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HAL Authorization

1 **On the psychological origins of tool use**

2

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17 **Abstract**

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

34 **Keywords:** affordance; dexterity; perception; technical reasoning; tooling

35 Introduction

36 The ubiquity of tools in human cultures since the origin of the genus *Homo* has provoked enduring
37 philosophical inquiries into humans' engagement with tools (Gibson & Ingold, 1994), in part because
38 tool use is often considered to reflect a unique dimension of technical intelligence (Preston, 2012).
39 Aristotle wrote more than 2,000 years ago, "The hand can become a claw, a fist, a horn or spear or
40 sword or any other weapon or tool. It can be everything because it can grasp anything or hold
41 anything" (Aristotle, *The Animal Parts* (IV, 10)). Today, anthropologists, ethologists, psychologists, and
42 neuroscientists investigate the development and expression of humans' engagement with tools in
43 relation to other dimensions of human experience, and the increased efficiency and complexity of tool
44 use in human populations over generations (Boyd and Richerson, 1996; Osiurak and Reynaud,
45 2020a; Tomasello et al., 1993). The origin of this phenomenon, called cumulative technological culture,
46 was judged in 2005 by the journal *Science* as one of the 125 big scientific questions of the millennium.
47 It appears that deepening our understanding of the psychological bases of tool use is fundamental to
48 understanding the origins of tool technological culture. One might conjecture at first glance the answers
49 would be within easy reach. After all, they only require conceiving experiments in which individuals use
50 tools, with researchers manipulating different variables to reveal the underlying psychological
51 processes. However, behind this apparent simplicity, research on tool use faces several
52 epistemological challenges in which the same set of questions generate many different answers. In
53 this work, six research groups answer four critical questions about tool use, which are intimately
54 intertwined, and suggest what should be the direction of future research on tool use. We provide a
55 brief overview of the four questions before presenting each group's answers.

56 **What constitutes tool use?** This question may appear trivial yet it is not. The process of defining any
57 psychological concept is neither neutral nor viewpoint-free—any definition is necessarily limited and
58 oriented toward the theoretical solutions provided to account for the phenomenon studied (Osiurak
59 and Heinke, 2018). We have often posed this question to our friends, and their responses have been
60 quite varied. Some people exclusively reserve the term "tool use" for the use of handheld objects to
61 solve a mechanical problem (e.g., a hammer to drive in a nail). Others referred to using any handheld
62 implement (e.g., a calculator and a smartphone). Some considered any use of an object as tool use,
63 irrespective of how it is used (e.g., a paperweight, a house). Some even argued that wearing clothing
64 qualifies as tool use because it achieves the goal of avoiding sunburn or regulating body temperature.
65 The responses have been all over the place. (The readers may try asking the same question to their
66 friends over a beer some evening!). The same difficulties also arise in the scientific community, in
67 which there is no strict consensus on what tool use is (Fragaszy & Mangalam, 2018; Osiurak et al.,
68 2010). This lack of consensus is not surprising if we remind ourselves that consensus on a definition
69 of tool use amounts to consensus on the underlying psychological processes. Regardless, the
70 definitions given by Beck (1980), and updated by Shumaker et al. (2011) are perhaps the most
71 thoroughgoing and influential attempt in this respect, although Beck (1980; also see Hansell & Ruxton,
72 2008) warned that his definition only reflects a behavioral description and does not imply any
73 biological or psychological distinctness. These definitions have two significant merits. The first feature
74 is that these authors did not merely define 'tool use', but also concepts that are very close to tool use,
75 such as tool making and construction (Table 1). Thus, their definition of tool use is also a definition by
76 exclusion (e.g., excluding tool making and construction). The second merit is that their definition is
77 derived from the animal behavior literature, which facilitates discussions of the specificity of tool use to
78 particular species.

79 **What psychological processes are involved in tool use?** The emphasis placed by Beck (1980)
80 and Shumaker et al. (2011) on object manipulation is consistent with a vast literature on tool use that
81 has repeatedly stressed the critical role of manipulation-related psychological processes or, more
82 generally, of embodied cognitive processes. However, the embodied cognition approach is not unitary
83 —there are several different versions. The first version is in direct line with the ecological approach to
84 perception and action initially developed by Gibson (Gibson, 1966, 1979), in assuming that tool use
85 can be fully understood as perception-action processes required for effective execution (Biryukova &
86 Bril, 2012; Bril et al., 2009, 2012; Frigaszy & Mangalam, 2018; Kahrs & Lockman, 2014; Lockman,

87 2005; Mangalam, 2016; Mangalam & Frigaszy, 2016; Pagano & Day, 2020; Smitsman, 1997;
88 Smitsman et al., 2005; Wagman & Carello, 2003). This perspective pays particular attention to the
89 lawfully structured patterns of energy in the environment available to the perceiver as information. Tool
90 users exploit this information when manipulating a tool. For instance, as mass increases and the
91 center of mass is located farther from the point of rotation, objects are perceived to be more
92 appropriate for power tasks (e.g., striking a nail or throwing for distance), and as mass decreases and
93 the center of mass is located closer to the point of rotation, objects are perceived to be more
94 appropriate for precision tasks (e.g., striking a small nail or throwing for precision) (Michaels et al.,
95 2007; Wagman et al., 2016; Wagman & Carello, 2001).

96 Another version has been developed in parallel, mainly from the neuropsychological literature
97 (Buxbaum, 2001; Heilman et al., 1982; Rothi et al., 1991; van Elk et al., 2014). Contrary to the
98 aforementioned (ecological) perceptuomotor approach, this version assumes that conceptual
99 knowledge is directly extracted from the sensorimotor experience with familiar tools (e.g., hammer,
100 knife). This knowledge about manipulation offers a processing advantage by avoiding the
101 reconstruction de novo of each step of the process. A third approach has been formulated mainly from
102 the idea that tools help modify the physical environment. Here, the emphasis is on the physical (or
103 technical) reasoning involved to understand and perform these modifications (Goldenberg and Spatt,
104 2009; Johnson-Frey, 2004, 2003; Osiurak et al., 2020b; Vaesen, 2012). This approach can be viewed
105 as ‘disembodied,’ considering that manipulative aspects are secondary and not the critical component
106 of tool use.

107 **Which of these psychological processes are specific to tool use?** As defined by Beck (1980; see
108 Frigaszy & Mangalam, 2018; Shumaker et al., 2011), tool use is notably characterized by the fact that
109 it implies manipulating an external object to modify the state of the physical environment. However,
110 tool use is not the only behavior that involves both features (i.e., manipulation and physical
111 modifications). Humans and many nonhuman species alike manipulate objects. Tool use concerns not
112 just object-manipulation but also object-object manipulation. This supposes the existence of an
113 attentional shift from the effector on the body (e.g., hand, beak) to that on the tool (e.g., hammer’s
114 head, screwdriver’s tip) (Frigaszy & Mangalam, 2018; Mangalam & Frigaszy, 2016; Osiurak &
115 Federico, 2020), a phenomenon called “distalization of the end effector” (Arbib et al., 2009). A critical
116 question is whether distalization of the end effector is specific to tool use. Construction behavior, like
117 tool use, also results in modification in the physical environment, raising the question whether the
118 same psychological processes underlie tool use and construction behavior (Arbib, 2012; Walsh et al.,
119 2011). The question of the specificity of psychological processes to tool-use behavior can be extended
120 to other aspects, such as the ability to combine several tool-use actions (meta-tool-use, such as using
121 a tool to acquire another one; Taylor et al., 2007) or to use one tool to create another one.

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

132 *This brief overview of these four significant questions that dominate the literature on tool use*
133 *illustrates the richness of the research topic. However, it also stresses the divergences among the*
134 *different approaches to addressing these questions, which can be confusing for specialists and*
135 *nonspecialists alike. A synthesis that confronts divergent approaches is critical to identify productive*
136 *ways forward to investigate this phenomenon. The present review aims to fill this gap. Its originality*
137 *lies in including a contribution from scientists from experimental psychology, developmental*

138 *psychology, comparative psychology, cognitive neuroscience, cognitive archaeology, and ergonomics,*
139 *addressing the above questions. A global synthesis will be offered at the end of this review to help*
140 *orient future research on this fascinating topic.*

141 **Embodied tooling**

142

143 **Madhur Mangalam & Dorothy M. Fragaszy**

144

145 **Overview**

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

152 A theory that supports prospective experimental work is essential for progress in this field. We
153 have been developing an embodied theory of tooling (Fragaszy & Mangalam, 2018) that integrates
154 concepts from ecological psychology and movement science. Ecological psychology provides the
155 concept of affordances, enabled by the perception of object properties and surface layouts (including
156 spatial relations among objects and orientation of body segments and objects attached to the body as
157 a unit to objects in the environment) through the use of exteroceptive and exproprioceptive information
158 (Gibson, 1966; Shaw, 2001). Movement science provides the concept of controlling the bodily degrees
159 of freedom for functional coordination of movements (Bernstein, 1967; Bernstein et al., 1996) and the
160 concept of situating an activity within the organism-task-environment system (Newell, 1986; Newell
161 and Jordan, 2007). This embodied theory of tooling is equally applicable to humans and other animal
162 species. We use ‘to tool’ as a verb, meaning to act with an object to achieve a mechanical goal in the
163 service of a functional goal (e.g., hit a nail to drive it into adjoining planks—the mechanical goal—to
164 join the two planks into a rigid unit—the functional goal) and ‘tooling’ as a noun label for these actions.
165 This wording privileges actions rather than an object, although an object is intrinsic to the activity, just
166 as when we speak of “eating” rather than ‘ingesting food’ as the general phenomenon.

167 **What constitutes tool use?** We propose the following definition derived from our embodied theory:
168 “Tooling is deliberately producing a mechanical effect upon a target object/surface by first grasping an
169 object, thus transforming the body into the body-object system, and then using the body-object system
170 to manage (at least one) spatial relation(s) between a grasped object and a target object/surface,
171 creating a mechanical interface between the two” (Fragaszy & Mangalam, 2018, p. 194). Here,
172 ‘deliberately’ implies that tooling is goal-directed. This definition necessitates that the actor, the
173 [grasped or attached-to-the-body] object, and the target come in contact with each other during the
174 activity. That is, tooling begins with the act of establishing a spatial relation between the object
175 attached to the body and the target, and lasts as long as this relation is maintained. For example,
176 when hammering a nail into adjoining planks to make a rigid structure, tooling begins when the actor
177 places the nail against the surface of one plank, continues as the actor strikes the nail with the
178 hammer, and ends when the actor stops striking the nail and switches to some other activity.

179 This narrow definition of tooling differs from prevalent definitions (e.g., Shumaker et al., 2011)
180 that define tool use as the use of an external object to achieve a goal, with diverse additional
181 conditions appended by various authors (Crain et al., 2013). In our view, many behaviors that have
182 been traditionally described as tool use in nonhuman animals are properly categorized as instrumental
183 problem-solving (acting on/with an object in some way to solve a problem, such as opening a door to
184 pass through a wall), but not as tooling, which is a particular subset of this large class of behaviors
185 (Table 2). A definition of tool use primarily couched in the goal-directed nature of action with an object,
186 which may be adequate when applied to humans because tooling is so pervasive in our behavior, is so
187 ambiguous when applied to nonhuman animals that the topic of tooling in nonhuman animals largely
188 remains a scientific curiosity, outside of theoretically-motivated biological or psychological inquiry. A
189 narrower definition drawn from a particular theory affords analytical clarity and could support

190 productive engagement of scientists across disciplines. Note that whether a behavior with an object
191 qualifies as tooling or rather as some other form of instrumental problem-solving has no bearing on a
192 judgment about the user's 'intellect' or the complexity of its behavioral/cognitive/neural processes. In
193 fact, all forms of instrumental problem-solving merit investigation of their distinctive characteristics. A
194 classification of action as tooling or not determines the analytical strategy one takes to examine the
195 action; that is all.

196 **What psychological processes are involved in tool use?** Our theory addresses tooling at the
197 behavioral level. It draws attention to functional task demands (to create a particular form of
198 mechanical interface—e.g., striking a nail at a particular angle with enough force to drive it into the
199 plank), and to movement coordination in meeting these demands (Fragaszy & Mangalam, 2018). It
200 further draws our attention to the perceptuomotor processes supporting relational actions (moving a
201 grasped object in relation to another object or surface) necessary to meet functional task demands. In
202 accord with our ecological stance (Gibson, 1966; Harrison & Stergiou, 2015; Wagman & Miller, 2003),
203 we do not distinguish between perception and cognition. Perceptuomotor processes relating to (a)
204 perceiving spatial relations among objects and surfaces, (b) developing agency over objects attached
205 to the body (the distalization of the end effector), and (c) controlling the bodily degrees of freedom to
206 meet functional task demands characterize tooling. These processes occur in the unified body-object-
207 task-environment system; that is, tooling is an action of a given individual with specific materials to
208 accomplish a particular task in a particular setting (Bril et al., 2012; Mangalam & Fragaszy, 2016;
209 Smitsman, 1997).

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

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

231 • ***Distalization of the end-effector.*** Tooling requires the distalization of the end-effector—the
232 locus of perceptuomotor control—from the body to the part on the tool that acts upon the target object
233 or surface (Arbib et al., 2009). Studies have shown that in monkeys using pliers to grasp a food item,
234 the grasp-related cortical regions encode for movements of the pliers' jaws rather than movements of
235 the fingers (Umiltà et al., 2008). A specific grip configuration may be imposed by the mass, shape, and
236 size of the pliers, and movements are adapted to the pliers' jointed feature (direct vs. reverse pliers).
237 These findings have been replicated in humans (Gallivan et al., 2013). Tooling is also associated with
238 the remapping of the space surrounding the body to perceive reaching affordances from the frame of
239 reference of the handheld tool rather than the hand (Berti and Frassinetti, 2000; Farnè et al., 2005;

240 Maravita and Iriki, 2004), and remapping of somatic senses to perceive what is happening at the tool
241 tip rather than at the fingertips (Miller et al., 2018; Takahashi & Watt, 2017).

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

250 **Which of these psychological processes are specific to tool use?** None of the above
251 perceptuomotor processes is specific to tooling. The acts of establishing and managing spatial
252 relation(s) between an object attached to the body and a target object or surface are part of several
253 non-tooling activities and are observed in both humans and nonhuman species, such as chimpanzees
254 and capuchin monkeys aligning a stick to a matching cut-out in an experimental task (Fragaszy et al.,
255 2011, 2015; la Cour et al., 2014), or a weaver bird inserting grass or twigs into a partially completed
256 nest (Walsh et al., 2011). The end-effector is distalized in many non-tooling contexts, such as when
257 using a manipulandum to move a cursor on the screen, although this behavior has been classified by
258 some as tool use (Heald et al., 2018; Ingram et al., 2010). (Using a manipulandum to move a cursor
259 does not qualify as tooling according to our definition because the manipulandum does not directly
260 and mechanically affect the screen.) We coordinate the body-object system all the time in non-tooling
261 contexts, such as when passing through a doorway sideways when holding an object wider than the
262 doorway (Higuchi et al., 2006), or when using assistive devices—from wheelchair to exoskeleton
263 (Pazzaglia and Molinari, 2016). Transporting an object inevitably involves coordinating the body-object
264 system, irrespective of the context. These examples clearly illustrate that each perceptuomotor
265 process is involved in many activities beyond tooling.

266 **Which psychological processes involved in tool use are specific to *Homo sapiens*?** We do not
267 suppose that tooling is specific to humans in a holistic way, although we have no doubt that there are
268 large differences among species in the elaboration and efficiency of each of the three perceptuomotor
269 processes listed above. Unfortunately, few comparative studies isolate each one of the three
270 processes. The few we have suggest deep differences across species in two of the three processes
271 but some commonality between humans and other species in the third. With respect to perceiving and
272 managing spatial relations between a grasped object and another object, by two years of age, humans
273 readily align a straight stick to a matching cutout in a platform surface, whereas adult chimpanzees
274 and capuchin monkeys do so imprecisely (Fig. 1) (Fragaszy et al., 2011, 2015; la Cour et al., 2014),
275 suggesting a deep difference between humans and nonhuman primates in this domain. With respect
276 to coordinating the body-object system when tooling, some evidence indicates that nonhuman species
277 can do this modestly, but not as effectively as humans. For example, when cracking nuts using stone
278 hammers, capuchin monkeys alter their strikes to strike a nut with less or more force based on the
279 type and condition of the nut (Mangalam et al., 2016; Mangalam & Fragaszy, 2015); they do so by
280 adjusting the amplitude [and velocity] of the strike but do not adjust the hammer's kinetic energy at
281 impact (Fig. 2) (Mangalam, Pacheco, et al., 2018), as do humans (Mangalam et al., 2020; also see Bril
282 et al., 2012). Humans can control a larger number of functional parameters of the task when
283 hammering with stones, as when manufacturing sharp flakes from stone cores, than nonhuman
284 primates using stone hammers (Bril et al., 2015, 2012). With respect to distalization of the end-
285 effector, Umiltà et al.'s (2008) work with macaques using pliers, mentioned above, stands as one
286 example suggesting that nonhuman species, like humans, do distalize the end-effector when tooling to
287 meet task demands.

288 **What must be the direction for future work on tool use?** We suggest that expanding our
289 understanding of each of the three component perceptuomotor processes we have highlighted above,
290 and our understanding of their integration in tooling and other instrumental actions with objects, will be

291 particularly useful. Ethologists may most naturally consider these processes in diverse species and
292 developmental, ecological, and evolutionary perspectives. Psychologists may most naturally consider
293 them in relation to attentional and related cognitive demands, particularly affordance learning and skill
294 learning. Neuroscientists may most naturally consider them in relation to the organization and function
295 of the nervous system. One obvious question for neuroscientists is to identify which tooling actions are
296 coordinated differently than achieving the same goal with the unaugmented hand. Findings from
297 studies on reach-to-grasp movements using the hand or using the hand with a tool (e.g., grasping with
298 fingers or with a tong) suggest an effector-independent neural encoding of movements (Gallivan et al.,
299 2013, 2011; Umiltà et al., 2008). The interpretational nuances added by comparing actions with
300 different effectors to achieve the same goal would yield a more reliable neurophysiological
301 understanding of tooling than the currently available explanations based on comparisons of actual
302 tooling with gesturing with an object (Hermsdörfer et al., 2012, 2007).

303 Gesturing with an object (pantomiming) is the principal paradigm used to investigate the neural
304 basis of tooling particularly in relation to cognitive and sensorimotor deficits in neurological patients
305 (Buxbaum et al., 2005; Króliczak and Frey, 2009; Martin et al., 2016b). A plethora of interesting
306 findings of how brain-damaged individuals move objects gesturally paint an optimistic picture of what
307 we understand about the neural correlates of tooling (Goldenberg and Spatt, 2009; Johnson-Frey,
308 2004; Renfrew et al., 2008). However, pantomiming with objects is not comparable to tooling in any
309 biologically relevant way (a detailed discussion is beyond the scope of this essay; we hope to address
310 this issue in greater detail in a future piece). Behavioral neuroscientists could investigate tooling more
311 productively if they set aside the notion that tooling is an index of ‘complexity’ to focus on the
312 distinctive perceptuomotor processes of tooling noted above.

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

319 **Tool use as detection and exploitation of information in an ecological** 320 **niche**

321

322 **Jeffrey B. Wagman & Brian M. Day**

323

324 **Overview**

325 In the ecological approach to perception-action, the relationship between animal and environment
326 lawfully structures pattered energy arrays so as to provide information about this relationship. The
327 lawful structuring of energy distributions entails that information about a given affordance is invariant
328 over transformations including whether or not a tool alters this fit. Therefore, **perceiving and**
329 **actualizing affordances for performing a goal-directed behavior with or by means of a tool is**
330 **the detection (and exploitation) of information—no more and no less.** Moreover, any animal
331 species capable of detecting and exploiting such information is capable tool use. Although tool use
332 does not seem to be dependent on the sophistication of particular cognitive apparatus, it may be
333 dependent on the sophistication of a given niche. Consequently, tools that are unique to the human
334 niche (such as technological interfaces or virtual tools) are an important area for future research.

335

336 **What constitutes tool use?** The ecological approach to perceiving and acting focuses on a scientific
337 understanding of the lawful perceptual control of everyday goal-directed behavior. In this approach,
338 the fundamental unit of analysis is the animal-environment system, not the animal or the environment
339 in isolation (Gibson, 1979; Turvey, 2018). In the ecological approach, it is (only) at this level that all
340 psychological processes—including tool use—occur. A key reason for this focus is that the relationship
341 (i.e., the fit) between the animal and environment determines what possibilities for behaviors—what
342 *affordances*— are available to that animal (Wagman, 2020). It is *also* at this level that these
343 possibilities become actualized in the performance of a given behavior.

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

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

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

365 **What psychological processes are involved in tool use?** In the ecological approach to perceiving
366 and acting, the relationship between animal and environment lawfully structures patterned energy
367 arrays. The structure actively encountered at a point of observation in such arrays provides
368 information about this relationship (Fig. 3, bottom). That is, it provides *information about affordances*—
369 whether, when, and how to move to achieve a given goal. *Thus, perceiving affordances for performing*
370 *a goal-directed behavior is the detection (and exploitation) of such information—no more and no less*
371 (Wagman et al., 2019).

372 When the fit between animal and environment is altered by means of a tool, the structure
373 encountered at a point of observation provides *information about this altered relationship* (see Fig. 3,
374 middle). That is, it provides *information about affordances for tool use*—whether, when, and how to
375 use the tool to achieve a given goal. **Consequently, perceiving and actualizing affordances for**
376 **performing a goal-directed behavior with or by means of a tool is also the detection (and**
377 **exploitation) of information—no more and no less.**

378 The lawful structuring of energy distributions entails that information about a given affordance
379 is invariant over transformations, including the particulars of the energy being structured and the
380 anatomical component(s) used to detect such structure. This invariance over transformation is readily
381 demonstrated in a context common to tool use—the hefting, welding, or manipulating of objects by
382 muscular effort (see Carello & Turvey, 2016). When wielding an occluded object, people can perceive
383 many different affordances of that object, and they can perceive a given affordance of that object
384 under many different wielding circumstances (Hajnal et al., 2007; Mangalam et al., 2017; Wagman et
385 al., 2017). By the same token, when people probe a surface with an object, they can perceive many
386 different affordances of that surface, and they can perceive a given affordance of that surface under
387 many different probing circumstances (Wagman and Hajnal, 2016, 2014a, 2014b).

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

394 **Which of these psychological processes are specific to tool use?** As described in Section 2, in
395 the ecological approach, lawfully structured patterned energy arrays provide information about
396 whether, when, and how to move to achieve a goal. Such information is invariant not only across
397 transformations of the energy media and anatomical components *but also whether or not an animal*
398 *exploits an altered animal-environment fit in the context of achieving the goal (i.e., whether or not an*
399 *animal engages in tool use).*

400 When an animal moves from place to place in a cluttered environment, it encounters a lawfully
401 generated pattern of optical structure that is informative about the animal-environment relationship—
402 how, when, and where it is moving. Moreover, such patterns are informative about whether, when, and
403 how a person *must move to achieve a goal* (e.g., catching a ball, see Fink et al., 2009). Critically, such
404 patterns are also informative as to whether, when, and how a person *must move a tool such as a*
405 *vehicle* to achieve a goal (e.g., steering or stopping safely, Fajen, 2013; Fajen, 2007; Fajen & Matthis,
406 2011; Kadar & Shaw, 2000).

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

414 In both cases, it is irrelevant whether achieving the goal requires controlling the movements of
415 the person or the person-plus-object system. The lawful structuring of patterned energy arrays by the
416 relationship between animal and environment entails that the information about how, where, and when
417 to move to achieve the goal is invariant across this transformation (see Fig. 3, middle). This likely
418 explains why tools, be they vehicles or hand-held objects, are often 'functionally transparent' to skilled
419 users. In both cases, tools are perceived as part of the body because they are perceived *in the same*
420 *way as the body* (Pagano and Turvey, 1998).

421 **Which psychological processes involved in tool use are specific to *Homo sapiens*?** The lawful
422 structuring of energy distributions by the relationship between animal and environment entails that
423 information about a given affordance is invariant across the sensory apparatus, nervous system, and
424 brain of the animal doing the perceiving. Such details are irrelevant so long as that animal can detect
425 the information about whether, when, and how to move to achieve a given goal. Incontrovertibly,
426 animals across all phyla perceive and actualize affordances. According to the ecological approach,
427 these abilities result from *the same* lawful processes across species (Turvey, 2018; Wagman et al.,
428 2019). **Moreover, the abilities of animals to exploit how a tool alters the ability to perceive and**
429 **actualize affordances are also the result of *the same* lawful processes across species.**

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

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

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

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

458 In the general case, information about affordances for tool use is available in the structure in
459 patterned energy encountered at a point of observation. However, in the situations described above,
460 information about affordances is available only by means of an interface (e.g., a computer-mediated
461 visual display). In these cases, preserving the lawful structuring of information about affordances
462 requires designing the interface to preserve, enhance, or (in some cases) even generate such
463 lawfulness (Pagano & Day, 2020; Fig. 3, top). **Designing interfaces that allow for the perceiving**

464 **and actualizing affordances of virtual tools to be the detection (and exploitation) of information**
465 **—no more and no less—is an essential area for future research.**

466 Along these lines, researchers programmed a custom laparoscopic surgery simulator to
467 provide (haptic) information about the extent to which (simulated) bodily tissue could be manipulated
468 until it was (accidentally) torn (Altenhoff et al., 2017; Hartman et al., 2016; Long et al., 2016). They
469 modeled haptic information about 'distance to break' on optical information about 'time to contact' with
470 a surface. They found that both novice participants and experienced surgeons improved their
471 performance in this task with only minimal practice. That only minimal practice was required
472 (regardless of expertise) is impressive. However, it also demonstrates a fundamental fact about
473 perception of affordances with or without a tool or interface. Namely, the mere availability of
474 information about whether, when, and how a person must move to achieve a goal does not entail that
475 such information is detected or exploited. **Therefore, investigating the necessary and sufficient**
476 **experiences to facilitate the functional transparency of a virtual tool or a user-tool interface**
477 **(Day et al., 2019, 2017) is another important area for future research.**

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

480

481 **Damian G. Kelty-Stephen**

482

483 **Overview**

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

493 Tools are necessarily tuned to the scale of a task. So, their intermittency may require viewing
494 Gibsonian ecological psychology through Mandelbrot's multifractal-geometrical lens. For Gibson
495 (1979), organisms and the environment entail one another, and any coastline between them is porous
496 and blurry. When studying the coastlines bounding Britain, Mandelbrot (1967) realized that such
497 boundaries embody fractional (or 'fractal' for short) dimensions. Off-putting at first glance, fractal
498 dimensionality aims to do the important job of quantifying structure that fails to be integer-dimensional
499 (e.g., zero-, one-, two-, or three-dimensional points, lines, surfaces, or Euclidean solids). Coastlines
500 with varying fractionality can crucially originate from nonlinear interactions across scales. Indeed, the
501 nonlinear interactions across scales—that is, the cascades—entail variation in these fractal
502 dimensions. That is, they entail 'multifractal' dimensionality (Mandelbrot, 2013).

503 The multifractal structure is thus a meaningful way to understand and model tool use.
504 Organisms' exploration of tools and task context depends on multifractal fluctuations in organisms'
505 movement (Doyon et al., 2019; Hajnal et al., 2018; Kelty-Stephen & Dixon, 2014; Mangalam et al.,
506 2019; Mangalam, Carver, et al., 2020a; Mangalam, Chen, et al., 2020; Mangalam, Carver, et al.,
507 2020b; Mangalam & Kelty-Stephen, 2020; Stephen et al., 2009, 2010; Stephen & Hajnal, 2011). This
508 insight may lead to the startling idea that that tools could be intermittent, blinking in and out of
509 existence as a separate entity from the body. In this sense, the muddiness of 'tool' concepts noted by
510 Fragaszy and Mangalam (2018) may be a defining feature rather than muddiness in the scholarship.

511

512 **What constitutes tool use?** An organism uses a tool when it takes hold of an object to engage in
513 direct mechanical interaction with a target surface (Fragaszy & Mangalam, 2018). However, the scale-
514 free aspect of cascade dynamics suggests that tool use should extend beyond the constraints of this
515 definition.

516 Tool use involves a mutual contingency between tool and user, not simply addition entailed by
517 Fragaszy and Mangalam's (2018) 'body-plus-object' system. Specifically, tools inherit multifractal
518 fluctuations from manipulating limbs, and tools pay back a dividend of new multifractal fluctuations to
519 limbs. This point is borne out if we examine the manual exploration of a handheld tool. We can use
520 vector autoregression to model specific dyadic relationships among multifractality estimates on the
521 tool, the hand, the wrist, the forearm, and the elbow (Mangalam, Carver, et al., 2020a, 2020b).

522 Because the organism-environment relationship is never adrift from long-scale contingencies, it
523 is not crucial that the tool and skin remain in constant immediate contact. Fragaszy and Mangalam
524 (2018) stress the need for immediate contact with grasping skin or target surface, but cascade-driven

525 interactions allow no straightforward segregation of short-range interaction from more distal forces.
526 Rather than an empty expanse, environmental space is full of clutter whose integral flow supports
527 organisms via contact through distributed-but-rarely-distinct modalities (e.g., optical, acoustic, and
528 haptic (1979), Stoffregen & Pittenger (1995), and Harrison et al. (2021), respectively). The specificity
529 of localized sensor cells is physiologically real, but they distract from the non-exclusivity and often
530 mutuality of manipulation and, say, observation when mechanical contact is lost (Stoffregen et al.,
531 2017). Cascades span cross-scale interactions through these ecological flows like a spiderweb of
532 contingency that the organism then manipulates to extend its reach. Even if a tool drops from reach or
533 hurtles towards a visible target, the looking for or after the tool is no less mechanical even if the skin
534 contact is lost.

535 **What psychological processes are involved in tool use?** The processes involved are cascades,
536 that is, physical processes that branch, fracture, avalanche, diffuse, or otherwise spread apart across
537 multiple scales across space or across time. Organism physiology exhibit cascades spatially (e.g.,
538 hierarchical branching of neural dendrites, cardiovascular vessels, and capillaries (Goldberger et al.,
539 1990), actin-myosin architectures (Fernandez-Gonzalez and Zallen, 2011), DNA supporting cells
540 (Dragovich and Mišić, 2019), collagen composing bones (Fratzl, 2008), and tensegrity-like networks of
541 connective tissue that span the entire organism, wrapped tautly across the muscles and bones
542 (Turvey and Fonseca, 2014)) as well as through a correspondingly hierarchical temporal structure
543 whenever these multifractally-shaped parts operate (e.g., neuronal avalanches (Zorick et al., 2020).
544 The spreading interactions across multiple scales of this hierarchy (e.g., Ingber, 2006) entail a
545 multifractal structure (Turvey and Fonseca, 2014).

546 The cascades pervade the organism-environment system—not just through neurons but
547 through musculoskeletal systems and connective tissue supporting manipulation and observation
548 alike. The nesting within an organism, within the environment, of the organism within the environment
549 does not leave any other alternative. The only issue is how these nestings change as events trigger
550 new cross-scale relationships. Multifractal fluctuations appears to predict this cascade-driven
551 coordination of events—within a single organism (Carver & Kelty-Stephen, 2017; Mangalam, Carver,
552 et al., 2020b), between organisms (Carver and Kelty-Stephen, 2017), and between organism and
553 environment (Stephen and Dixon, 2011; Teng et al., 2016)—no matter whether the coordination is
554 visual or mechanical.

555 **Which of these psychological processes are specific to tool use?** These processes are not
556 specific to tool use. Cascading fluctuations support organism-organism links as well as organism-
557 environment links. For instance, coordination within honey-bee colonies correlates with cascade
558 dynamics: multifractality of individual-bee activity is an effective classifier of colony membership
559 (Carver and Kelty-Stephen, 2017). Organisms are not tools, except in cases of social dominance or
560 parasitism. The agency of an organism contrasts clearly with the passivity of the tool. The only
561 potential ambiguity worth focusing our attention on is the blurring of the distinction between tool and
562 organism, for example, when tools become part of the bodies or when body parts can serve as tools.

563 **Which psychological processes involved in tool use are specific to *Homo sapiens*?** The
564 capacity to manipulate environmental materials as tools to further goals belongs to more species than
565 humans. For instance, an amoeboid slime mold (*Dictyostelium discoideum*) uses the molecule cyclic
566 adenosine monophosphate (cAMP) to navigate a ground surface to find and coordinate with other
567 conspecific amoebae. *D. discoideum* spend the earlier, better-fed days as an amoeba, and it is only as
568 food becomes more scarce that the amoebae coalesce into a multicellular body—either a fruiting body
569 or a slug for locomotion to a niche with better nutrient stores (e.g., Schaap, 2021). This drama has all
570 of the necessary features of tool use, but it also shows how the distinctions between tool and user
571 may blur.

572 In the traditional sense, cAMP fits all the needs of a mechanical tool. The amoebae are
573 manipulating cAMP, grasping molecules with its cell-membrane receptors, using the molecules to
574 orient their cytoskeletal posture towards and to inch up the cAMP gradient to the source (Chisholm
575 and Firtel, 2004). Eventually, individual amoebae on the move will use cAMP to attract each other

576 along the way, using a cAMP relay to latch on to slow amoeba behind them (Bagorda et al., 2006).
577 Hence, at all points, the amoeba grasps cAMP and manipulates it to operate on the ground surface
578 and the surface of other cell membranes.

579 The organismic coastlines of this example blur in three significant respects. First, the tool is not
580 so clearly separate from the body. The cAMP is a molecule that amoeboid slime molds secrete
581 themselves in the first place. This chemical attractant is the stress response of a hungry amoeba that
582 has run out of food. So, if one amoeba can grasp cAMP, it means that another amoeba has run out of
583 food. Moreover, the relay use of cAMP involves the amoeba producing its new cAMP (Chisholm and
584 Firtel, 2004). Second, this tool essentially invents a new body, dramatically redrawing the coastline
585 between organism and environment. All of the cAMP-chasing culminates in amoebae aggregating to
586 form a multi-cellular fruiting body that will disseminate the next generation of amoeboid slime-mold
587 spores. The aggregate can also take the intermediary form of a slug that can sense light and heat to
588 navigate a more conducive niche. The multi-cellular aggregates are richly differentiated but integrated
589 whole: the aggregate prompts once-uniform amoeba to take on specialized forms and functions to
590 serve the goals of the whole slime-mold colony (Bagorda et al., 2006). The multi-cellular body is no
591 less real or integral than the amoeboid one had been. Furthermore, cAMP flows within just the same,
592 regulating the now tighter-knit coordinations of many no-longer-amoebae. In the first blurring, a cast-
593 off product of one body had become another body's tool. In this second blurring, the tool vanishes,
594 receding within the newly redrawn coastline of the organism. Indeed, the tool has left the biological
595 theorist befuddled (e.g., Wilson, 2000). How many organisms are there? One? Hundreds? The tool for
596 hundreds of bodies has become the endogenous fuel for the one larger body that remains.

597 The third sense in which the organism-tool coastline blurs is that the body can fashion tools
598 from itself. This larger multicellular body builds itself a form that features tool-like extensions. The
599 differentiation process produces a rounded tip at the head of the slug or fruiting body. The slug can
600 navigate towards light and heat. There is no internal body part, no protein or molecule to do this
601 sensing. No, it is the organism's mechanics: it is the tip's external curvature that focuses on visible and
602 infrared light just like a lens. Hence, the body shapes its degrees of freedom into a tool allowing new
603 manipulation and mechanical contact. The rounded tip focuses visible and infrared light in a way that
604 stimulates metabolic processes to produce more ammonia, which inhibits internal cAMP production at
605 the back or bottom of the slug or fruiting body. Interrupting the cAMP leaves the back or bottom end of
606 the slug or fruiting body slack, leaving the cAMP-full tip to drag it forward (Schaap, 2021).
607 Furthermore, although the tip touches no surface, the light remains no less patterned by the ambient
608 surfaces than in Gibson's (1979). As ever, observation is still mechanical amidst the ecological
609 cascades.

610 Again, do we need this separate species to make the case that tool use is not specifically
611 human? After all, human bodies are porous and flexible enough. We can fashion tools out of our bodily
612 degrees of freedom, for example, fingertips to dig or eyes, faces, or fingerprints that once scanned can
613 open locks. We also make our tools part of our body when we learn to use prosthetic limbs or teeth.
614 One of the competing theories of the evolution of our own camera-like eyes begins with the possibility
615 that billions of years ago, non-algal organisms learned to subsume photosynthesizing algae (Gavelis
616 et al., 2017; Hayakawa et al., 2015; Lundberg et al., 2012). Algal DNA—that is, no organism but a tool
617 made of (Kianianmomeni and Hallmann, 2014), offering even humans an alternative to retinal
618 prosthesis (Wood et al., 2019). So, our very own eyes need not always have been our own. Our
619 bodies themselves are a patchwork of environmental detritus, emerging over long time scales in a way
620 that might sometimes support adaptive behaviors in the short term.

621 **What must be the direction for future work on tool use?** The intermittency of tools points
622 immediately to the question of agency and its bounds. How do organisms extend or retract their scope
623 of influence? How do they push their coastline outwards? Or give ground back to the environment? As
624 the tool shimmers in and out of existence, the organism concedes and engulfs more of its
625 surroundings, respectively. This intermittency of tools is nothing but the negative image of

626 intermittency of control. An important focus for future study is whether the multifractal geometry of tool
627 use can formalize a cascade-driven notion of agency or control.

628 **A tool in use is incorporated into synergies**

629

630 **Raoul M. Bongers**

631

632 **Overview**

633 The current contribution presents the first steps of an ecological-dynamical approach to tool use. It is
634 argued that tools are integrated in synergies and that properties of the tool determine the effectivities
635 by which to scale the affordances in the environment. In line with an ecological-dynamical account
636 these processes are not specific for tool use nor for any given species. Some future routes are
637 presented to expand these first steps to a full-blown account of tool use.

638

639 **What constitutes tool use?** During our daily life activities, we often grasp an object in the
640 environment to use that object as a tool to reach our goal. For instance, we use a knife to cut bread
641 and a spoon to stir our coffee. Hence, a tool can be casually defined as an object in the environment
642 that is temporarily attached to the body to act on other objects in the environment to reach a goal (cf.
643 Beck, 1980; Frigaszy & Mangalam, 2018). Most of the time objects are used as tools when our own
644 action system falls short or when action goals can be achieved more conveniently when performed
645 with a tool, that is, tools alter our capacity for action. Therefore, we take an action-perception
646 perspective on tool use, one of the main lines of research on tool use that are outlined by Frigaszy &
647 Mangalam (2018). In the current contribution we take this perspective as a starting point to give an
648 outline of how to rigorously apply the ecological-dynamical approach (cf. Profeta & Turvey, 2018) to
649 tool use.

650 **What psychological processes are involved in tool use?** The starting point of an Ecological
651 approach to action-perception is that control of an action does not come from an internal structure
652 (such as a part of the central nervous system), but that coordination of action and perception takes
653 place in an organism-environment system (Gibson, 1979; see Michaels & Carello, 2000; Richardson
654 et al., 2008; Warren, 2005 for overview papers of this approach). Properties of the elements making
655 up the organism-environment system, together with physical law constrain the myriad of action
656 possibilities to result in goal-directed behavior. An organism moving through an environment creates
657 perceptual flow fields and these flow fields contain invariants that specify properties of an
658 environmental feature or the relation between the organism and the environment. That is, the
659 perceptual flow fields specify functional relations between an organism and its environment that have
660 meaning for an organism and this meaning is perceived directly. Therefore, organisms directly
661 perceive affordances, the possibilities for action in the environment. For instance, someone can
662 perceive whether the size of a handle affords a tool to be graspable with one hand.

663 Important for understanding tool use is that affordances have their counterparts in the
664 organism, which are dubbed effectivities (cf. Michaels & Carello, 2000; Shaw et al., 1995). Turvey
665 (1992) argued that an affordance is a dispositional property of the environment that requires a
666 complementary dispositional property in the organism. Both dispositions are necessary conditions for
667 an organism-environment system to actualize an action. For instance, in his seminal paper on
668 affordance perception, Warren (1984) demonstrated that the climbability of a stairs as well as the
669 perception of the climbability (i.e., the affordance) both depend on a body-scaled measure of riser
670 height. Hence, properties of the environment (i.e., affordances) are perceived in terms of the
671 properties of the organism (i.e., effectivities) and an action can only be performed if there is a fit
672 between both properties.

673 Effectivities are determined by the synergies that can emerge in the action system. From a
674 dynamical systems perspective to movement coordination, synergies emerge from task, organism and
675 environmental constraints in a self-organizing manner. Synergies are defined as the temporary

676 functional units in which the abundant degrees of freedom are organized (Kelso, 2009; Turvey, 1990,
677 2007). Synergies maintain stability of its organization through co-variation of the degrees of freedom
678 that make up the synergy (Kelso et al., 1984; Latash et al., 2007; Riley et al., 2011; Schöner, 1995).
679 For instance, when pistol shooting the joint angles in the arm co-vary such that the aiming at the target
680 is stabilized (Scholz et al., 2000). In sum, combining the principles presented in the foregoing gives an
681 account of action-perception in which perceptual invariants act as constraints on the formation of
682 synergies thereby affecting the emergent coordinative pattern in the degrees of freedom in the body in
683 such a way that they are organized in a way to actualize the affordance specified by the perceptual
684 invariants.

685 An object in the environment that is attached to the body to function as a tool changes the
686 geometry of the action system. For instance, a tool is often held in the hand and thereby the tool
687 changes the shape (i.e., length) of the action system. Equally important, a handheld tool produces
688 forces and torques in the muscles and joints that affect the constraints on the basis of which synergies
689 in the action system emerge. For instance, a tool has a certain weight, and this weight changes the
690 interactions between task, organism and environmental constraints on the basis of which synergies
691 emerge. Hence, a tool in use affects the geometry of the action system as well as the available
692 synergies (Fig. 4). Both these changes affect the effectivities that function as a scale to which the
693 properties of the environment are perceived. That is, a tool in use becomes a part of the action system
694 that establishes the effectivities and therefore the affordances (Bongers, 2001; Bongers et al., 2003).

695 The incorporation of the tool in the action system has been suggested in different studies
696 examining the kinematic characteristics of the tooling end-effector. When learning to use a complex
697 tool, kinematic characteristics that normally show up in hand movements can also be observed in
698 movements of the tool tip (Heuer and Sülzenbrück, 2009). Moreover, Jacobs et al. (2009) showed that
699 differences in kinematics of the end-effector for tool and non-tool conditions were more pronounced for
700 apraxic patients than for non-apraxic people. In examining the mechanisms underlying these
701 phenomena we analyzed the synergy in the arm during pointing with a rod to a target. Using an
702 Uncontrolled Manifold analysis (Scholz and Schöner, 1999; Schöner, 1995), we showed that there is
703 more co-variation in joint angles stabilizing the position of the rod's tip in space than that there is other
704 variability in the joint angles de-stabilizing the rod's tip position (Valk et al., 2016; van der Steen and
705 Bongers, 2011). Moreover, this effect did not depend on the length of the rod (10-40cm) used to reach
706 to a target. In a similar vein, Rein et al. (2013) showed that stone-knappers had more co-variation in
707 their joint angles than variation affecting the position of the hand and Mangalam et al. (2018) showed
708 that bearded capuchin monkeys stabilize the path of the hammer when cracking nuts. Therefore,
709 several studies showed that joint angles co-vary to stabilize the end-effector at the tool. This implies
710 that the tool is incorporated in the elements making up the action system that relate to each other in a
711 synergistic manner. Hence, the tool is integrated in the synergy emerging in the action system
712 consisting of body plus tool.

713 The incorporation of the tool in the synergy in the arm implies that constraints of the tool
714 interact with constraints of the task, organism and environment to determine the effectivities. A change
715 in effectivities as a function of the properties of the tool in use does also result in a change in
716 affordances (Fig. 4). That is, the environment is perceived with reference to the properties of the action
717 system that consists of the body and the tool. To examine this, several experiments were conducted in
718 which participants had to select a distance from which to displace an object with the tip of a hand held
719 rod (Bongers et al., 2004, 2003). Importantly, the to-be-displaced object was placed at hip-height and
720 it was approached, and the distance had to be selected, with the tip of the rod pointing upwards so
721 that the perceived affordance could be studied. Findings demonstrate that the selected distance was a
722 function of the length of the rod and of the dynamic forces and torques created by the rod. Importantly,
723 these effects interacted with properties of the to be displaced object (Bongers et al., 2004)
724 emphasizing that tooling affordances refer to the relation between the properties of the action system,
725 including the tool, and properties of the environment. The idea that tools affect the affordances and
726 that the specifics of the tooling affordances are perceived by the organism is supported by studies of
727 Wagman and colleagues. For instance, Wagman & Taylor (2005) showed that affordances can be

728 perceived for the tool and for the body+tool system. Moreover, Wagman et al. (2016) showed that
729 affordances of tools are perceived that are assembled out of other objects while also the affordances
730 of the individual objects making up the tool can be perceived.

731 From the perspective outlined here we define a tool as an object from the environment that is
732 incorporated in the emergent synergies in the action system to perform a goal-directed action. Based
733 on this integration of the tool in the action system the end-effector displaces from the body to the tool
734 and affects the effectivities and thus the affordances. Therefore, tools allow for actions that are not
735 possible without the tool. Effectivities and affordances follow from interactions between constraints in
736 the organism-environment system and physical laws. Hence, from this perspective tool use is a
737 behavior as all other behaviors and does not require a specific label nor a specific toolbox for its
738 understanding.

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

753 **What must be the direction for future work on tool use?** The current paper only takes the first
754 steps in applying an ecological-dynamical approach to tool use. This approach needs to be expanded
755 to a broader range of behaviors and tools to be able to give a full-blown account of tool use. Here we
756 present three possible routes in which the approach could be further expanded in the future. First, our
757 earlier studies regarding synergies in rod reaching (Valk et al., 2016; van der Steen and Bongers,
758 2011) can be taken one step further. A defining characteristic of a synergy is not just co-variation of
759 joint angles, but also the actual location in joint space where the synergy emerges (Tuitert et al., 2020;
760 Wissing et al., 2020). Studying whether, and if so how, the location in joint space where the synergy
761 emerges depends on the tool's properties could further our understanding of the roles of tool
762 constraints in the emergence of synergies.

763 Second, a topic that is relevant to understand tool use but has not been emphasized in this
764 paper so far is the ability of organisms to construct tools. Tool construction has been studied in the
765 ecological-dynamical framework by Van Dijk & Bongers (2014), who examined the emergence of an
766 action system when participants constructed new tools from available objects. Since affordances are
767 prospective, they should be particularly apt to explain tool construction. A future line of research could
768 focus on framing the problem of tool construction in terms of perceiving and actualizing affordances to
769 expand the ecological-dynamical framework in the direction of tool construction.

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

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

782 **More than just tool use**

783

784 **Dietrich Stout**

785

786 **Overview**

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

794

795 **What constitutes tool use (and is that the right question) ?** Many animals make and use tools, but
796 humans are distinctive in the complexity, diversity, sophistication, omnipresence, and obligatory nature
797 of our reliance on tools. Simply put, other animals use tools but only humans have technology. Indeed,
798 humans inhabit a uniquely technological niche that we ourselves have constructed (Stout and Hecht,
799 2017), and which continues to shape our biology, behavior, and cognition. Attention to this broader
800 technological sphere is clearly warranted. For example, Osiurak and colleagues (Osiurak and Heinke,
801 2018; Osiurak and Reynaud, 2020a) have argued that the prevailing conception of tool-use as object
802 manipulation is too narrow because it excludes 'tools' such as machines, computers, containers, and
803 structures and fails to emphasize a uniquely human capacity for 'technical reasoning.' Osiurak et al.
804 propose neologisms like intoelligence (Osiurak and Heinke, 2018) to describe this broader sphere of
805 investigation but the existing term technology might prove more apt if its meaning can be suitably
806 constrained.

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

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

831 al., 2016; Tylén et al., 2016), learning strategies (Heyes, 2016; Kendal et al., 2018; Legare & Nielsen,
832 2015), and cultural evolutionary dynamics (Derex and Mesoudi, 2020).

833 **What psychological processes are involved in technology?** Attempts to specify a critical ‘essence’
834 of technology have invoked everything from skilled prehension (Buxbaum, 2017), to causal reasoning
835 (Osiurak and Reynaud, 2020a), mental time travel (Suddendorf et al., 2018), imitation (Derex et al.,
836 2019), and mentalizing (Tomasello et al., 1993). A technological niche perspective recognizes all these
837 as relevant and interacting. For example, the sophistication of human technology is often attributed to
838 a process of incremental improvement termed as cumulative cultural evolution (CCE) (Mesoudi and
839 Thornton, 2021). CCE is widely believed to require ‘high fidelity’ social reproduction dependent on
840 mentalizing and/or imitation to enable the lossless accumulation of innovations (Derex et al., 2019;
841 Tomasello et al., 1993). In the case of technology, however, capacities for causal and analogical
842 reasoning (Gentner and Hoyos, 2017; Osiurak and Reynaud, 2020a), cognitive control (Gönül et al.,
843 2018; McDougle et al., 2016; Stout et al., 2015), memory (Gruber and Ranganath, 2019), and
844 perceptual-motor control (Sánchez et al., 2017) will often be implicated in the generation,
845 identification, and retention of beneficial innovations (Legare and Nielsen, 2015; Miu et al., 2020).
846 Insofar as innovation requires expertise, processes of knowledge reproduction (Gentner and Hoyos,
847 2017; Pan et al., 2020), skill acquisition (Gowlland, 2019), and innovation (Legare and Nielsen, 2015)
848 will be thoroughly intertwined (Osiurak and Reynaud, 2020a; Stout and Hecht, 2017). Finally, the
849 same capacities for intersubjectivity (Tomasello et al., 1993) and interactive synchrony (Pagnotta et
850 al., 2020; Pan et al., 2020) that support the social reproduction of technology also underpin
851 cooperation and coordination (Hill et al., 2009; Powers et al., 2016) that enable the complexity of
852 collective human technologies to so far exceed that of individual animal tool-use. These complex
853 interactions are organized around three key features of technology: production, collaboration, and
854 reproduction.

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

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

872 Implicit technical reasoning supported by frontoparietal cortex may be sufficient for everyday
873 tool use (Osiurak and Heinke, 2018), but more complex activities like the tool making and design
874 impose additional demands (Ball and Christensen, 2019; Stout et al., 2015). These include
875 prospection for future planning (Suddendorf et al., 2018), analogy and relational reasoning to find
876 novel solutions (Ball and Christensen, 2019; Vendetti and Bunge, 2014), and metacognitive monitoring
877 of strategic suitability and progress (Ball and Christensen, 2019) all of which involve a shift in attention
878 from external stimuli to internal cognition that is thought to be supported by dynamic interactions
879 between frontoparietal control and the default mode networks (Dixon et al., 2018).

880 **Collaboration.** Technology is most clearly distinguished from simple tool-use by its
881 coordination of multiple individuals over extended periods of time and space. Small scale coordination

882 between individuals relies on reciprocal prediction achieved by interpersonal coupling of internal
883 forward models for anticipatory motor control (Curioni et al., 2019). This coupling can occur at multiple
884 levels of abstraction (Hasson and Frith, 2016) and provides a key mechanism supporting the implicit
885 mentalizing, empathy, communication, learning, and social affiliation (Alcalá-López et al., 2019;
886 Hasson and Frith, 2016; Pan et al., 2020; Shamay-Tsoory et al., 2019) that in turn support larger scale
887 collaboration. In addition to implicit processes of social alignment (Shamay-Tsoory et al., 2019)
888 collaboration may require explicit negotiation to allocate responsibilities and agree on plans of action
889 (Bang et al., 2017; Mathieu et al., 2017). This may involve metacognitive strategies such as
890 confidence matching, deference to status or experience, and open discussion (Bang et al., 2017; Bang
891 and Frith, 2021; Miu et al., 2020; Shea et al., 2014). Finally, collaboration may be enforced (Bang et
892 al., 2017; Hughes, 1987) by explicit institutional rules and authority, which are in turn the emergent
893 product of interactions between and within smaller groups (Powers et al., 2016; Pryor et al., 2019).

894 **Reproduction.** Technological learning is a protracted, collaborative process (Gobet, 2015;
895 Gowlland, 2019; Pargeter et al., 2019; Suddendorf et al., 2016) reflective of demands for precise
896 control of physical contingencies during material production. This problematizes dichotomies of social
897 vs. asocial learning (Galef, 2013; Heyes, 2018), product vs. process copying (e.g., Tennie et al.,
898 2009), and 'blind' vs. guided innovation (Mesoudi, 2021) that have been prevalent in culture evolution
899 research. This is exemplified in technological apprenticeship (Gowlland, 2019; Sterelny, 2012), in
900 which an extended program of alternating social learning and individual practice (Stout, 2013; Whiten,
901 2015) enables the reproduction increasingly sophisticated skills. Such learning is scaffolded by
902 everything from the exemplar artifacts, available tools, recurring situations, and observable behaviors
903 of culturally constructed 'learning niches' (Flynn et al., 2013; Frigaszy et al., 2013; Stout and Hecht,
904 2017) to intentional demonstration, explicit instruction, and affective feedback from teachers (Kline,
905 2015) guides learners to re-create increasingly sophisticated skills through deliberate practice over
906 extended periods, with each round of individual practice allowing deeper appreciation of the available
907 social information.

908 The resulting expertise combines internal models for efficient action perception, control, and
909 prediction (McNamee and Wolpert, 2019; Sokolov et al., 2017) with flexible task-related, hierarchical
910 knowledge structures of increasing depth and complexity (Gobet, 2015; Stout, 2013). The relevance of
911 each to particular technologies will help determine the efficacy of different learning strategies such as
912 trial-and-error experimentation (Truskanov and Prat, 2018), end-product emulation (Reindl et al.,
913 2017), body movement mimicry (Heyes, 2018; Tennie et al., 2009), intention sharing (Tomasello et al.,
914 1993), and various forms of social scaffolding and teaching (Kline, 2015). Rather than one key
915 reproductive mechanism we should thus expect context-dependent diversity (Caldwell, 2020).

916 **Which of these psychological processes are specific to technology?** By the definition proposed
917 here, technology is an evolutionarily relevant domain of human activity rather than a discrete process
918 or capacity. As such, technological cognition is "soft-assembled" from neurocognitive mechanisms and
919 systems as they become behaviorally relevant, rather than hard wired as a dedicated system. Thus,
920 there would be no particular processes specific only to technology although the functional networks
921 recruited by various technologies might be expected show a family resemblance distinct from other
922 behavioral domains. On the other hand, the definition proposed here is motivated by specific
923 evolutionary hypotheses positing that key processes supporting modern technology are elaborated in
924 humans specifically due to selection on technological capacity and aptitude (Stout & Hecht, 2017). In
925 this evolutionary sense, processes such as intuitive physical reasoning, kinematic monitoring of self
926 and other, and even interactional synchrony would be specifically 'for' technology.

927 **Which psychological processes involved in technology are specific to *Homo sapiens*?** It is not
928 clear that any of the processes involved in supporting technology are qualitatively unique to humans.
929 Perhaps the strongest case could be made for cognitive mechanisms like explicit theory of mind,
930 metacognitive strategies, or analogical reasoning that may themselves be products of cultural
931 evolution in a fully linguistic species (Heyes, 2018). It has, however, been said (although it is unclear
932 by whom) that "Quantity has a quality all its own." Humans may not be qualitatively unique on any one

933 dimension of technology but we are quantitatively exceptional on so many different dimensions at the
934 same time that piecemeal adaptive accounts seem to miss a bigger picture.

935 As reviewed above, exceptional human capacities for skilled interaction with the physical world
936 appear central to the evolution and development of many key aspects technological cognition. Stout
937 and Hecht (2017) thus suggest a Perceptual Motor Hypothesis (PMH) for the evolutionary-
938 developmental-cultural construction of human cognition from ancient primate systems for body
939 awareness and sensorimotor engagement with the world. These systems are early-developing (Baum
940 et al., 2020) and directly engaged with the (internal and external) sensory periphery (Margulies et al.,
941 2016), making them a nexus for interaction between externalizing processes of technological niche
942 construction and internalizing processes of neurocognitive development (Byrge et al., 2014; Flynn et
943 al., 2013; Heyes, 2018; Kennedy et al., 2017). According to the PMH, enhanced human sensorimotor
944 acuity and the experiences this enables guide construction of the internal models and intuitive physics
945 required for technological production. Sensory predictions by these models support the sense of
946 agency and self-other discrimination (Haggard, 2017) that underpin human self-awareness, imitation,
947 social cognition, and empathy (de Guzman et al., 2016) and ultimately the development of “Theory of
948 Mind” capacities (Heyes, 2018), all of which support further technological collaboration, reproduction,
949 and biocultural evolutionary feedback. According to this view, the proper study of technology must
950 cross levels of analysis from neurophysiological dynamics to the cultural evolution of norms and
951 institutions in order to seek unity in diversity by identifying the common processes underlying diverse
952 outcomes across different real-world contexts.

953 **What must be the direction for future work on tool use?** Broadly speaking, a future “cognitive
954 science of technology” would be a comparative science seeking to identify patterned relations
955 between contexts, mechanisms, and functions across superficially diverse technologies. This means
956 embracing the real-world complexity, variation, and contextual particularism (Matusz et al., 2019) of
957 technological behaviors. Among the many challenges facing this endeavor are the large spatial and
958 temporal scale of many technological phenomena, which may require long-term study and a
959 combination of experiments (e.g., Pargeter et al., 2019), ethnographic case studies (e.g., Gowlland,
960 2019), and comparative analyses (e.g., Koster et al., 2020). One more specific direction could be to
961 test the PMH. This would require expanding our surprisingly limited understanding of perceptual-motor
962 variation across primates as well as the proposal that patterns of human technological diversity can be
963 explained in relation to underlying variation in perceptual-motor processes, demands, and
964 developmental interactions. One critical test of the PMH would be the extent to which learning and
965 reasoning about non-mechanical technological properties (e.g. chemical reactivity) rely on concrete
966 perceptual-motor simulation vs. abstract symbolic and analogical thinking (Brand et al., 2021).

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

980 **The technical-reasoning hypothesis**

981

982 **François Osiurak**

983

984 **Overview**

985 Technical reasoning refers to the ability to reason implicitly about physical object properties (see
986 Osiurak et al., 2010, 2020; Osiurak & Badets, 2016). This reasoning is both causal (i.e., predicting the
987 effects on the environment) and analogical (i.e., transfer of what is understood from one situation to
988 another). It is based on non-verbal knowledge, called mechanical knowledge, which contains
989 information about physical principles/mechanical actions (e.g., leverage, cutting, percussion).
990 Technical reasoning is much more than spatial reasoning, which can consist, for instance, in
991 determining whether a car can pass between two trees or whether two puzzle pieces can be arranged
992 together. Indeed, it involves the understanding of the material dimension of objects (e.g., hardness,
993 sharpness), which is the basis for the emergence of mechanical actions. Technical reasoning is
994 involved in any manifestation of human materiality such as the use of physical tools (e.g., stone tool,
995 hammer), but also tool making or construction (e.g., building a shelter). It is also thought to be specific
996 to the human lineage. Thus, because it allows humans to discover and master a great amount of
997 technical content, its emergence over evolution might explain why cumulative technological culture,
998 that is the increase in efficiency and complexity of tools and techniques over generations, has been
999 observed only in human populations (Osiurak and Reynaud, 2020b). In the following lines, I present
1000 the technical-reasoning hypothesis in more detail¹.

1001 **What constitutes tool use?** The technical-reasoning hypothesis does not really confer any special
1002 status to tool use because it considers it as one of the manifestations of human materiality in the same
1003 ways as tool making or construction (or any technical devices that need the use of natural forces such
1004 as wind or fire). In this respect, as argued by Beck (1980) and Shumaker et al. (2011), any definition of
1005 tool use necessarily refers to a behavioral description, which does not imply any psychological or
1006 biological prerequisites. Thus, it is not because two species exhibit tool behavior that the same
1007 cognitive processes are at work in both species (Osiurak and Heinke, 2018). Note that the same is
1008 true for tool making or construction behavior. For these reasons, the technical-reasoning hypothesis is
1009 in line with the behavioral definitions of tool use, tool making, and construction proposed by Beck
1010 (1980) and more recently updated by Shumaker et al. (2011; **Table 1**). As explained, although the
1011 technical-reasoning hypothesis assumes that, in humans, technical reasoning is involved in any
1012 manifestation of human materiality (i.e., tool use, tool making, and construction), it nevertheless
1013 recognizes that tool use is characterized by an additional mechanism, that is, distalization (Osiurak
1014 and Federico, 2020). Distalization refers to the fact that, once a tool is grasped appropriately to be
1015 used, the natural effector (usually the hand) is no longer the end-effector. Instead, this end-effector
1016 becomes the active part of the tool, that is, the part of the tool that is used to act upon another object
1017 (e.g., the head of the hammer). Thus, there is an attentional shift, from the natural effector to the active
1018 part of the tool, while it is still the hand that needs to be controlled (for evidence for this distalization
1019 mechanism, see Cardinali et al., 2009; Iriki et al., 1996; Maravita et al., 2001; Maravita & Iriki, 2004;
1020 Miller et al., 2018; Osiurak et al., 2017). This distalization mechanism also implies that the user needs
1021 to control the degrees of freedom of the body-tool system differently to the body-only system, a

1 I will limit the discussion on tool use to physical tool use (e.g., stone tool, hammer, fork; also called free tool use in Osiurak & Heinke, 2018). In other words, I will not discuss the use of arbitrary tools (i.e., interface-based technologies; e.g., washing machine, computer, smartphone) or assistive tools (i.e., “autonomous” technologies; e.g., heating system), that is, two phylogenetically recent categories of tools that need technical reasoning to be made but, at best, procedural or associative learning to be used (for more discussion on these tool categories; see (Osiurak, 2020; Osiurak and Heinke, 2018). In this way, they differ from physical tool use, which need technical reasoning to be made and used. The terms tool use and physical tool use will be employed here interchangeably.

1022 phenomenon called tooling (Fragaszy & Mangalam, 2018; Mangalam, 2016; Mangalam & Fragaszy,
1023 2016). Importantly, this distalization mechanism is not unique to humans, which can explain why tool
1024 use can also be reported in nonhuman species. In broad terms, this distalization mechanism is
1025 orthogonal to technical reasoning in that it only allows a species to use tools, but it does not imply that
1026 this species possesses technical-reasoning skills.

1027 **What psychological processes are involved in tool use?** Four cognitive functions are mainly
1028 involved in human tool use, each dedicated to a specific role (Fig. 5): Technical reasoning, motor
1029 control, semantic memory, and planning². The role of technical reasoning is to generate technical
1030 solutions to solve physical problems, which can be novel (e.g., to get a small ball that rolled under a
1031 couch) or familiar (e.g., to peel an apple). In this respect, the technical-reasoning hypothesis diverges
1032 from related proposals, which consider that technical-reasoning-like processes are primarily involved
1033 in novel situations and, at best, can be employed as an alternative strategy in familiar activities (e.g.,
1034 Buxbaum, 2017; Caruana & Cuccio, 2017; Martin et al., 2016; Norman, 2002). According to the
1035 technical-reasoning hypothesis, technical-reasoning skills support both familiar and novel tool use,
1036 even if the process can be faster for familiar activities than for novel situations. Technical reasoning is
1037 critical to determine the appropriate mechanical actions as well as to select the appropriate tools and
1038 objects to solve these problems. The outcome of technical reasoning is a mental simulation of the
1039 mechanical action to be performed (e.g., the motion of a knife on an apple). However, simulating a
1040 mechanical action is not sufficient to realize it in the physical environment. This realization needs the
1041 selection and on-line control of the most appropriate motor actions. This is the role of the motor-control
1042 system, which is unaware of the goal of the action (e.g., tool use, object transport). If someone intends
1043 to perform back-and-forth movements with a knife on an apple, this is the expected effect, which
1044 constrains the motor actions selected within the motor-control system. Likewise, if someone has the
1045 idea to move an object from one location to another, the expected effect is the motion of the object,
1046 which also constrains the motor actions selected. Said differently, the motor-control system is only
1047 concerned with the economy of motor actions performed. Because tools and objects are not always
1048 directly available, the user needs to get them from other places. The role of semantic memory is to
1049 organize the search in episodic memory to know and, thus, to remember where to get the tools and
1050 objects appropriate for the ongoing activity (for discussion, see Osiurak, 2014, 2017). Indeed,
1051 knowledge about semantic categories (e.g., cooking, washing) is helpful to carry out an efficient
1052 search in episodic memory and to think of about tools and objects that are not here now (see Tulving,
1053 1985). Finally, tool-use activities usually require a sequence of mechanical actions that can involve
1054 several tools and objects. An individual can generate these different mechanical actions in an
1055 unordered way. The role of planning skills is to rearrange this sequence in an ordered way so that to
1056 optimize time and to avoid potential fatal errors (i.e., the realization of a mechanical action that blocks
1057 the realization of another one). Thus, planning skills allow the individual to foresee future changes of
1058 the environment.

1059 Evidence for the technical-reasoning hypothesis has come from the study of left brain-
1060 damaged patients, which has revealed a strong relationship between the ability to use and select
1061 familiar tools as well as to use, select and make novel tools to solve mechanical problems
1062 (Goldenberg & Hagmann, 1998; Goldenberg & Spatt, 2009; Osiurak et al., 2009; for a review, see
1063 Osiurak et al., 2020). This behavioral association has also been confirmed by brain lesion studies,
1064 which have indicated that difficulties in using both familiar and novel tools are associated with damage
1065 to the brain area PF within the left inferior parietal lobe (Goldenberg and Spatt, 2009; Martin et al.,
1066 2016a; Mengotti et al., 2013; Salazar-López et al., 2016). Two recent neuroimaging meta-analyses
1067 have also revealed that the left area PF is preferentially and selectively activated when healthy
1068 participants focus on the mechanical actions between a tool and an object as well as when they
1069 observe others using tools (Reynaud et al., 2019, 2016). In other words, technical-reasoning skills
1070 could mainly be supported by the left area PF, allowing humans to generate and understand
1071 mechanical actions. By contrast, the ability to select the appropriate motor actions (to use tools or not)

2 I am aware that motor control is not a cognitive function, strictly speaking. Nevertheless, for the sake of simplicity, I will consider it as one of the four main “cognitive” functions discussed in this section.

1072 has been associated with more superior parietal structures and particularly the intraparietal sulci (e.g.,
1073 Reynaud et al., 2016; Vingerhoets, 2014). Concerning semantic memory, a significant body of
1074 evidence has shown that semantic memory is neither necessary nor sufficient to actually use familiar
1075 or novel tools with objects (e.g., Buxbaum, 2017; Hodges et al., 2000; Lesourd et al., 2016; Silveri &
1076 Ciccarelli, 2009; for discussion, see Osiurak & Badets, 2016). In broad terms, this indicates that
1077 semantic memory is not useful to determine appropriate mechanical actions. However, the loss of
1078 semantic memory after temporal lobe lesions can impair the ability to use tools presented in isolation
1079 (Baumard et al., 2016; Hodges et al., 2000; Osiurak et al., 2008; Sirigu et al., 1991). thereby
1080 suggesting that semantic memory is first and foremost involved in the ability to link a tool with a
1081 specific usage (Osiurak, 2014). Finally, it has been found that patients with frontal lobe
1082 lesions/dysexecutive syndrome are impaired when they have to perform complex tool-use activities
1083 that require a sequence of mechanical actions and not when they have to solve less complex tool-use
1084 activities that require only one mechanical action (e.g., Goldenberg et al., 2007). To sum up, the four
1085 main cognitive functions that support human tool use are each dedicated to a specific role and
1086 associated with a specific neural basis (Technical reasoning: To solve physical problems/Left area PF;
1087 Motor control: To perform appropriate motor actions/Intraparietal sulcus; Semantic memory: To get
1088 absent tools and objects/Temporal lobes; Planning: To rearrange sequences of actions in an
1089 economical way/Prefrontal cortex).

1090 **Which of these psychological processes are specific to tool use?** None of the four
1091 aforementioned cognitive functions are considered as specific to tool use, except the distalization
1092 mechanism of the motor-control system, which could constitute the very essence of tool use (see
1093 above). Indeed, as explained, technical reasoning is also at work when humans make tools or build
1094 constructions. The motor-control system is unaware of the goal of the action. Semantic memory is
1095 involved more generally in our knowledge about the world and is not critical to actually use tools
1096 with objects. Finally, planning skills are in charge of optimizing time when a sequence of actions is
1097 performed, irrespective of whether this sequence is tool-centered or not (e.g., construction behavior,
1098 but also when people play chess or optimize their shopping trips).

1099 **Which psychological processes involved in tool use are specific to *Homo sapiens*?** There is a
1100 tendency in the animal cognition literature to give to nonhuman tool-using species a special status, as
1101 if tool use reflected a specific sign of intelligence. As argued by Hansell and Ruxton (Hansell and
1102 Ruxton, 2008), this status might be exaggerated because based on a confusion or even a kind of
1103 bijection between tool use and specific physical-cognitive skills. As explained above, tool use could be
1104 observed in any species that possesses a distalization ability. However, this ability is orthogonal to the
1105 level of physical understanding that the species has. In this way, the technical-reasoning hypothesis
1106 obviously recognizes that tool use is not specific to humans. However, it also stresses that the study of
1107 tool use is not sufficient to understand how humans and nonhuman animals are able to understand
1108 their physical environment. As a matter of fact, the technical-reasoning hypothesis suggests that even
1109 if some animals could possess some of the components of technical reasoning (e.g., the causal
1110 component), technical reasoning in its entirety could be specific to humans. This claim is based on
1111 evidence from micro-society paradigms³, which have shown that cumulative performance can emerge
1112 over generations even when individuals only transmit the product made (e.g., a tower or a basket; i.e.,
1113 reverse engineering; (Caldwell and Millen, 2009; Derex et al., 2019; Osiurak et al., 2021b; Zwirner and
1114 Thornton, 2015). Technical-reasoning skills (assessed with psychotechnical tests) have also been
1115 found to be the best predictor of cumulative performance in these micro-society experiments (De
1116 Oliveira et al., 2019; Osiurak et al., 2021a, 2020a, 2016). Conversely, cumulative performance

3 Micro-society paradigms aim to investigate cultural evolution in laboratory (e.g., Caldwell & 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 themselves. Then, the third participant does the same with the second one, and so on.

1117 observed in this kind of paradigm is also accompanied by an increase in understanding of the physical
1118 system (Osiurak et al., 2021b). Taken together, these results indicate that technical-reasoning skills
1119 could have played a key role in cumulative technological culture, namely, a phenomenon that is
1120 considered as unique to the human lineage⁴. In sum, although tool use is not unique to humans, it
1121 might be nevertheless be specific in humans because of its 'recycling' by technical-reasoning skills.

1122 **What must be the direction for future work on tool use?** There is a crucial need in the literature to
1123 draw a marked distinction between tool-use skills from technical-reasoning skills, because of their
1124 orthogonality at a cognitive level. It is one thing to be able to manipulate a tool to use it with an object
1125 and another to understand the physical effects of this interaction. In this respect, three distinct lines of
1126 research should be developed. The first line should consist in extending the question of physical
1127 understanding in human tool use to tool making and construction behavior. One of the goals of this
1128 extension can be to test whether technical-reasoning skills and its neural correlates, that is the left
1129 area PF, is really involved in any manifestation of human materiality. More generally, this could allow
1130 emergence of a specific field in cognitive sciences investigating cognitive skills needed to modify the
1131 physical environment, that is, technition (Osiurak et al., 2020b). The second line should consist in
1132 deepening our understanding of the cognitive mechanisms that are required to use tools (potentially
1133 the distalization mechanism). Taken together, these two lines of research can help us to specify the
1134 cognitive components associated with tool-use skills *versus* technical-reasoning skills. Finally, a third
1135 line of research could explore whether a certain link can exist between both. For instance, even if
1136 these two kinds of skills are orthogonal, it remains very plausible that the ability to manipulate tools
1137 can favor the exploration of the physical environment and can be an important prerequisite for the
1138 emergence of technical-reasoning skills in a given species. Thus, these three lines of research should
1139 be particularly useful to understand the specific trajectory of technological evolution in the human
1140 lineage on the basis of a plurality of methods and techniques from distinct but complementary
1141 disciplines, such as neuropsychology, cognitive neuroscience, developmental and comparative
1142 psychology, archaeological and anthropological sciences.

4 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).

1143 **Discussion**

1144 Multiple lines of scientific and philosophical investigation are concerned with the development and
1145 expression of humans' engagement with tools and its relation to other dimensions of human
1146 experience. At first sight, these multiple lines of inquiry (including those described by the six author
1147 groups in this collection) may appear to be incongruent. However, as we shall discuss below, these
1148 seemingly divergent perspectives converge on some common themes and consequently foster a more
1149 comprehensive, interdisciplinary understanding of tool use than any of these perspectives would (or
1150 could) on their own. It is to these seeming consistencies and their resolution that we turn now.

1151 **What constitutes tool use?** The six author groups addressed this fundamental question differently.
1152 Mangalam and Fragaszy provide a definition in which tooling is a deliberate act in which the body-
1153 object system produces a mechanical effect on a target. This definition necessitates that the actor,
1154 tool, and target physically contact each other during the activity of tooling and that the act of tooling
1155 lasts only as long as this spatial relationship is maintained (Fragaszy & Mangalam, 2018; Mangalam &
1156 Fragaszy, 2016). The authors justify this narrow definition because it affords analytical clarity.

1157 Wagman and Day expand the scope of this definition by including any interaction with an
1158 intermediary object that changes the ability to perceive and actualize affordances in the context of
1159 performing a goal-directed behavior. Consequently, Wagman and Day classify behaviors as tool use
1160 that Mangalam and Fragaszy would not, such as throwing objects at a target and using a wheelbarrow
1161 to transport material. Except for this discrepancy, Wagman and Day's views are mostly compatible
1162 with those of Mangalam and Fragaszy—both rooted in the Gibsonian concepts of affordances and
1163 information detection. Bongers' perspective is rooted in these concepts as well: tool use occurs when
1164 an environmental object temporarily alters the capacity for action, requiring the new coordination
1165 patterns in the act of performing that action (cf. Profeta & Turvey, 2018).

1166 Kelty-Stephen goes beyond these authors by proposing that tool use is an intermittent cascade
1167 of contingencies across a permeable animal-environment boundary. This permeability allows tool
1168 movement to inherit the multifractal fluctuations inherent in limb movement and return new multifractal
1169 fluctuations to those limbs (Mangalam, Carver, et al., 2020a, 2020b). Fluctuations flow through a
1170 continuous medium spanning the organism, tool, and environment via informational contact (acoustic,
1171 mechanical, optical). So, for Kelty-Stephen (like Wagman & Day), tool use does not necessitate
1172 continual mechanical contact between the object and the body.

1173 Stout and Osiurak, respectively, take an entirely different tack in defining tool use. Stout finds
1174 no utility in defining tool use per se and instead chooses to subsume tool use under the broader
1175 umbrella of technology. For him, technology (but not tool use) is a uniquely human endeavor—tool use
1176 (considered on its own) fails to capture the uniquely human capacity for 'technical reasoning.' Stout's
1177 view is consistent with that of Osiurak for whom 'intelligence' is the intelligent use of technological
1178 innovations including, but not limited to, tools (Osiurak and Heinke, 2018; Osiurak and Reynaud,
1179 2020a).

1180 Osiurak does not confer any special status to tool use because it is merely one of the ways in
1181 which technical reasoning is brought to bear in human materiality. However, Osiurak suggests that tool
1182 use requires an additional mechanism beyond technical reasoning: distalization (Osiurak and
1183 Federico, 2020). Distalization is a shift in the locus of perception-action from the body to the active
1184 part of the tool, and several author groups highlighted the centrality of this phenomenon in using tools.
1185 A key implication is that controlling the body-tool system requires establishing different synergies
1186 across different sets of degrees of freedom than controlling the body itself. This aspect of Osiurak's
1187 analysis aligns with Mangalam and Fragaszy's embodied theory of tooling (Fragaszy & Mangalam,
1188 2018; Mangalam & Fragaszy, 2016), Wagman and Day's description of tools use as the exploitation of
1189 an altered animal-environment fit, Bongers' description of tool use as the control of synergies
1190 emerging across tool user and tool use task, and Kelty-Stephen's description of the nonlinear
1191 interactions across the porous boundary between user and tool.

1192 Hence, the six author groups differ in how inclusive or exclusive their definition of tool use is. It
1193 is important to remember that definitions provide a way of formulating a problem and an approach to
1194 solving it. Each of these definitions will yield distinct (though perhaps not entirely incompatible)
1195 answers to the following fundamental questions: **What psychological processes are involved in**
1196 **tool use? Which of these psychological processes are specific to tool use? Which**
1197 **psychological processes involved in tool use are specific to Homo sapiens?**

1198 **What psychological processes are involved in tool use?** A fundamental question in the study of
1199 tool use concerns the psychological processes that underlie this phenomenon, but the divergence
1200 among researchers about what constitutes tool use may hamper a coherent answer to this question.
1201 Some researchers have investigated the neurophysiological underpinnings of tool use by studying
1202 brain-damaged patients (Goldenberg and Spatt, 2009; Lewis, 2006; Wheaton and Hallett, 2007) or
1203 noninvasive functional neuroimaging in everyday settings (Bril et al., 2005; Krakauer et al., 2017).
1204 Others have done so by conducting comparative analyses of tool use across species (Bril et al., 2012;
1205 Mangalam et al., 2020; Mangalam & Fragaszy, 2016). Unfortunately, any observed pattern of brain
1206 activation is mute on the psychological processes reflected by that activation pattern. A lack of a
1207 coherent theoretical framework makes it challenging to conduct studies across species that yield
1208 testable predictions about the psychological processes involved in tool use. So, we take this
1209 opportunity to suggest some degree of convergence on the psychological processes involved in tool
1210 use.

1211 For Mangalam and Fragaszy, the psychological processes of interest in tool use are at the
1212 level of perception and action—in particular, the functional task demands establishing and maintaining
1213 a mechanical interface. In their embodied theory of tooling (Fragaszy and Mangalam, 2018), tool use
1214 depends on the perceptuomotor processes related to perceiving spatial relations among objects and
1215 surfaces, developing agency over objects attached to the body (the distalization of the end effector),
1216 and controlling the bodily degrees of freedom to meet functional task demands. Mangalam and
1217 Fragaszy emphasize that these processes occur in the body-object-task-environment system.
1218 Moreover, together, these processes distinguish tool use from other instrumental problem-solving.

1219 Similarly, for Wagman and Day, the psychological processes of interest in tool use are at the
1220 level of perception and action. They focus their analysis on detecting and exploiting lawfully structured
1221 stimulation patterns ('information'). When the animal-environment fit is altered by a tool, the structure
1222 encountered at the point of observation provides information about affordances for tool use—whether,
1223 when, and how the tool can be used to achieve a goal. The lawfulness of this process entails that
1224 information about tool use is invariant over transformations (Hajnal et al., 2007; Mangalam et al.,
1225 2017; Wagman et al., 2017; Wagman & Hajnal, 2014b, 2014a, 2016). Perceiving (and actualizing)
1226 such affordances requires spontaneously and temporarily assembling task-specific detection units
1227 (and task-specific control units) across body and tool capable of detecting (and exploiting) such
1228 information.

1229 Kelty-Stephen takes the lawful grounding of tool use described by Wagman & Day one step
1230 further. The processes that underlie tool use are cascade dynamics—the same generic processes that
1231 underlie the behavior of all systems that branch, avalanche, diffuse, or spread apart across multiple
1232 temporal or spatial scales. Cascade dynamics are exhibited at all levels of the organization and all
1233 levels of scale both within an organism and across the animal-environment system (Goldberger et al.,
1234 1990)(Fernandez-Gonzalez & Zallen, 2011)(Fratzl, 2008). Moreover, the spreading of these
1235 interactions across levels and scales of the analysis entails a multifractal structure (e.g., Ingber, 2006)
1236 (Turvey and Fonseca, 2014). The waxing and waning of multifractal fluctuations predict cascade-
1237 driven coordination of events during tool use (Mangalam, Carver, et al., 2020a, 2020b).

1238 Bongers' analysis is also at the level of perception and action and has the same lawful
1239 grounding in specificity relations as Wagman and Day and Kelty-Stephen, respectively. Bongers' focus
1240 is on the control of coordinated action in actualizing affordances for tool use. Actualizing affordances
1241 (with or without a tool) requires establishing synergies—emergent coordinative patterns among
1242 numerous degrees of freedom spanning the task, organism, and environmental constraints. The

1243 synergies that can emerge under these circumstances determine an animal's capability for acting—its
1244 effectivities. An object attached to the body that functions as a tool affects the emergence of synergies,
1245 and hence, the effectivities of the action system. Therefore, tool use requires integrating the tool into
1246 the synergy emerging in the action system consisting of body-tool. This thesis is consistent with the
1247 analysis provided by Mangalam and Frigaszy.

1248 Stout's emphasis on technology rather than tool use per se leads him to consider a broader
1249 range of psychological processes that are more intimately tied to traditional cognitive psychology than
1250 any of the preceding authors, especially so because of the relationship between technology and
1251 culture. At the technological level, these processes include causal and analogical reasoning, cognitive
1252 control, memory, and perceptual-motor control in behavioral exploration. At the level of a technological
1253 society, these processes are organized around production, collaboration, and reproduction.

1254 Finally, Osiurak posits that tool use is supported by four cognitive functions: technical
1255 reasoning, motor control, semantic memory, and planning. Importantly, technical reasoning results in a
1256 simulation of the mechanical action performed but not the performance of those actions. Motor control
1257 is thus required to select and control the simulated actions. Semantic memory is required to think
1258 about tools appropriate for performing the simulated action and where such tools might be located.
1259 Planning is required to prospectively organize the actions involving tools in a way that is efficient and
1260 as error-free as possible.

1261 So, what are the points of convergence across researchers in their ideas about the
1262 psychological processes involved in tool use? All author groups note that tool use is associated with
1263 transforming the body into the body-tool system (i.e., all incorporate the notion of distalization of the
1264 end-effector). Mangalam and Frigaszy, Wagman and Day, and Bongers each focus on tool use to
1265 detect and exploit lawfully structured patterns of energy that provide 'information about' affordances of
1266 tools. Kelty-Stephen also grounds his analysis in lawful relations, but shifts focus away from
1267 psychological processes per se and toward generic processes of cascade dynamics. Stout and
1268 Osiurak, respectively, focus more on processing and cultural transmission of information. Specifically,
1269 they identify technical reasoning, semantic memory, and planning as cognitive abilities fundamental to
1270 the production, collaboration in, and reproduction of novel tool-use behaviors.

1271 **Which of these psychological processes are specific to tool use?** This question is important
1272 because if any psychological process is specific to tool use, it will imply that a particular developmental
1273 and/or evolutionary trajectory enables or facilitates tool use. Indeed, this trajectory is what Mangalam
1274 and Frigaszy's definition attempts to uncover. Their definition of tool use attempts to provide a
1275 theoretical foundation for making testable predictions about which individuals (and species) can use
1276 tools, to what extent they can do so, and under which conditions. For Mangalam and Frigaszy, the
1277 three processes that support tool use are: (1) establishing and managing spatial relation(s) between
1278 an object attached to the body and a target object; (2) distalization of the end-effector; (3) coordinating
1279 the body-object system. They propose that while none of these perceptuomotor processes are specific
1280 to tool use, the concurrent involvement all three is a distinctive feature of tool use.

1281 Osiurak posits that four cognitive functions that support tool use (technical reasoning, motor
1282 control, semantic memory, and planning), but only one of them—distalization—is specific to tool use.
1283 For Wagman & Day, the lawfully structured patterned energy arrays that provide information about
1284 whether, when, and how to move to achieve a goal are invariant across transformations—including
1285 whether (or not) a tool is used in the act (e.g., invariant mechanical patterns are informative about
1286 controlling limb movement regardless of whether a person is using a hand-held object). Along similar
1287 (but perhaps not identical) lines, Bongers and Kelty-Stephen advocate that the processes underlying
1288 self-organization in complex tool-using systems are entirely generic, underlying self-organization in all
1289 complex systems—human and animal, living and non-living.

1290 For the other authors, however, there are no psychological processes that are specific to tool
1291 use. For Wagman & Day, the lawfully structured patterned energy arrays that provide information
1292 about whether, when, and how to move to achieve a goal are invariant across transformations—

1293 including whether (or not) a tool is used in the act of doing do (e.g., invariant mechanical patterns are
1294 informative about controlling limb movement regardless of whether a person is using a hand-held
1295 object). Along similar (but perhaps not identical lines), Bongers and Kelty-Stephen advocate that the
1296 processes underlying self-organization in complex tool-using systems are entirely generic, underlying
1297 self-organization in all complex systems—human and animal, living and non-living.

1298 The distalization of the end-effector when using tools has received attention in various forms,
1299 such as the tooltip becoming the end-effector (Arbib et al., 2009; Takahashi and Watt, 2017; Umiltà et
1300 al., 2008), changes in the perception of space (Berti and Frassinetti, 2000; Canzoneri et al., 2013),
1301 and the extension of sensorimotor processing (Miller et al., 2018). Mangalam and Frigaszy (and to
1302 some extent Osiurak) argue that this condition is necessary but not sufficient for tool use. Yet Wagman
1303 and Day, Kelty-Stephen, and Bongers' argue that distalization (or any other psychological process) is
1304 neither sufficient nor necessary for tool use. How might this be resolved? For Mangalam and
1305 Frigaszy, the distalization of the end-effector is a behavioral description associated with the shift of
1306 the locus of perceptual and action control from the biological effector (e.g., hand, beak). Hence, any
1307 investigation must, at least, explain such patterns of variation in the perceptual and action outcomes of
1308 using a tool. For Wagman and Day, Bongers, and Kelty-Stephen, these processes are the same ones
1309 that enable perception and movement of the body without a tool (Harrison et al., 2011; Mangalam,
1310 Pacheco, et al., 2019; Pagano et al., 1993; Wagman et al., 2017). These two approaches address two
1311 distinct sets of questions—one associated with perception-action shift (Mangalam & Frigaszy, 2016),
1312 and the other associated with informational support for perception (Thomas et al., 2019).

1313 **Which psychological processes involved in tool use are specific to *Homo sapiens*?** Any special
1314 association of tool use with humans depends on whether any psychological process involved in tool
1315 use is specific to humans. Otherwise, shared processes would suggest that human tool use differs
1316 from that observed in nonhuman species in the degree but not the type of psychological processes.

1317 Mangalam and Frigaszy address tool use at the behavioral level, emphasizing
1318 perceptuomotor processes of perceiving spatial relations among objects and surfaces, developing
1319 agency over objects attached to the body (the distalization of the end effector), and controlling the
1320 bodily degrees of freedom to meet functional task demands. Importantly, Mangalam and Frigaszy
1321 suggest that none of these processes are unique to humans—nonhuman species show behaviors
1322 supported by each of these processes in isolation. However, they propose that what is unique to
1323 humans is the degree to which these processes can be regulated simultaneously and the number of
1324 functional parameters that can be controlled in a given tool use task, such as when manufacturing
1325 sharp flakes from stone cores (Bril et al., 2015, 2012).

1326 Wagman and Day argue that lawful structuring of energy distributions by the animal-
1327 environment relationship entails that the information about a given affordance (for tool use) is invariant
1328 over the sensory apparatus, nervous system, and brain of the animal doing the perceiving. Therefore,
1329 any animal capable of detecting (and exploiting) such structure is capable of tool use. For them, any
1330 differences in the ability to use tools between humans and non-humans is due to the sophistication of
1331 the ecological niche occupied by that species (Gibson, 1979; Turvey, 2018). The more sophisticated
1332 the environment occupied by a given species, the more sophisticated the affordances available to that
1333 species. This argument explains why nonhuman primates that do not use tools in their natural habitat
1334 use tools more frequently when in captivity (Haslam, 2013). Hence, Wagman and Day's thesis is
1335 consistent with that of Stout who argues that humans inhabit a uniquely technological environment
1336 and (like all animal species) participate in the construction of that environment.

1337 Bongers offers a similar view, arguing that the lawfulness underlying (the self-organization of)
1338 perception-action entails that the processes underlying tool use are not (and cannot be) species-
1339 specific. Any differences between species in their capacity to use tools will be due (in part) to
1340 differences in emergent synergies given task, organism, and environmental constraints. Kelty-Stephen
1341 also relies on the lawful dynamics of self-organization by drawing an analogy between how an
1342 amoeboid slime mold fashions a tool from its bodily degrees of freedom and how a human fashions a
1343 tool from some external object.

1344 Stout emphasizes that none of the processes involved in supporting technology are
1345 qualitatively unique to humans.

1346 Osiurak argues that whereas tool use itself is not a uniquely human phenomenon, some of the
1347 psychological processes underlying it (technical reasoning skills) may be so. He argues that these
1348 technical reasoning skills have contributed to the cumulative technical culture that is specific to
1349 humans.

1350 In summary, although the authors differ significantly in their views on whether any
1351 psychological process is specific to tool use, none identified even a single psychological process
1352 involved in tool use that is specific to humans. The emerging theme is that the psychological
1353 processes that underlie humans' unprecedented capability to use tools, make new tools, and recycle
1354 old tools for new purposes are shared in some manner with other species.

1355 **What must be the direction for future work on tool use?** As noted above, how each author group
1356 defines tool use drives how that author group investigates tool use and hence envisions the direction
1357 for future work on tool use. Mangalam and Frigaszy suggest that future work must be concerned with
1358 the three-component perceptuomotor processes involved in tool use: (1) establishing and managing
1359 spatial relation(s) between an object attached to the body and a target object; (2) distalization of the
1360 end-effector; and (3) coordinating the body-object system during tool use. Kelty-Stephen suggests
1361 applying his perspectives on tool use to a broader set of questions related to whether and how the
1362 multifractal geometry of tool use can formalize agency as a cascade-driven process. Examples of
1363 such studies include the role of fluctuations within the body (Mangalam, Conners, & Singh, 2019;
1364 Mangalam, Conners, Kelty-Stephen, et al., 2019), the role of fluctuations at the postural center of
1365 pressure (Mangalam, Chen, et al., 2020; Mangalam & Kelty-Stephen, 2020), and the flow of
1366 multifractal fluctuations to-and-fro between the body and the tool (Mangalam, Carver, et al., 2020a,
1367 2020b). Bongers makes three specific suggestions about applying the ecological-dynamics approach
1368 to the emergence of synergies in tool use, tool construction, and higher cognitive behaviors such as
1369 action selection and language. Osiurak and Stout, respectively, also suggest that future work must
1370 focus on the processes underlying tool (and technology) use; both suggest taking advantage of
1371 noninvasive brain imaging techniques to investigate the neurophysiological underpinnings of tool use.
1372 Specifically, Stout highlights that using multiple techniques simultaneously such as motion tracking
1373 and electroencephalography (EEG) (Haar et al., 2020) has enormous potential for the study of
1374 technological production.

1375 Like Bongers, Osiurak suggests that future work must investigate tool making and tool
1376 construction, but for him, the goal of such investigations should be to uncover the technical reasoning
1377 skills as well as the cognitive mechanisms that underlie distalization of the end-effector. Wagman and
1378 Day propose that future work on tool use focus on the technological, communication, and
1379 representation systems characteristic of (tool use in) the human niche. They propose the development
1380 of interfaces for teleoperation of devices such as laparoscopic surgical tools, surveillance drones, or
1381 phone apps that preserve, enhance, or generate lawful structuring of energy patterns at any point of
1382 observation, and how to best train users of such devices (cf. Pagano & Day, 2020). Similarly, Stout
1383 promotes 'real-world technological situations' to investigate relations among structure, function, and
1384 behavior. However, he focuses less on the development of technology itself and more on
1385 understanding relations between performance in tool-use tasks and individual differences and/or
1386 experience-related plasticity in neuroanatomical, cognitive, affective, and perceptuomotor traits
1387 assessed in the lab.

1388 In summary, the six author groups with extensive research experience (> 100 years in total)
1389 present quite distinct perspectives on the direction of future work on tool use. To a student just
1390 beginning his/her research career, or to a seasoned researcher, tool use might not appear as
1391 multifaceted a phenomenon with a wide scope for study as this review suggests. All eight authors
1392 hope that this review inspires both new and seasoned researchers alike to look again at tool use—a
1393 behavior that sparks the feeling of wow in a child successfully hammering a nail for the first time, and
1394 that is arguably a keystone of human existence.

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2265 **Table 1.** Definitions of tool use, tool making and construction according to Shumaker et al. (2011).

Label	Definition
Tool use	The external employment of an unattached or <i>manipulable attached</i> environmental object to alter more efficiently the form, position, or condition of another object, another organism, or the user itself, when the user holds <i>and directly manipulates</i> the tool during <i>or prior</i> to use and is responsible for the proper and effective orientation of the tool (p. 5).
Tool making	Structural modification of an object or an existing tool by the user or a conspecific so that the object/tool serves, or serves more effectively, as a tool (p. 11).
Construction	Two or more tools and/or objects physically linked to make a functional, semipermanent thing that, once completed, is not held or directly manipulated in its entirety. A construction itself is therefore <i>not</i> a tool. Nor is it tool manufacture, because the product is not a tool (p. 19).

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Table 2. Example behaviors identified in the literature as tool use, categorized as ‘Instrumental problem solving’ or ‘Tooling’ according to Frigaszy and Mangalam’s (2018) definition of tool use. Adapted from Frigaszy and Mangalam (2018).

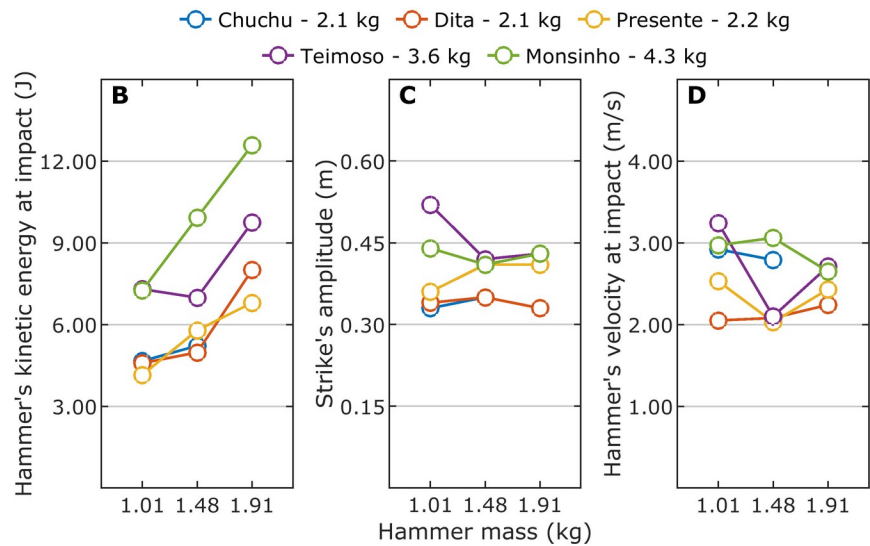
Taxon	Instrumental problem solving	Source
Ants, <i>Aphaenogaster</i> spp.	Carry soft foods on or in pieces of leaf, mud, and sand grains	Fellers and Fellers (1976)
Collector urchins, <i>Tripneustes gratilla</i> *	Camouflage by draping own body with objects	Ziegenhorn (2016)
Octopuses, <i>Octopus vulgaris</i> *	Cover the entrance to their den with rocks	Mather (1994)
Octopuses, <i>Amphioctopus marginatus</i>	Obtain shelter in coconut shell halves	Finn et al. (2009)
Archerfish, <i>Toxotes jaculatrix</i>	Catch flying insects by spitting water droplets on them	Gerullis and Schuster (2014)
Crocodiles, <i>Crocodylus porosus</i> *	Lure birds with twigs and sticks placed on body	Dinets et al. (2015)
Egyptian vultures, <i>Neophron percnopterus</i> *	Break open eggs by throwing and dropping stones on them	Lawick-Goodall (1971)
Northwestern crows, <i>Corvus caurinus</i>	Break open whelks by dropping them on rock outcroppings	Zach (1978)
Rooks, <i>Corvus frugilegus</i> *	Raise water level in a container to reach floating worms by dropping pebbles	Bird & Emery (2017)
North American badgers, <i>Taxidea taxus</i>	Block the entrance of the burrows of ground squirrels to assist in capturing them	Michener (2004)
Baboons, <i>Papio</i> spp.*	Threaten humans by throwing stones	Hamilton et al. (1975)
Bornean orangutans, <i>Pongo pygmaeus</i>	Modulate the frequency of their vocalizations with leaves	Hardus et al. (2009)
Bonobos, <i>Pan paniscus</i> *	Reach a distant branch by climbing on conspecifics	Ingmanson (1996)

Chimpanzees, <i>Pan troglodytes</i>	Reach for a hanging banana by stepping on wooden boxes	Köhler (1925)
Chimpanzees, <i>Pan troglodytes</i> *	Drink water from tree hollows using leaves to sponge up the water	Tonooka (2001)
Taxon	Tooling	Source
New Caledonian crows, <i>Corvus moneduloides</i> *	Extract insect larvae from cavities in branches with probes	Hunt (Hunt, 1996)
Hyacinth macaws, <i>Anodorhynchus hyacinthinus</i>	Stabilize a nut in the beak with wood wedges	Borsari and Ottoni (2005)
Lion, <i>Panthera leo</i>	Rub a sore area of its paw using a thorn held in the mouth	Bauer (2001)
Elephants, <i>Elephas maximus</i>	Brush flies off their body with branches held in the trunk	Hart et al. (2001)
Bearded capuchin monkeys, <i>Sapajus libidinosus</i> *	Dig soil with stones to excavate tubers	Falótico and Ottoni (2016)
Long-tailed macaques, <i>Macaca fascicularis</i>	Floss their teeth with hair	Watanabe et al. (2007)
Sumatran orangutans, <i>Pongo abelii</i> *	Wipe body with leaves to remove substance	Fox et al. (1999)
Chimpanzees, <i>Pan troglodytes</i> *	Flush or disable vertebrate prey in tree hollow with stick	Pruetz and Bertolani (2007)
Chimpanzees, <i>Pan troglodytes</i>	Puncture soil with stick to reach underground termite nests	Sanz and Morgan (2007)
Golden lion tamarin, <i>Leontopithecus rosalia</i> *	Groom conspecific with stick	Stoinski and Beck (2001)

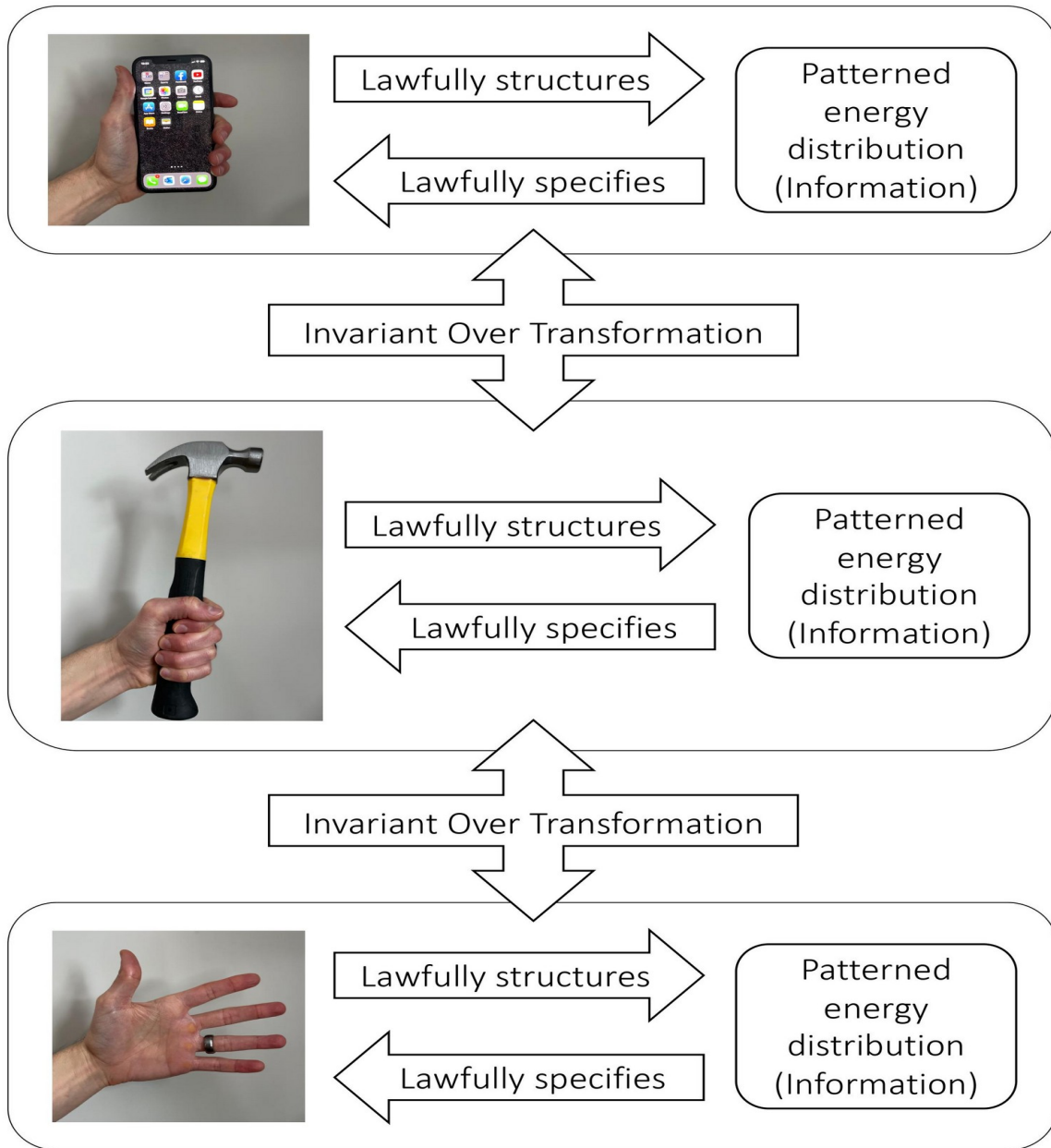
2269 *Additional taxa have been reported to behave in similar ways.



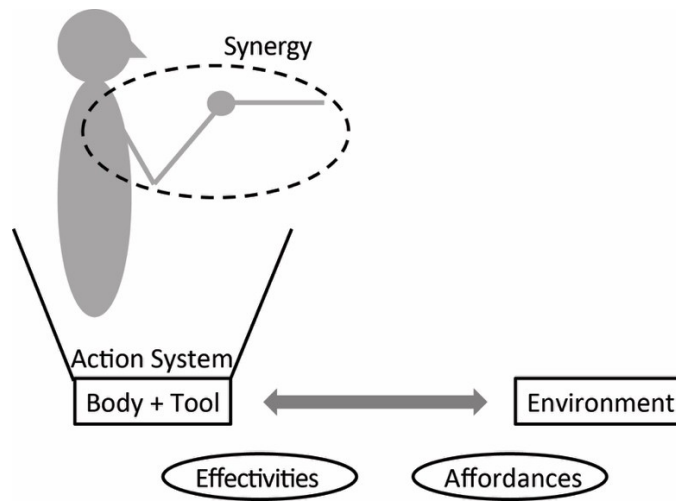
2271 **Fig. 1.** Drawing of bar, cross, tomahawk shapes, and the respective cut-outs presented to two-, three-,
2272 and four-year-old children, adult tufted capuchin monkeys (*Sapajus* spp.), and adult chimpanzees
2273 (*Pan troglodytes*). Two- and three-year-old children routinely aligned a bar-shaped stick and a cross-
2274 shaped stick to its matching cut-out, and four-year-old children can also align a tomahawk-shaped
2275 stick, which entails attending to multiple spatial features concurrently, but capuchin monkeys and
2276 chimpanzees faced severe difficulties in aligning even a simple bar-shaped stick to its matching cut-
2277 out. See Fragaszy et al. (2011), la Cour et al. (2014), and Fragaszy et al. (2015) for details. *Drawing*
2278 *courtesy of D. Sharpe.*



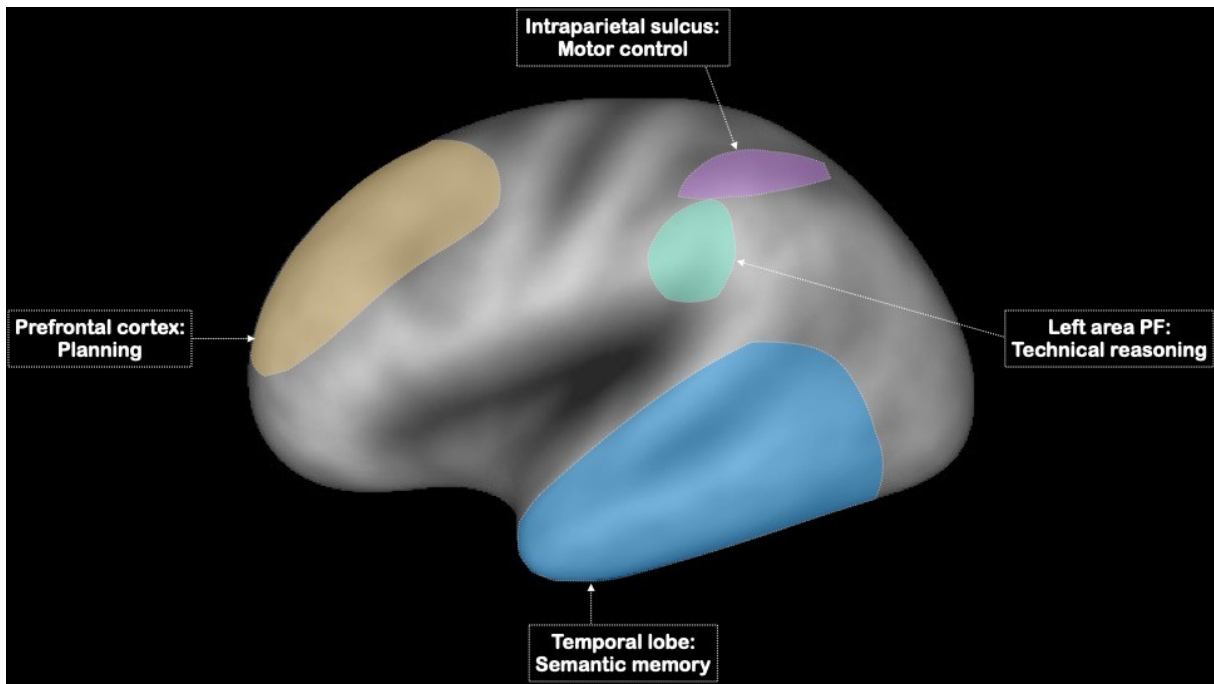
2280 **Fig. 2.** When cracking nuts using stone hammers, wild bearded capuchin monkeys (*Sapajus*
 2281 *libidinosus*) alter their strikes to strike a nut with less or more force based on the type and condition of
 2282 the nut; they do so by adjusting the amplitude [and velocity] of the strike but do not adjust the
 2283 hammer's kinetic energy at impact. (a) An adult monkey is striking an intact piçava nut (inset)—
 2284 placed in a pit on a log anvil—with a quartzite stone hammer. *Photo courtesy of Barth A. Wright.* (b)
 2285 Hammer's kinetic energy at impact. (c) Strike's amplitude. (d) Hammer's velocity at impact. Adapted
 2286 from Mangalam, Pacheco, et al. (2018).



2288 **Fig. 3.** The relationship between animal and environment lawfully structures patterned energy array so
 2289 as to provide information about this relationship (bottom). Such lawfulness entails that information
 2290 about a given affordance is invariant over transformations including whether or not a tool alters the fit
 2291 between animal and environment (middle) and whether or not the tool is virtual (top).



2293 **Fig. 4.** The tool in the hand of the use is schematically depicted. The tool affects the synergies in the
2294 action system, and therefore the effectivities and the affordances.



2296 **Fig. 5.** Neurocognitive functions involved in tool use according to the technical-reasoning hypothesis.