential, not a tool on hand in direct contact with the skin. At a longer time scale, the key has been cast out into the hiding spaces in the front yard, much like a projectile that we have thrown away from ourselves only to catch it later. In the meantime, we have been clawing through the detritus of a purse or a pocket for a key that is not there, with curled and jabbing fingers that act just as a trowel or shovel might. The key under the flower pot has not been in hand and is not a tool until we ferret it out. By their narrow definition from Mangalam and Fragaszy (2018), the tool is here one minute and gone the next only to appear later. The hidden key is not a tool until we actualize its potential, that is, as we retrieve it from its status as just another projectile left out in the front yard.

The exploratory behaviors that allow us to dig for and then try to grasp tools are hazy, blurry structures. We thrive on this blurriness and would not want it another way—indeed, we might find ourselves locked out of our house if we did not have this fluid capacity to strategically launch tools far from our grasp and find them again later improving tools of our bodily parts. As organism searches the environment, fashions tools out of their resources, copies and hide those tools at various locations, the coastline between organism and environment becomes very fluid and hazy indeed. Science need not shrug at this haziness and surrender to ignorance—instead, we might just as soon use the same multifractal geometry to probe this fluid coastline for the layout of cross-scale interactions (e.g., from movement to submovement so forth). Indeed, when we measure these behaviors, the multifractal geometry of these exploratory behaviors interacting with tools is predictive of what an organism comes to know about what the tool can do (Doyon et al., 2019; Hajnal et al., 2018; Kelty-Stephens and Dixon, 2014; Mangalam et al., 2020a,b,c; Mangalam and Kelty-Stephen, 2020; Stephen et al., 2010; Stephen and Hajnal, 2011).

What psychological processes underlie tool use in humans and nonhuman animals? Tools rest on the boundary between organism and environment, and the fate of the tool—its hobbling, its workings, and its flickering in and out of distinct existence—is bound up entirely in how this organism-environment coastline develops as a cascade. The term ‘cascade’ refers to any physical processes that branch, fracture, avalanche, diffuse, or otherwise spread apart across multiple scales across space or time. Blending information from events at multiple scales is centrally how biological systems of all types operate—another way to say this point is that any given event in a biological system only takes its meaning from smaller events composing it and from the larger events contextualizing it. Organism physiology exhibits cascades spatially (e.g., hierarchical branching of neural dendrites, cardiovascular vessels, and capillaries (Goldberger et al., 1990), actin-myosin architecture (Fernandez-Gonzalez and Zallen, 2011), and cuboidal supporting cells (Dragovich and Mišić, 2015), collagen composing bones, (Fratzl, 2008), and tensity-like networks of connective tissue that span the entire organism, wrapped tautly across the muscles and bones (Turvey and Fonseca, 2014) as well as through a correspondingly hierarchical temporal structure whenever these multifractally-shaped parts operate (e.g., neuronal avalanches (Zorick et al., 2020). The spreading interactions across multiple scales of this hierarchy (e.g., Ingber, 2006) entail a multifractal structure (Turvey and Fonseca, 2014).

These physiological hierarchies work hand-in-glove with the psychological hierarchies, for example, looking for a key, fidgeting about for it, remembering a prior plan to hide a key, and then planning a new strategy of fidgeting for the hidden key. Furthermore, the multifractal geometries of exploratory behaviors will predict verbal, psychological reports of what a tool can do (Mangalam et al., 2020a,b,c; Mangalam and Kelty-Stephen, 2020). The knotting and curdling of the organism-environment coastline call for such startling mathematical constructs as fractional dimensions—let alone multiple fractional dimensions—to model this coastline on which tools bobble, work, and blink in and out of existence. Multifractal geometry is the primary mode of understanding how events coordinate across multiple scales—whether within a single organism (Carver and Kelty-Stephen, 2017; Mangalam, Carver, et al., 2020b), between organisms (Carver and Kelty-Stephen, 2017), or between organism and environment (Stephen and Dixon, 2011; Teng et al., 2016)—no matter whether the coordination is visual or mechanical.

Which of these psychological processes are exclusive to tool use? These processes are not exclusive to tool use because tools are not specifically different. Tools are most valuable because they are not a closed set; they are craftable and fleeting structures that appear, disappear, come to hand and drop from grasp as needed. Tools are helpful because they are artifacts that grow, decay, and wander towards and away from the organism-environment coastline. Cascades and multifractal processes are the specific modeling framework that explains intermittent structures like tools. Tools themselves are happenstance structures that grow to mediate the organism-environment relationship. They are not a firm set of objects with a firm set of always-true conditions. My point here is that the muddiness of definitions of the toolset is less a problem for psychological research than it is a sign that tool use might benefit from not carving out an insulated niche for itself that keeps tools as solid rigidly defined structures. We need the muddiness of tool definitions because muddiness is what makes tools useful. The happenstance intermittency of tools is not a reason to shrug at tools but rather to take better stock of the reality of the muddiness. My concern is that over-formal distinctions between tool and not-tool could risk pricing this literature out of the chance to explain the critical issue of how an organism can use a tool to mediate its experiences of the environment.

Which psychological processes involved in tool use are exclusive to Homo sapiens? As I had discussed in the example of fishing for keys in pockets or under flower pots, humans exploit the intermittency of tools across their own organism-environment coastline. Nothing about this capacity to exploit a murky organism-environment coastline is unique to humans, and even the simplest species have the wondrous capacity to make a tool appear and disappear, to blend it in or distill it from either body or environment. For instance, an amoeboid slime mold (Dictyostelium discoideum) uses the molecule cyclic adenosine monophosphate (cAMP) to navigate a ground surface find and coordinate other conspecific amoebae. D. discoideum spend the earlier, better-fed days as an amoeba, and it is only as food becomes more scarce that the amoebae coalesce into a multicellular body—either a fruiting body or a slug for locomotion to a niche with better nutrient stores (e.g., Schaap, 2021). This drama has all of the necessary features of tool use, but it also shows how the distinctions between tool and user may blur.

In the traditional sense, cAMP fits all the needs of a mechanical tool. The amoebae are manipulating cAMP, grasping molecules with its cell-membrane receptors, using the molecules to orient their own cytoskeletal posture towards and to inch up the cAMP gradient to the source (Chisholm and Firtel, 2004). Eventually, individual amoebae on the move will use cAMP to attract each other along the way, using a cAMP relay to latch on to slow amoeba behind them (Bagrodia et al., 2006). Hence, at all points, the amoeba grasps cAMP and manipulates it to operate on the ground surface as well as on the surface of other cell membranes. However, the same intermittency of the tool that supports their
adaptive use in humans gives us just the same intermittency in tools that amoebae use. Amoebae do the same not-quite-magic trick of making things tools or unmaking those tools that give the humans such flexibility in their tool use. The organismic coastlines of this example blur in three major respects. First, the tool is sometimes but not always clearly separate from the body. The relay use of cAMP involves the amoeba producing its own new cAMP under food scarcity (Chisholm and Firtel, 2004). Second, this tool use essentially invents a new body, a multi-cellular aggregate, effectively redrawing the organism-environment coastline (Bagorda et al., 2006). The third sense in which the organism-tool coastline blurs is that the body can fashion tools from itself. The slug tip’s external curvature focuses visible and infrared light just like a lens, focusing light towards the rear the slug or fruiting body and thus Interrupting rearward cAMP production, leaving the cAMP-ful tip to drag it forward (Schaap, 2021). And although the tip touches no surface, light remains no less patterned by the ambient surfaces than in Gibson’s (1979). So, there is no lack of contact—there is in fact, no empty room in which the slime mold can fail to respond to the constraints shaping and stimulating its body.

It is a clever thing that humans can make a thing a tool that did not meet the criteria for ‘tool’ before and then also break down or send elsewhere a tool into something that again no longer meets the criteria for ‘tool.’ And it is no less clever and remarkable when non-human species can engage in the same pragmatic use of resources to make and break tools as needed. The intermittency of the tool is of the same benefit to all species, which is all the more reason to care about tool use—even if the intermittency is also a stumbling block to scientists aiming at concise and closed definition of tools.

What must be the direction for future work on tool use? The intermittency of tools points immediately to the question of agency and its bounds. How do organisms extend or retract their scope of influence? How do they push their coastline outwards? Or give ground back to the environment? As the tool shimmers in and out of existence, the organism—interrupting the environment that is temporarily attached to the body to act on other objects—must be the direction for future work on tool use. The tool use becomes a part of the action system that establishes the effectivities that function as a scale to account these processes are not specific for tool use nor for any given species. Some future routes are presented to expand this approach to account for more aspects of tool use than just perception-action.

What constitutes tool use? During our daily life activities, we often grasp an object in the environment to use that object as a tool to reach our goal. For instance, we use a knife to cut bread and a spoon to stir our coffee. Hence, a tool can be casually defined as an object in the environment that is temporarily attached to the body to act on other objects in the environment to reach a goal (cf. Beck, 1980; Fraganzo and Mangalam, 2018). Most of the time objects are used as tools when our own action system falls short or when action goals can be achieved more conveniently with a tool, that is, tools alter our capacity for action. Therefore, we take a perception-action perspective on tool use, one of the main lines of research on tool use that are outlined by Fraganzo and Mangalam (2018). We rigorously apply the ecological-dynamical approach (cf. Profeta and Turvey, 2018) to tool use within this perspective.

What psychological processes underlie tool use in humans and nonhuman animals? In the ecological approach to perception-action, control of an action does not come from an internal structure (such as a part of the central nervous system), but coordination of action and perception takes place in an organism-environment system (Gibson, 1979; see Michaels and Carello, 2000; Richardson et al., 2008; Warren, 2005 for overview papers of this approach). Properties of the organism as well as properties of the environment, which shape the organism-environment system, determine behavior. For instance, arm length (organism property) as well as the property of the object determine trunk-leaning during object grasping. An organism moving through an environment creates perceptual flow fields and these flow fields contain invariants that specify properties of an environmental feature or the relation between the organism and the environment (i.e., the focus of expansion in an optical flow field is informative about heading direction). That is, the perceptual flow fields specify functional relations between an organism and its environment that have meaning for an organism and this meaning is perceived directly (see the contribution of Wageman & Day). Therefore, organisms directly perceive affordances, the possibilities for action in the environment. For instance, someone can perceive whether the size of a handle affords a tool to be graspable with one hand.

Important for understanding tool use is that affordances have their counterparts in the organism, which are dubbed effectivities (cf. Michaels and Carello, 2008; Shaw et al., 1995). For instance, in his seminal paper on affordance perception, Warren (1984) demonstrated that the climability of a stairs (i.e., its affordance) is perceived in terms of the riser height of the perceiver. Hence, properties of the environment (i.e., affordances) are perceived in terms of the properties of the organism (i.e., effectivities).

Effectivities are determined by the synergies that can emerge in the action system. From a dynamical systems perspective to movement coordination, synergies emerge from task, organism and environmental constraints in a self-organizing manner. Synergies are defined as the temporary functional units in which the abundant degrees of freedom are organized (Kelso, 2009; Turvey, 1990, 2007). Synergies maintain a functional organization through covariation of the degrees of freedom that make up the synergy (Kelso et al., 1984; Latash et al., 2007; Riley et al., 2011; Schöner, 1995). For instance, when pistol shooting the joint angles in the arm covary such that the aiming at the target is stabilized (Scholz et al., 2000). In sum, combining the principles presented in the foregoing gives an account of perception-action in which perceptual invariants act specify affordances that are linked to the effectivities that determine the synergies that should be formed.

An object in the environment that is attached to the body to function as a tool changes the geometry of the action system. For instance, a tool is often held in the hand and thereby the tool changes the shape (i.e., length) of the action system. Equally important, a handheld tool produces forces and torques in the muscles and joints that affect the constraints on the basis of which synergies in the action system emerge. For instance, a tool has a certain weight, and this weight changes the interactions between task, organism and environmental constraints on the basis of which synergies emerge. Hence, a tool in use affects the geometry of the action system as well as the available synergies (Fig. 5). Both these changes affect the effectivities that function as a scale to which the properties of the environment are perceived. That is, a tool in use becomes a part of the action system that establishes the effectivities and therefore the affordances (Bongers, 2001; Bongers et al., 2003).

The incorporation of the tool in the action system has been suggested in different studies examining the kinematic characteristics of the tooling end-effector. When learning to use a complex tool, kinematic characteristics that normally show up in hand movements can also be observed in movements of the tool tip (Heuer and Sülzenbrück, 2009). In examining the mechanisms underlying these phenomena we analyzed the synergy in the arm during pointing with a rod to a target. Using an Uncontrolled Manifold (UCM) analysis (Scholz and Schöner, 1999; Schöner, 1995), we showed that there is more covariation in joint angles stabilizing the position of the rod’s tip in space than that there is other variability in the joint angles de-stabilizing the rod’s tip position (Valk
The tool in the hand of the use is schematically depicted. Two arm postures are shown in which joint angles covary to stabilize the position of the tip of the tool in the environment, indicating that the tool is integrated in the synergy. The tool affects the synergies in the action system, and therefore the effectivities and the affordances.

Fig. 5. The tool in the hand of the use is schematically depicted. Two arm postures are shown in which joint angles covary to stabilize the position of the tip of the tool in the environment, indicating that the tool is integrated in the synergy. The tool affects the synergies in the action system, and therefore the effectivities and the affordances.

Moreover, this effect did not depend on the length of the rod (10 – 40 cm) used to reach to a target. In a similar vein, Rein et al. (2013) showed that stone-knappers had more covariation in their joint angles than variation affecting the position of the hand and Mangalam et al. (2018a,b) showed that bearded capuchin monkeys stabilize the path of the hammer when cracking nuts. Therefore, several studies showed that joint angles covary to stabilize the end-effector at the tool, indicating that a tooling synergy is formed that incorporates the tool.

The incorporation of the tool in the synergy in the arm implies that constraints of the tool interact with constraints of the task, organism and environment to determine the effectivities. A change in effectivities as a function of the properties of the tool in use does also result in a change in affordances (Fig. 5). That is, the environment is perceived with reference to the properties of the action system that consists of the body and the tool. To examine this, several experiments were conducted in which participants had to select a distance from which to displace an object with the tip of a handheld rod (Bongers et al., 2004, 2003). Importantly, the to-be-displaced object was placed at hip-height and it was approached, and the distance had to be selected, with the tip of the rod pointing upwards so that the perceived affordance could be studied. Findings demonstrated that the selected distance was a function of the length of the rod and of the dynamic forces and torques created by the rod. Importantly, these effects interacted with properties of the to be displaced object (Bongers et al., 2004) emphasizing that tooling affordances refer to the relation between the properties of the action system, including the tool, and properties of the environment. The idea that tools affect the affordances and that the specifics of the tooling affordances are perceived by the organism is supported by studies of Wagman and colleagues. For instance, Wagman and Taylor (2005) showed that affordances can be perceived for the tool and for the body + tool system. Moreover, Wagman et al. (2016) showed that affordances of tools are perceived that are assembled out of other objects while also the affordances of the individual objects making up the tool can be perceived.

From the perspective outlined here we define a tool as an object from the environment that is incorporated in the emergent synergies in the action system to perform a goal-directed action. Based on this integration of the tool in the action system the end-effector displaces from the body to the tool and affects the effectivities and thus the affordances. Therefore, tools allow for actions that are not possible without the tool, while the performing of goal-directed actions with a tool emerge from similar principles as any other action. Hence, from this perspective tool use is a behavior as all other behaviors and does not require a specific label nor invoking specific psychological processes for its understanding.

Which of these psychological processes are exclusive to tool use? Which psychological processes involved in tool use are exclusive to Homo sapiens? From the ecological-dynamical approach it is straightforward to see that processes underlying tool use are not species specific. This is supported by the notion that affordances can be perceived by animals, as is specifically shown by Wagman et al. (Wagman et al., 2018, 2017). Moreover, self-organization is omnipresent as an organizing principle in the animate and the in-animate world. However, this does not mean that the same tooling behavior will be observed among species. That is, Mangalam et al. (2020) showed differences in striking behavior in nut-cracking for bearded capuchin monkeys, expert humans and novice humans. Since these three groups have different organic constraints, it is to be expected that their effectivities differ, their affordances differ and that the actualization of the affordances by the synergies differ. In sum, two basic notions of the ecological-dynamical approach, affordances and self-organization, play an essential role in tooling and non-tooling behavior among different species. Therefore, there is no principle reason why tool use cannot be understood with similar mechanisms as non-tooling behavior and over different species.

What must be the direction for future work on tool use? The approach presented in this contribution needs to be expanded to a broader range of behaviors and tools to be able to give a full-blown account of tool use. Here we present three possible routes in which the approach could be further expanded in the future. First, our earlier studies regarding synergies in rod reaching (Valk et al., 2016; van der Steen and Bongers, 2011) can be taken one step further. A defining characteristic of a synergy is not just covariation of joint angles, but also the actual location in joint space where the synergy emerges (Tuitert et al., 2020; Wissing et al., 2020). Studying whether, and if so how, the location in joint space where the synergy emerges depends on the tool’s properties could further our understanding of the roles of tool constraints in the emergence of synergies.

Second, a topic that is relevant to understand tool use is the ability of organisms to construct tools (see contributions by Wagman & Day, Stout, Osiurak). Tool construction has been studied in the ecological-dynamical framework by Van Dijk and Bongers (2014), who examined the emergence of an action system when participants constructed new tools from available objects. Since affordances are prospective, they should be particularly apt to explain tool construction. A future line of research could focus on framing the problem of tool construction in terms of perceiving and actualizing affordances.

Third, tool use has often been approached as problem-solving behavior. Several approaches of tool use therefore incorporated cognitive mechanisms related to reasoning to give a full account of tool use (cf. Osiurak et al., 2010, 2017). Recently attempts have been made to broaden the ecological-dynamical approach to higher cognitive behaviors, such as action selection (Cox and Smitsman, 2019; Dineva and Schöner, 2018), representation-hungry behaviors (Golonka and Wilson, 2019), and language (Rączaszek-Leonardi et al., 2018; van den Herik, 2021). These expansions of an ecological-dynamical approach should in the future make it possible to explain aspects of tool use that are currently explained using cognitive mechanisms.

Together these developments should enable us to advance a full-blown account of tool use starting from the principles of an ecological-dynamical perspective. We believe that the starting point of such an account should lie in that tools are incorporated in synergies, and as such determine effectivities and affordances.

6. More than just tool use — Dietrich Stout

Humans have been described as tool-making animals but what is really distinctive is the broader realm of human technology. Technology is a broad and variable behavioral domain spanning a spatiotemporal range from neurons to institutions. Understanding its cognitive
foundations will require comparative research across diverse technologies unified by an overarching evolutionary-developmental theoretical framework. This perspective highlights interactions between technological production, collaboration, and reproduction and the key role played by internal models for action prediction and synchronization.

**What constitutes tool use (and is that the right question)?** Many animals make and use tools, but humans are distinctive in the complexity, diversity, sophistication, omnipresence, and obligatory nature of our reliance on tools. Simply put, other animals use tools but only humans have technology. Indeed, humans inhabit a uniquely technological niche that we ourselves have constructed (Stout and Hecht, 2017), and which continues to shape our biology, behavior, and cognition. Attention to this broader technological sphere is clearly warranted. For example, Osiurak and colleagues (Osiurak and Heinke, 2018; Osiurak and Reynaud, 2020a) have argued that the prevailing conception of tool-use as object manipulation is too narrow because it excludes ‘tools’ such as machines, computers, containers, and structures. Thus, they suggest that it fails to emphasize a uniquely human capacity for ‘technical reasoning.’ Osiurak et al. propose neologisms like intool-logy (Osiurak and Heinke, 2018) to describe this broader sphere of investigation but the existing term technology might prove more apt if its meaning can be suitably constrained.

One approach is to ground the concept in an evolutionary perspective. Humans have evolved a tightly integrated adaptive strategy (Kaplan et al., 2010) in which a focus on high-value, difficult-to-acquire food resources provides the surplus nutrition needed to fund growth, survival, and reproduction, and is in turn enabled by the increased longevity and brain size that allow teaching, learning, and the cultural evolution of increasingly effective skills, knowledge, and equipment. This human-constructed niche is thereby populated by increasingly complex technological systems focused on material production. This evolutionary perspective converges with the ‘technological systems’ approach in the social sciences, which identifies a technology as an integrated system of hardware, people, skills, knowledge, social relations, and institutions (Dusek, 2006; Hughes, 1987).

On this view, technology comprises socially reproduced activities involving the manipulation or modification of objects to enact changes in the physical environment (Stout, 2013). This extends beyond simple tool use to encompass longer causal chains involving: 1) the coordinated activity of many individuals, 2) use of objects and materials in a wide range of roles other than as hand-held instruments, and 3) processes of social reproduction that sustain and elaborate technological systems. Communication is thus essential to technological systems but is not their ultimate goal. Technologies primarily pursue materially instrumental tasks to achieve physical changes in the world and only incidentally involve communicative tasks that seek to alter thoughts, behaviors, or experiences (cf. Legare and Nielsen, 2015). We could thus speak of technologies for the production of communications tools such as books or musical instruments but not for practices of teaching, storytelling, or musical composition. Systematic approaches to communications might then be termed ‘arts’ or ‘sciences’ rather than technologies. This semantic distinction is important because materially instrumental goals are shaped by relatively invariant physical constraints whereas the communicative goals must adapt to human psychology in the context of specific cultural systems of meaning. They will thus tend to implicate different cognitive processes (Finkel et al., 2016; Fischer et al., 2016; Tylen et al., 2016), learning strategies (Heyes, 2016; Kendal et al., 2018; Legare and Nielsen, 2015), and cultural evolutionary dynamics (Dere`x and Mesoudi, 2020).

**What psychological processes underlie technology in humans and nonhuman animals?** Attempts to specify a critical ‘essence’ of technology have invoked everything from skilled prehension (Buxbaum, 2017), to causal reasoning (Osiurak and Reynaud, 2020a), mental time travel (Suddendorf et al., 2018), imitation (Dere`x and Mesoudi, 2019), and mentalizing (Tomasello et al., 1993). The technological niche perspective developed in the previous section recognizes all these as relevant and interacting. For example, the sophistication of human technology is often attributed to a process of incremental improvement termed as cumulative cultural evolution (CCE) (Mesoudi and Thornton, 2021). CCE is widely believed to require ‘high fidelity’ social reproduction dependent on mentalizing or imitation to enable the lossless accumulation of innovations (Derex et al., 2019; Tomasello et al., 1993). In the case of technology, however, capacities for causal and analogical reasoning (Gentner and Hoyos, 2017; Osiurak and Reynaud, 2020a), cognitive control (Gon`oli et al., 2018; McDougle et al., 2016; Stout et al., 2015), memory (Gru¨ber and Ranganath, 2019), and perceptual-motor control (Sanchez et al., 2017) will often be implicated in the generation, identification, and retention of beneficial innovations (Legare and Nielsen, 2015; Miu et al., 2020). Insofar as innovation requires expertise, processes of knowledge reproduction (Gentner and Hoyos, 2017; Pan et al., 2020), skill acquisition (Gowlland, 2019), and innovation (Legare and Nielsen, 2015) will be thoroughly intertwined (Osiurak and Reynaud, 2020a; Stout and Hecht, 2017). Finally, the same capacities for intersubjectivity (Tomasello et al., 1993) and interactive synchrony (Pagnotta et al., 2020; Pan et al., 2020) that support the social reproduction of technology also underpin cooperation and coordination (Hill et al., 2009; Powers et al., 2016) that enable the complexity of collective human technologies to so far exceed that of individual animal tool-use. These complex interactions are organized around three key features of technology: production, collaboration, and reproduction.

**Production.** The materiality of technological production allows the open-ended accumulation of components and procedures (Derex and Mesoudi, 2020; Stout, 2013) and provides a durable medium for collaboration across time and space. Objects and infrastructure embody information and persist across generations, constituting a novel channel of cultural transmission and evolutionary inheritance (Laland et al., 2015). Technological artifacts and situations also scaffold cognition by externalizing information representation and manipulation and cueing the retrieval of appropriate event schemas (Barbey et al., 2009; Newen et al., 2018; Stout and Hecht, 2017).

Neuroscientific studies have largely focused on simple, hand-held tool use, leading to the identification of a dorsal occipital-parietal-fron tal pathway instantiating spatial and kinematic object + body (Martel et al., 2016) models for action planning and perception and a ventral occipital-temporal pathway representing semantic information about properties and dynamics (Orban and Caruana, 2014; Stout and Hecht, 2017). This has now been extended to a broader account of object-driven cortex (Yildirim et al., 2019) including object and scene perception in ventral temporal cortex and intuitive physical reasoning about object dynamics (motion, support, collision) in frontoparietal cortex (Fischer et al., 2016). This “physics engine in the brain” is an assembly of regions involved in generating internal models for action planning (McNamee and Wolpert, 2019) and in cognitive control more generally (cf. frontoparietal control network; Dixon et al., 2018; Ptak et al., 2017).

Implicit technical reasoning supported by frontoparietal cortex may be sufficient for everyday tool use (Osiurak and Heinke, 2018), but more complex activities like the tool making and design impose additional demands (Ball and Christensen, 2019; Stout et al., 2015). These include prospection for future planning (Saddendorf et al., 2018), analogy and relational reasoning to find novel solutions (Ball and Christensen, 2019; Vendetti and Bunge, 2014), and metacognitive monitoring of strategic suitability and progress (Ball and Christensen, 2019) all of which involve a high degree of attention from the stimulus to the goal followed by thought to be supported by dynamic interactions between frontoparietal control and the default mode networks (Dixon et al., 2018).

**Collaboration.** Technology is most clearly distinguished from simple tool-use by its coordination of multiple individuals over extended periods of time and space. Small scale coordination between individuals relies on reciprocal prediction achieved by interpersonal coupling of internal forward models for anticipatory motor control (Curioni et al., 2019). This coupling can occur at multiple levels of abstraction (Hasson et al., 2018).
and Frith, 2016) and provides a key mechanism supporting the implicit mentalizing, empathy, communication, learning, and social affiliation (Alcalá-López et al., 2019; Hasson and Frith, 2016; Pan et al., 2020; Shamay-Tsoory et al., 2019) that in turn support larger scale collaboration. In addition to implicit processes of social alignment (Shamay-Tsoory et al., 2019) collaboration may require explicit negotiation to allocate responsibilities and agree on plans of action (Bang et al., 2017; Mathieu et al., 2017). This may involve metacognitive strategies such as confidence matching, deference to status or experience, and open discussion (Bang et al., 2017; Bang and Frith, 2021; Miu et al., 2020; Shea et al., 2014). Finally, collaboration may be enforced (Bang et al., 2017; Hughes, 1987) by explicit institutional rules and authority, which are in turn the emergent product of interactions between and within smaller groups (Powers et al., 2016; Pryor et al., 2019).

**Reproduction.** Technological learning is a protracted, collaborative process (Gobet, 2015; Gowlland, 2019; Pargeter et al., 2019; Suddendorf et al., 2016) reflective of demands for precise control of physical contingencies during material production. This problematizes dichotomies of social vs. asocial learning (Galef, 2009; Heyes, 2018), product vs. process copying (e.g., Tennie et al., 2009), and ‘blind’ vs. guided innovation (Mesoudi, 2021) that have been prevalent in culture evolution research. This is exemplified in technological apprenticeship (Gowlland, 2019; Sterelny, 2012), in which an extended program of alternating social learning and individual practice (Stout, 2013; Whiten, 2015) enables the reproduction of increasingly sophisticated skills. Such learning is scaffolded by everything from the exemplar artifacts, available tools, recurring situations, and observable behaviors of culturally constructed ‘learning niches’ (Flynn et al., 2013; Fragaszy et al., 2013; Stout and Hecht, 2017) to intentional demonstration, explicit instruction, and affective feedback from teachers (Kline, 2015) guides learners to re-create increasingly sophisticated skills though deliberate practice over extended periods, with each round of individual practice allowing deeper appreciation of the available social information.

The resulting expertise combines internal models for efficient action perception, control, and prediction (McNamee and Wolpert, 2019; Sokolov et al., 2017) with flexible task-related, hierarchical knowledge structures of increasing depth and complexity (Gobet, 2015; Stout, 2013). The relevance of each to particular technologies will help determine the efficacy of different learning strategies such as trial-and-error experimentation (Truskav and Prat, 2018), end-product emulation (Reindl et al., 2017), body movement mimicry (Heyes, 2018; Tennie et al., 2009), intention sharing (Tomassello et al., 1993), and various forms of social scaffolding and teaching (Kline, 2015). Rather than one key reproductive mechanism we should thus expect context-dependent diversity (Caldwell, 2020).

**Which of these psychological processes are exclusive to technology?** By the definition proposed here, technology is an evolutionarily relevant domain of human activity rather than a discrete process or capacity. As such, technological cognition is ‘soft-assembled’ from neurocognitive mechanisms and systems as they become behaviorally relevant, rather than hard wired as a dedicated system. Thus, there would be no particular processes exclusive only to technology although the functional networks recruited by various technologies might be expected show a family resemblance distinct from other behavioral domains. On the other hand, the definition proposed here is motivated by specific evolutionary hypotheses positing that key processes supporting modern technology are elaborated in humans specifically due to selection on technological capacity and aptitude (Stout and Hecht, 2017). In this evolutionary sense, processes such as intuitive physical reasoning, kinematic monitoring of self and other, and even interactional synchrony would be specifically ‘for’ technology. Similar logic would apply to answering the original question of psychological processes exclusive to tool use, which is also a highly diverse behavioral domain that has proved surprisingly difficult to define (Crain et al., 2013; Fragaszy and Mangalam, 2018).

Which psychological processes involved in technology are **exclusive to Homo sapiens?** It is not clear that any of the processes involved in supporting technology are qualitatively unique to humans. Perhaps the strongest case could be made for cognitive mechanisms like explicit theory of mind, metacognitive strategies, or analogical reasoning that may themselves be products of cultural evolution in a fully linguistic species (Heyes, 2018). It has, however, been said (although it is unclear by whom) that “Quantity has a quality all its own.” Humans may not be qualitatively unique on any one dimension of technology but we are quantitatively exceptional on so many different dimensions at the same time that piecemeal adaptive accounts seem to miss a bigger picture.

As reviewed above, exceptional human capacities for skilled interaction with the physical world appear central to the evolution and development of many key aspects technological cognition. Stout and Hecht (2017) thus suggest a Perceptual Motor Hypothesis (PMH) for the evolutionary-development-al-cultural construction of human cognition from ancient primate systems for body awareness and sensorimotor engagement with the world. These systems are early-developing (Baum et al., 2020) and directly engaged with the internal and external sensory-perceptual (Arguelles et al., 2016), making them a nexus for interaction between externalizing processes of technological niche construction and internalizing processes of neurocognitive development (Byrge et al., 2014; Flynn et al., 2013; Heyes, 2018; Kennedy et al., 2017). According to the PMH, enhanced human sensorimotor acuity and the experiences this enables guide construction of the internal models and intuitive physics required for technological production. Sensory predictions by these models support the sense of agency and self-other discrimination (Haggard, 2017) that underpin human self-awareness, imitation, social cognition, and empathy (de Guzman et al., 2016) and ultimately the development of “Theory of Mind” capacities (Heyes, 2018), all of which support further technological collaboration, reproduction, and biocultural evolutionary feedback. According to this view, the proper study of technology must cross levels of analysis from neurophysiological dynamics to the cultural evolution of norms and institutions in order to seek unity in diversity by identifying the common processes underlying diverse outcomes across different real-world contexts.

**What must be the direction for future work on tool use?** Broadly speaking, a future “cognitive science of technology” would be a comparative science seeking to identify patterned relations between contexts, mechanisms, and functions across superficially diverse technologies. This means embracing the real-world complexity, variation, and contextual particularism (Matusz et al., 2019) of technological behaviors. Among the many challenges facing this endeavor are the large spatial and temporal scale of many technological phenomena, which may require long-term study and a combination of experiments (e.g., Pargeter et al., 2019), ethnographic case studies (e.g., Gowlland, 2019), and comparative analyses (e.g., Koster et al., 2020). One more specific direction could be to test the PMH. This would require expanding our surprisingly limited understanding of perceptual-motor variation across primates as well as the proposal that patterns of human technological diversity can be explained in relation to underlying variation in perceptual-motor processes, demands, and developmental interactions. One key prediction of the PMH is that learning and reasoning about even non-mechanical technological properties (e.g., chemical reactivity) should rely substantially on concrete perceptual-motor simulation (Barsalou, 1999) vs. abstract symbolic and analogical thinking (Brand et al., 2021). This prediction might be tested across various tasks and contexts using methods such as neuroimaging (cf. Fischer et al., 2016), behavioral studies of the impact of linguistic instruction on learning different skills both in the lab and “in the wild” (Brand et al., 2021), and the combination of the two to study the neurocognitive basis of individual differences in technological learning (Hecht et al., 2015; Prat et al., 2020).

Such ambitious aims are increasingly plausible with the development of new methods for the study of behavior and cognition in natural
contexts. Techniques such as motion tracking and EEG are promising for the study of motor control (Haar et al., 2020) and attention (Ladouce et al., 2019) in real-life technological settings, while methods for the study of interactional synchrony (Pan et al., 2020; Schirmer et al., 2021) offer insight into mechanisms of small-scale collaboration and social reproduction. At a larger scale, smartphone-based digital phenotyping methods (Omla, 2021) might be adapted to study individual experience of and engagement with real-world technological situations and institutions. Finally, performance in unconstrained real-world situations can be related to individual differences or experience-related plasticity in neuroanatomical, cognitive, affective, and perceptual-motor traits assessed in the lab (e.g., Hecht et al., 2015; Prat et al., 2020). This will require novel methods for quantifying technological performance (e.g., Pargeter et al., 2019; Stout et al., 2018) but offers a critical link between structure, function, and behavior needed to place variation in a broader evolutionary and developmental frame (Stout and Hecht, 2017).

7. The technical-reasoning hypothesis — François Osiurak

The main tenets of the technical-reasoning hypothesis are as follows. Technical reasoning refers to the ability to reason implicitly about physical object properties (see Osiurak et al., 2010, Osiurak et al., 2020a,b; Osiurak and Badets, 2016). This reasoning is both causal (i.e., predicting the effects on the environment) and analogical (i.e., transferring what is understood from one situation to another). It is based on non-verbal knowledge, called mechanical knowledge, which contains information about physical principles about mechanical actions (i.e., actions that involve physical objects; leverage, cutting, percussion). Technical reasoning is much more than spatial reasoning, which can consist, for instance, in determining whether a car can pass between two trees or whether two puzzle pieces can be arranged together. Indeed, it involves the understanding of the material dimension of objects (e.g., hardness, sharpness), which is the basis for the emergence of mechanical actions. Technical reasoning is involved in any manifestation of human materiality such as the use of physical tools (e.g., stone tool, hammer), but also tool making or construction (e.g., building a shelter). It is also thought to be exclusive to the human lineage. Thus, because it allows humans to discover and master a great amount of technical content, its emergence over evolution might explain why cumulative technological culture, that is the increase in efficiency and complexity of tools and techniques over generations, has been observed only in human populations (Osiurak and Reynaud, 2020b). In the following lines, I present the technical-reasoning hypothesis in more detail.

What constitutes tool use? The technical-reasoning hypothesis does not really confer any special status to tool use because it considers it as one of the manifestations of human materiality in the same ways as tool making or construction (or any technical devices that need the use of natural forces such as wind or fire). In this respect, as argued by Beck (1980) and Shumaker et al. (2011), any definition of tool use necessarily refers to a behavioral description, which does not imply any psychological or biological prerequisites. Thus, it is not because two species exhibit tool behavior that the same cognitive processes are at work in both species (Osiurak and Heinke, 2018). Note that the same is true for tool making or construction behavior. For these reasons, the technical-reasoning hypothesis is in line with the behavioral definitions of tool use, tool making, and construction proposed by Beck (1980) and more recently updated by Shumaker et al. (2011; Table 1). As explained, although the technical-reasoning hypothesis assumes that, in humans, technical reasoning is involved in any manifestation of human materiality (i.e., tool use, tool making, and construction), it nevertheless recognizes that tool use is characterized by an additional mechanism, that is, distalization (Osiurak and Federico, 2020). Distalization refers to the fact that, once a tool is grasped appropriately to be used, the natural effector (usually the hand) is no longer the end-effector. Instead, this end-effector becomes the active part of the tool, that is, the part of the tool that is used to act upon another object (e.g., the head of the hammer). Thus, there is an attentional shift, from the natural effector to the active part of the tool, while it is still the hand that needs to be controlled (for evidence for this distalization mechanism, see Cardinali et al., 2009; Iriki et al., 1996; Maravita et al., 2001; Maravita and Iriki, 2004; Miller et al., 2018; Osiurak et al., 2017; for an alternative explanation, see Holmes, 2012). This distalization mechanism also implies that the user needs to control the degrees of freedom of the body-tool system differently to the body-only system, a phenomenon called tooling (Fragaszy and Mangalam, 2018; Mangalam, 2016; Mangalam and Fragaszy, 2016). Importantly, this distalization mechanism is not unique to humans, which can explain why tool use can also be reported in nonhuman species. In broad terms, this distalization mechanism is orthogonal to technical reasoning in that it only allows a species to use tools, but it does not imply that this species possesses technical-reasoning skills.

What psychological processes underlie tool use in humans and nonhuman animals? Four cognitive functions are mainly involved in human tool use, each dedicated to a specific role: Technical reasoning, motor control, semantic memory, and planning. The role of technical reasoning is to generate technical solutions to solve physical problems, which can be novel (e.g., to get a small ball that rolled under a couch) or familiar (e.g., to peel an apple). In this respect, the technical-reasoning hypothesis diverges from related proposals, which consider that technical-reasoning-like processes are primarily involved in novel situations and, at best, can be employed as an alternative strategy in familiar activities (e.g., Buxbaum, 2017; Caruana and Cuccio, 2017; Martin et al., 2016a,b; Norman, 2002). According to the technical-reasoning hypothesis, technical-reasoning skills support both familiar and novel tool use, even if the process can be faster for familiar activities than for novel situations. Technical reasoning is critical to determine the appropriate mechanical actions as well as to select the appropriate tools and objects to solve these problems. The outcome of technical reasoning is a mental simulation of the mechanical action to be performed (e.g., the motion of a knife on an apple). However, simulating a mechanical action is not sufficient to realize it in the physical environment. This realization needs the selection and on-line control of the most appropriate motor actions. This is the role of the motor-control system, which is unaware of the goal of the action (e.g., tool use, object transport). If someone intends to perform back-and-forth movements with a knife on an apple, this is the expected effect, which constrains the motor actions selected within the motor-control system. Likewise, if someone has the idea to move an object from one location to another, the expected effect is the motion of the object, which also constrains the motor actions selected. Said differently, the motor-control system is only concerned with the economy of motor actions performed. Because tools and objects are not always directly available, the user needs to get them from other places. The role of semantic memory is to organize the search in episodic...
memory to know and, thus, to remember where to get the tools and objects appropriate for the ongoing activity (for discussion, see Osiurak, 2014, 2017). Indeed, knowledge about semantic categories (e.g., cooking, washing) is helpful to carry out an efficient search in episodic memory and to think of about tools and objects that are not here now (see Tulving, 1985). Finally, tool-use activities usually require a sequence of mechanical actions that can involve several tools and objects. An individual can generate these different mechanical actions in an unordered way. The role of planning skills is to rearrange this sequence in an ordered way so that to optimize time and to avoid potential fatal errors (i.e., the realization of a mechanical action that blocks the realization of another one). Thus, planning skills allow the individual to foresee future changes of the environment.

Evidence for the technical-reasoning hypothesis has come from the study of left brain-damaged patients, which has revealed a strong relationship between the ability to use and select familiar tools as well as to use, select and make novel tools to solve mechanical problems (Goldenberg and Hagmann, 1998; Goldenberg and Spatt, 2009; Osiurak et al., 2009; Moreau, 2020, for a review, see Osiurak et al., 2020a, b). This behavioral association has also been confirmed by brain lesion studies, which have indicated that difficulties in using both familiar and novel tools are associated with damage to the brain area PF within the left inferior parietal lobe (Goldenberg and Spatt, 2009; Martin et al., 2016a; Mengotti et al., 2013; Salazar-Lopez et al., 2016). Two recent neuroimaging meta-analyses have also revealed that the left area PF is preferentially and selectively activated when healthy participants focus on the mechanical actions between a tool and an object as well as when they observe others using tools (Reynaud et al., 2019, 2016). In other words, technical-reasoning skills could mainly be supported by the left area PF, allowing humans to generate and understand mechanical actions. By contrast, the ability to select the appropriate motor actions (to use tools or not) has been associated with more superior parietal structures and particularly the intraparietal sulci (e.g., Reynaud et al., 2016; Vingerhoets, 2014). Concerning semantic memory, a significant body of evidence has shown that semantic memory is neither necessary nor sufficient to actually use familiar or novel tools with objects (e.g., Buxbaum, 2017; Hodges et al., 2000; Lesourd et al., 2016; Silveri and Ciccarelli, 2009; for discussion, see Osiurak and Badets, 2016). In broad terms, this indicates that semantic memory is not useful to determine appropriate mechanical actions. However, the loss of semantic memory after temporal lobe lesions can impair the ability to use tools presented in isolation (Baumard et al., 2016; Hodges et al., 2000; Osiurak et al., 2008; Sirigu et al., 1991), thereby suggesting that semantic memory is first and foremost involved in the ability to link a tool with a specific usage (Osiurak, 2014). Finally, it has been found that patients with frontal lobe lesions or disexecutive syndrome are impaired when they have to perform complex tool-use activities that require a sequence of mechanical actions and not when they have to solve less complex tool-use activities that require only one mechanical action (e.g., Goldenberg et al., 2007). To sum up, the four main cognitive functions that support human tool use are each dedicated to a specific role and associated with a specific neural basis (Technical reasoning: To solve physical problems/Mainly Left area PF; Motor control: To perform appropriate motor actions/Notably motor, premotor, and somatosensory cortices, along with the basal ganglia, thalamus, and cerebellum; Semantic memory: To get absent tools and objects/Mainly temporal lobes; Planning: To rearrange sequences of actions in an economical way/Mainly prefrontal cortex).

Which of these psychological processes are exclusive to tool use? None of the four aforementioned cognitive functions are considered as exclusive to tool use, except the distalization mechanism of the motor-control system, which could constitute the very essence of tool use (see above). Indeed, as explained, technical reasoning is also at work when humans make tools or build constructions. The motor-control system is unaware of the goal of the action. Semantic memory is involved more generally in our knowledge about the world and is not critical to actually use tools with objects. Finally, planning skills are in charge of optimizing time when a sequence of actions is performed, irrespective of whether this sequence is tool-centered or not (e.g., construction behavior, but also when people play chess or optimize their shopping trips).

Which psychological processes involved in tool use are exclusive to Homo sapiens? There is a tendency in the animal cognition literature to give to nonhuman tool-using species a special status, as if tool use reflected a specific sign of intelligence. As argued by Hansell and Ruxton (Hansell and Ruxton, 2008), this status might be exaggerated because it is based on a confusion or even a kind of bijection (i.e., strict correspondence) between tool use and specific physical-cognitive skills. As explained above, tool use could be observed in various species that possess a distalization ability. However, this ability is orthogonal to the level of physical understanding that the species has. In this way, the technical-reasoning hypothesis obviously recognizes that tool use is not exclusive to humans. However, it also stresses that the study of tool use is not sufficient to understand how humans and nonhuman animals are able to understand their physical environment. As a matter of fact, the technical-reasoning hypothesis suggests that even if some animals could possess some of the components of technical reasoning (e.g., the causal component), technical reasoning in its entirety could be exclusive to humans. This claim is based on evidence from micro-society paradigms, which have shown that cumulative performance can emerge over generations even when individuals only transmit the product made (e.g., a tower or a basket; i.e., reverse engineering; Caldwell and Millen, 2009; Derex et al., 2019; Osiurak et al., 2021b; Zwirner and Thornton, 2015). Technical-reasoning skills (assessed with psychotechnical tests; e.g., selecting among four pictures depicting four different nails the easiest one to hammer) have also been found to be the best predictor of cumulative performance in these micro-society experiments (De Oliveira et al., 2019; Osiurak et al., 2021a, 2020a, 2016). Conversely, cumulative performance observed in this kind of paradigm is also accompanied by an increase in understanding of the physical system (Osiurak et al., 2021b). Taken together, these results indicate that technical-reasoning skills could have played a key role in cumulative technological culture, namely, a phenomenon that is considered as unique to the human lineage1. In sum, although tool use is not unique to humans, it might be nevertheless exclusive in humans because of its ‘recycling’ by technical-reasoning skills.

What must be the direction for future work on tool use? There is a crucial need in the literature to draw a marked distinction between tool-use skills from technical-reasoning skills, because of their orthogonality at a cognitive level. It is one thing to be able to manipulate a tool to use it with an object and another to understand the physical effects of this interaction. In this respect, three distinct lines of research should be developed. The first line should consist in extending the question of physical understanding in human tool use to tool making and

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1. Micro-society paradigms aim to investigate cultural evolution in laboratory (e.g., Caldwell and Millen, 2009; Morgan et al., 2015). The most popular version is the transmission chain paradigm. The task can be to optimize the speed of a wheel that descends an inclined track by moving the four weights placed along each spoke of the wheel (Derex et al., 2019; Osiurak et al., 2021b). The first participant of the chain performs the task. The second participant can scrutinize the product of (i.e., reverse-engineering), observe the action made by, or communicate with the first participant before performing the task himself. Then, the third participant does the same with the second one, and so on.

2. Studies on New Caledonian crows indicate that some signs of cumulative technological culture have been observed in this species, which is for its elaborate causal-reasoning skills (Rutz and Hunt, 2020; Taylor and Jelbert, 2020). In other words, although the technical-reasoning hypothesis in its strong form posits that both cumulative technological culture and technical-reasoning skills might be unique to humans, much more evidence is needed to demonstrate it (or to invalidate this claim).
What constitutes tool use? So, what are the points of convergence across researchers in their ideas about what constitutes tool use. All authors noted that tool use is associated with transforming the body into the body-tool system (i.e., all incorporate the notion of distalization of the end-effector). Mangalam and Fragaszy, Wagman and Day, and Bongers each focus on tool use to detect and exploit lawfully structured patterns of energy that provide ‘information about’ affordances of tools. Mangalam and Fragaszy provide a definition in which tooling is a deliberate act in which the body-object system produces a mechanical effect on a target. This definition necessitates that the actor, tool, and target physically contact each other during the activity of tooling and that the act of tooling lasts only as long as this spatial relationship is maintained (Fragaszy and Mangalam, 2018; Mangalam and Fragaszy, 2016). The authors justify this narrow definition because it affords analytical clarity. Wagman and Day expand the scope of this definition by including any interaction with an intermediary object that changes the ability to perceive and actualize affordances in the context of performing a goal-directed behavior. Consequently, Wagman and Day classify behaviors as tool use that Mangalam and Fragaszy would not, such as throwing objects at a target and using a wheelbarrow to transport material. Except for this discrepancy, Wagman and Day’s views are mostly compatible with those of Mangalam and Fragaszy—both rooted in the Gibsonian concepts of affordances and information detection. Bongers’ perspective is rooted in these concepts as well: tool use occurs when an environmental object temporarily alters the capacity for action, requiring the new coordination patterns in the act of performing that action (cf. Profeta and Turvey, 2018).

Kelty-Stephen also grounds his analysis in lawful relations, but shifts focus away from psychological processes per se and toward generic processes of cascade dynamics. Kelty-Stephen emphasized that tool use is an intermittent cascade of contingencies across a permeable animal-environment boundary. This permeability allows tool movement to inherit the multifractal fluctuations inherent in limb movement and return new multifractal fluctuations to those limbs (see also Mangalam et al., 2020a,b). Fluctuations flow through a continuous medium spanning the organism, tool, and environment via informational contact (acoustic, mechanical, optical). So, for Kelty-Stephen (like Wagman & Day), tool use does not necessitate continual mechanical contact between the object and the body.

Stout and Osiurak, respectively, focus more on processing and cultural transmission of information. Stout finds no utility in defining tool use per se and instead chooses to subsume tool use under the broader umbrella of technology. For him, technology (but not tool use) is a uniquely human endeavor—tool use (considered on its own) fails to capture the uniquely human capacity for ‘technical reasoning.’ Stout’s view is consistent with that of Osiurak for whom ‘intelligence’ is the intelligent use of technological innovations including, but not limited to, tools (Osiurak and Heinke, 2018; Osiurak and Reynaud, 2020a). Osiurak does not confer any special status to tool use because it is merely one of the ways in which technical reasoning is brought to bear in human materiality. However, Osiurak suggests that tool use requires an additional mechanism beyond technical reasoning: distalization (Osiurak and Federico, 2020).

8. Discussion

Multiple lines of scientific and philosophical investigation are concerned with the development and expression of humans’ engagement with tools and its relation to other dimensions of human experience. At first sight, these multiple lines of inquiry (including those described by the six author groups in this collection) may appear to be incongruent. However, as we shall discuss below, these seemingly divergent perspectives converge on some common themes and consequently foster a more comprehensive, interdisciplinary understanding of tool use than any of these perspectives would (or could) on their own. It is to these seeming consistencies and their integration that we turn now.

What psychological processes underlie tool use in humans and nonhuman animals? A fundamental question in the study of tool use concerns the psychological processes that underlie this phenomenon, but the divergence among researchers about what constitutes tool use may hamper a coherent answer to this question. Some researchers have investigated the neurophysiological underpinnings of tool use by studying brain-damaged patients (Goldenberg and Spatt, 2009; Lewis, 2006; Wheaton and Hallett, 2007) or noninvasive functional neuro-imaging in everyday settings (Bril et al., 2005; Krakauer et al., 2017). Others have done so by conducting comparative analyses of tool use across species (Bril et al., 2012; Mangalam et al., 2020d; Mangalam and Fragaszy, 2016). Unfortunately, any observed pattern of brain activation is mute on the psychological processes reflected by that activation pattern. A lack of a coherent theoretical framework makes it challenging to conduct studies across species that yield testable predictions about the psychological processes involved in tool use. So, we take this opportunity to suggest some degree of convergence on the psychological processes involved in tool use.

For Mangalam and Fragaszy, the psychological processes of interest in tool use are at the level of perception and action—in particular, the functional task demands establishing and maintaining a mechanical interface. In their embodied theory of tooling (Fragaszy and Mangalam, 2018), tool use depends on the perceptuomotor processes related to perceiving spatial relations among objects and surfaces, developing agency over objects attached to the body (the distalization of the end-effector), and controlling the bodily degrees of freedom to meet functional task demands. Mangalam and Fragaszy emphasize that these processes occur in the body-object-task-environment system. Moreover, together, these processes distinguish tool use from other instrumental problem-solving.

Similarly, for Wagman and Day, the psychological processes of interest in tool use are at the level of perception and action. They focus their analysis on detecting and exploiting lawfully structured stimulation patterns (‘information’). When the animal-environment fit is altered by a tool, the structure encountered at the point of observation provides information about affordances for tool use—whether, when, and how the tool can be used to achieve a goal. The lawfulness of this process entails that information about tool use is invariant over transformations (Hajnal et al., 2007; Mangalam et al., 2017; Wagman et al., 2017; Wagman and Hajnal, 2014a, b, 2016). Perceiving (and actualizing) such affordances requires spontaneously and temporarily assembling task-specific detection units (and task-specific control units) across body and tool capable of detecting (and exploiting) such information.

Kelty-Stephen takes the lawful grounding of tool use described by Wagman & Day one step further. The processes that underlie tool use are
cascade dynamics—the same generic processes that underlie the behavior of all systems that branch, avalanche, diffuse, or spread apart across multiple temporal or spatial scales. Cascade dynamics are exhibited at all levels of the organization and all levels of scale both within an organism and across the animal-environment system (Fernandez-Gonzalez and Zallen, 2011; Fritz, 2008; Goldberger et al., 1990). Moreover, the spreading of these interactions across levels and scales of the analysis entails a multifractal structure (e.g., Inger, 2006; Turvey and Fonseca, 2014). The waxing and waning of multifractal fluctuations predict cascade-driven coordination of events during tool use (Mangalam et al., 2020a, b).

Bongers’ analysis is also at the level of perception and action and has the same lawful grounding in specificity relations as Wagman and Day’s analysis and Kelty-Stephens’s analysis. Bongers’ focus is on the control of coordinated action in actualizing affordances for tool use. Actualizing affordances (with or without a tool) requires establishing synergies—emergent coordinate patterns among numerous degrees of freedom spanning the task, organism, and environmental constraints. The synergies that can emerge under these circumstances determine an animal’s capability for acting—its effectiveness. An object attached to the body that functions as a tool affects the emergence of synergies, and hence, the effectiveness of the action system. Therefore, tool use requires integrating the tool into the synergy emerging in the action system consisting of body-tool. This thesis is consistent with the analysis provided by Mangalam and Fragaszy.

Stout’s emphasis on technology rather than tool use per se leads him to consider a broader range of psychological processes that are more intimately tied to traditional cognitive psychology than any of the preceding authors, especially so because of the relationship between technology and culture. At the technological level, these processes include causal and analogical reasoning, cognitive control, memory, and perceptual-motor control in behavioral exploration. At the level of a technological society, these processes are organized around production, collaboration, and reproduction.

Finally, Osirurak posits that tool use is supported by four cognitive functions: technical reasoning, motor control, semantic memory, and planning. Importantly, technical reasoning results in a simulation of the mechanical action performed but not the performance of those actions. Motor control is thus required to select and control the simulated actions. Semantic memory is required to think about tools appropriate for performing the simulated action and where such tools might be located. Planning is required to prospectively organize the actions involving tools in a way that is efficient and as error-free as possible.

So, what are the points of convergence across researchers in their ideas about the psychological processes involved in tool use? All author groups note that tool use is associated with transforming the body into the body-tool system (i.e., all incorporate the notion of distalization of the end-effector). Mangalam and Fragaszy, Wagman and Day, and Bongers each focus on tool use to detect and exploit lawfully structured patterns of energy that provide ‘information about’ affordances of tools. Kelty-Stephen also grounds his analysis in lawful relations, but shifts focus away from psychological processes per se and toward generic processes of cascade dynamics. Stout and Osirurak, respectively, focus more on processing and cultural transmission of information. Specifically, they identify technical reasoning, semantic memory, and planning as cognitive abilities fundamental to the production, collaboration in, and reproduction of novel tool-use behaviors.

Which of these psychological processes are exclusive to tool use? This question is important because if any psychological process is exclusive to tool use, it will imply that a particular developmental or evolutionary trajectory enables or facilitates tool use. Indeed, this trajectory is what Mangalam and Fragaszy’s definition attempts to uncover. Their definition of tool use attempts to provide a theoretical foundation for making testable predictions about which individuals (and species) can use tools, to what extent they can do so, and under which conditions. For Mangalam and Fragaszy, the three processes that support tool use are: (1) establishing and managing spatial relation(s) between an object attached to the body and a target object; (2) distalization of the end-effector; (3) coordinating the body-object system. They propose that while none of these perceptuomotor processes are exclusive to tool use, the concurrent involvement all three is a distinctive feature of tool use.

Osirurak posits that four cognitive functions support tool use (technical reasoning, motor control, semantic memory, and planning). For Wagman & Day, the lawfully structured patterned energy arrays that provide information about whether, when, and how to move to achieve a goal are invariant across transformations—including whether (or not) a tool is used in the act. For example, invariant mechanical patterns are informative about controlling limb movement regardless of whether a person is using a hand-held object. Along similar (but perhaps not identical) lines, Bongers and Kelty-Stephen advocate that the processes underlying self-organization in complex tool-using systems are entirely generic, underlying self-organization in all complex systems—human and animal, living and non-living.

For all authors except Osirurak, there are no psychological processes that are exclusive to tool use. For Wagman & Day, the lawfully structured patterned energy arrays that provide information about whether, when, and how to move to achieve a goal are invariant across transformations—including whether (or not) a tool is used in the act of doing (e.g., invariant mechanical patterns are informative about controlling limb movement regardless of whether a person is using a hand-held object). Along similar (but perhaps not identical lines), Bongers and Kelty-Stephen advocate that the processes underlying self-organization in complex tool-using systems are entirely generic, underlying self-organization in all complex systems—human and animal, living and non-living.

The distalization of the end-effector when using tools has received attention in various forms, such as the tooltip becoming the end-effector (Arbib et al., 2009; Takahashi and Watt, 2017; Umlita et al., 2008), changes in the perception of space (Berti and Frassinetti, 2000; Canonieri et al., 2013), and the extension of sensorimotor processing (Miller et al., 2018). Mangalam and Fragaszy (and to some extent Osirurak) argue that this condition is necessary but not sufficient for tool use. Yet Wagman and Day, Kelty-Stephen, and Bongers’ argue that distalization (or any other psychological process) is neither sufficient nor necessary for tool use. How might this be resolved? For Mangalam and Fragaszy, the distalization of the end-effector is a behavioral description associated with the shift of the locus of perceptual and action control from the biological effector (e.g., hand, head). Hence, any investigation must, at least, explain such patterns of variation in the perceptual and action outcomes of using a tool. For Wagman and Day, Bongers, and Kelty-Stephen, these processes are the same ones that enable perception and movement of the body without a tool (Harrison et al., 2011; Mangalam et al., 2019c; Pagano et al., 1993; Wagman et al., 2017). These two approaches address different sets of questions—one associated with perception-action shift (Mangalam and Fragaszy, 2016), and the other associated with informational support for perception (Thomas et al., 2019).

Which psychological processes involved in tool use are exclusive to Homo sapiens? Any special association of tool use with humans depends on whether any psychological process involved in tool use is exclusive to humans. Otherwise, shared processes would suggest that human tool use differs from that observed in nonhuman species in the degree but not the type of psychological processes.

Mangalam and Fragaszy address tool use at the behavioral level, emphasizing perceptuomotor processes of perceiving spatial relations among objects and surfaces, developing agency over objects attached to the body (the distalization of the end effector), and controlling the bodily degrees of freedom to meet functional task demands. Importantly, Mangalam and Fragaszy suggest that none of these processes are unique to humans—nonhuman species show behaviors supported by each of these processes in isolation. However, they propose that what is unique to humans is the degree to which these processes can be
regulated simultaneously and the number of functional parameters that can be controlled in a given tool use task, such as when manufacturing sharp flakes from stone cores (Bril et al., 2015, 2012).

Wagman and Day argue that lawful structuring of energy distributions by the animal-environment relationship entails that the information about a given affordance (for tool use) is invariant over the sensory apparatus, nervous system, and brain of the animal doing the perceiving. Therefore, any animal capable of detecting (and exploiting) such structure is capable of tool use. For them, any differences in the ability to use tools between humans and non-humans is due to the sophistication of the ecological niche occupied by that species (Gibson, 1979; Turvey, 2018). The more sophisticated the environment occupied by a given species, the more sophisticated the affordances available to that species. This argument explains why nonhuman primates that do not use tools in their natural habitat use tools more frequently when in captivity (Mangalam, 2013). Hence, Wagman and Day’s thesis is consistent with that of Stout who argues that humans inhabit a uniquely technological environment and (like many nonhuman animal species) participate in the construction of that environment.

Bongers offers a similar view, arguing that the lawfulness underlying (the self-organization of) perception-action entails that the processes underlying tool use are not (and cannot be) species-specific. Any differences between species in their capacity to use tools will be due in (part) to differences in emergent synergies given task, organism, and environmental constraints. Kelty-Stephen also relies on the lawful dynamics of self-organization by drawing an analogy between how an amoeboid slime mold fashions a tool from its bodily degrees of freedom and how a human fashions a tool from some external object. Stout emphasizes that none of the processes involved in supporting technology are qualitatively unique to humans. Finally, Osiurak argues that whereas tool use itself is not a uniquely human phenomenon, some of the psychological processes underlying it (technical reasoning skills) may be so. He argues that these technical reasoning skills have contributed to the cumulative technical culture that is exclusive to humans.

In summary, although the authors differ significantly in their views on whether any psychological process is exclusive to tool use, none identified even a single psychological process involved in tool use that is exclusive to humans. The emerging theme is that the psychological processes that underlie humans’ unprecedented capability to use tools, make new tools, and recycle old tools for new purposes are shared in some manner with other species.

What must be the direction for future work on tool use? As noted above, how each author group defines tool use drives how that author group investigates tool use and hence envisions the direction for future work on tool use. Mangalam and Fragaszy suggest that future work must be concerned with the three-component perceptuomotor processes involved in tool use: (1) establishing and managing spatial relation(s) between an object attached to the body and a target object; (2) distalization of the end-effector; and (3) coordinating the body-object system during tool use. Kelty-Stephen suggests applying his perspective on tool use to a broader set of questions related to whether and how the multifractal geometry of tool use can formalize agency as a cascade-driven process. Examples of such studies include the role of fluctuations within the body (Mangalam et al., 2019b), the role of fluctuations at the postural center of pressure (Mangalam et al., 2020c; Mangalam and Kelty-Stephen, 2020), and the flow of multifractal fluctuations to-and-fro between the body and the tool (Mangalam et al., 2020a). Bongers makes three specific suggestions about applying the ecological-dynamics approach to the emergence of synergies in tool use, tool construction, and higher cognitive behaviors such as action selection and language (Cox and Smithson, 2006; Keen et al., 2014; Smithson and Cox, 2008; Valk et al., 2016; van Dijk and Bongers, 2014). Osiurak and Stout, respectively, also suggest that future work must focus on the processes underlying tool (and technology) use; both suggest taking advantage of noninvasive brain imaging techniques to investigate the neurophysiological underpinnings of tool use (Baumard et al., 2016; Jarry et al., 2013; Osiurak et al., 2009; Reynaud et al., 2016; Stout et al., 2015, 2008; Stout and Chaminade, 2007). Specifically, Stout highlights that using multiple techniques simultaneously such as motion tracking and electroencephalography (EEG) (Haar et al., 2020) has enormous potential for the study of technological production.

Like Bongers, Osiurak suggests that future work must investigate tool making and tool construction, but for him, the goal of such investigations should be to uncover the technical reasoning skills as well as the cognitive mechanisms that underlie distalization of the end-effector (Osiurak et al., 2018; Pazen et al., 2020). Wagman and Day propose that future work on tool use focus on the technological, communication, and representation systems characteristic of tool use in the human niche. They propose the development of interfaces for teleoperation of devices such as laparoscopic surgical tools, surveillance drones, or phone apps that preserve, enhance, or generate lawful structuring of energy patterns at any point of observation, and how to best train users of such devices (cf. Pagano and Day, 2020). Similarly, Stout promotes ‘real-world technological situations’ to investigate relations among structure, function, and behavior. However, he focuses less on the development of technology itself and more on understanding relations between performance in tool-use tasks and individual differences or experience-related plasticity in neuroanatomical, cognitive, affective, and perceptuomotor traits assessed in the lab (Stout, 2021; Stout et al., 2008; Stout and Chaminade, 2012).

In summary, the six author groups with extensive research experience (~100 years in total) present quite distinct perspectives on the direction of future work on tool use. To a student just beginning his/her research career, or to a seasoned researcher, tool use might not appear as multifaceted a phenomenon with a wide scope for study as this review suggests. All eight authors hope that this review inspires both new and seasoned researchers alike to look again at tool use—a behavior that sparks the feeling of wow in a child successfully hammering a nail for the first time, and that is arguably a keystone of human existence.

Data availability
Data sharing is not applicable to this article as no new data were created or analyzed in this study.

References


Embodied tooling

**Ecological psychology:** An approach to psychology developed by James Gibson that takes the animal-environment system to be the fundamental unit of analysis and that describes perception as a process of detecting energy patterns that are unambiguously (lawfully) related to the set of behaviors that are possible in the surroundings.

**Movement science:** A scientific discipline concerned with the study of movement in humans and nonhuman animals from various perspectives, including biomechanics, physiology, and motor control and development.

**Interface:** How a person monitors or controls the operation of a machine such as a computer. Examples include a keyboard, visual display, touchscreen, and computer mouse, among many others.

**Perceptron:** Describing the movement of a limb in response to a perception.

**Affordance:** An affordance is what an organism can do with an object or a surface based on its action capabilities. For example, the arm, hand, and crutch can be coordinated in moving from place to place.

**Perception:** Describing the movement of a limb in response to a perception.

**Tool use as detection and exploitation of information in an ecological niche**

**Patterned energy distributions:** Surrounding energy distributions such as reflected light, odor gradients, and patterns of deformation on bodily tissue that are lawfully structured by surface and substance properties.

**Task-specific detection units:** Independent anatomical (and sometimes inert) units that are coordinated to perceive a particular affordance. For example, the arm, hand, and crutch can be coordinated in perceiving properties using the probe.

**Task-specific control units:** Independent anatomical (and sometimes inert) units that are coordinated to perform a particular behavior. For example, the legs, arm, hand, and crutch can be coordinated in moving from place to place.

**Sensory apparatus:** The various anatomical and physiological components (sense organs, associated receptors) used to receive a given property.

**Ecological niche:** Niche is how a species of animal lives in its environment determined by the fit between its action capabilities and environmental properties. It can be contrasted with habitat, which is where an animal lives independent of its action capabilities.

**Functional transparency:** The phenomenal experience in which a tool no longer feels like a separate object and instead feels like part of the body.

Tools as intermittent properties of the fractal coastlines between organism and environment

**Intermittent environment:** An uneven dimension of events across time or space, characterized by the unpredictable, sudden appearance or disappearance of stability—or by the unpredictable, sudden transitions among stable states.

**Cascades:** A physical process characterized by a blending of information or structure built at multiple scales. For instance, when events spread from one scale to another, e.g., cellular to genetic, or cellular to whole-tissue, and then to organ- and whole-organism scale, what we have is a cascade of effects.

**Fractal dimension:** A statistical index of complexity—which lies between 1 and 2—describing how detail in a fractal pattern changes with the scale at which it is measured.

**Multifractality:** A generalization of a fractal system in which one fractal dimension is not enough to describe its dynamics; instead, a continuous spectrum of exponents (so-called singularity spectrum) is needed.
cAMP: Cyclic adenosine monophosphate is an organic molecule that participates in second-messenger signaling in a wide variety of organisms. Slime mold cells (*Dictyostelium discoideum*) secrete cAMP when their food sources dwindle, and cAMP released by starving slime mold cells becomes a cue for other slime mold cells to approach.

A tool in use is incorporated into synergies

**Perceptual flow field:** Lawful, patterned changes in perceptual stimulation—due to physical constraints on how the visual, auditory, and mechanical energy flow through a medium—revealing the information that it affords for controlling activity, about both the topography of the environment and the movement of the organism relative to the environment.

**Effectivities:** The properties of an animal that allow an action to place in a specific environment.

**Synergies:** Temporary functional units in which the degrees of freedom of the neuromotor system (e.g., joint angles, muscles) are organized. Task performance is maintained within a synergy through co-variation in degrees of freedom making up the synergies. These functional units emerge from interaction between organismic, environmental and task constraints.

**Uncontrolled Manifold (UCM) analysis:** An analytical technique used to evaluate the joint coordination by focusing on the trial-to-trial variance of angular motion about joints. The target UCM is a subspace of joint angles whose variability does not affect the end-effector’s position (e.g., the tip of the hammer when using it to drive in a nail).

More than just tool use

**Causal reasoning:** Systematic thinking about the relation between events based on logical, statistical, or simulation-based mental models. Some recent literature offers to causal reasoning about physical object properties as technical reasoning.

**Initiation:** Behavior copying. This term has been used to mean everything from social learning to the reproduction of action intentions but is now most commonly used in the narrow sense of copying the form or topography of observed movements.

**Mentalizing:** The process of representing and reasoning about the mental states, thought, and feelings of the self and others. Also known as Theory of Mind.

**Intersubjectivity:** Sharing mental states through mutual attempts to understand or perceive a situation from the other’s perspective.

**Internal model:** A simulation of a system’s response to events or states. In motor control, forward models use motor commands to predict sensory consequences, whereas inverse models use intended sensory consequences to generate appropriate motor commands.

**Prospection:** The ability to represent, reason about, and evaluate possible future conditions and events.

**Deliberate practice:** Systematic practice deploying focused attention with the explicit goal of improving performance.

**Simulation:** Outcome copying. This term has been used to mean everything from object movement re-enactment to goal reproduction but is most commonly intended to mean using one’s means to achieve observed action outcomes.

**Niche construction:** A form of ecological inheritance in which organisms alter the environment to affect the developmental context and selection pressures acting on subsequent generations.

The technical-reasoning hypothesis

**Technical reasoning:** Ability to solve physical problems by using abstract physical principles acquired through experience. This reasoning is both analogical and causal.

**Mechanical knowledge:** Non-declarative knowledge about physical principles, which is acquired through experience.

**Cumulative technological culture:** Accumulation of socially learned information over generations, allowing humans to develop tools and technologies that are too complex to have been invented by a single individual.

**Distalization:** Attentional shift from the effector to the active part of a tool, while it is still the effector that must be controlled.

**Microsociety paradigms:** Paradigms modeling cumulative technological culture in experimental conditions where participants can share information either via direct (i.e., observation, communication or indirect transmission (i.e., reverse engineering).