LITHIC ANALYSIS AS A COGNITIVE SCIENCE: A FRAMEWORK

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Research into the cognitive foundations of lithic technology has been increasingly prolific and productive over the last 30 years. However, Evolutionary Cognitive Archaeology (ECA) lacks an explicit theoretical framework. In this paper, I selectively review past work and propose a theoretical framework to open discussion amongst researchers. First, I distinguish between the two components of cognition: knowledge and the intelligent systems that make that knowledge possible. The chaîne opératoire approach provides a powerful method for describing and analyzing technical knowledge. Thomas Wynn's (1993) three-layer model of tool behavior provides a useful heuristic for organizing research into the underlying neurocognitive processes that make technical knowledge possible. Contemporary work by Wynn, Gowlett, Bril, Moore, Stout, and Uomini are placed within this framework. Notable findings are reviewed to describe the current state of knowledge in ECA. Without an adequate theoretical framework, ECA will continue to produce intriguing results without relating them to each other. It will also lack a medium within which to pose and resolve theoretical and empirical debates.

KEYWORDS: *evolutionary cognitive archaeology, cognition, lithic analysis, chaîne opératoire, cognitive science*

INTRODUCTION: EVOLUTIONARY COGNITIVE ARCHAEOLOGY

Paleoanthropologists have long hypothesized that toolmaking played an important role in human evolution (Oakley 1944; Washburn 1959). Since the discovery of widespread tool-use in other species such as chimpanzees in the late 1960s (Van Lawick-Goodall 1970), it has become clear that this is not a unique human trait. However, during the same period the nascent field of Evolutionary Cognitive Archaeology (ECA) (Wynn 2009) began to take form in a series of analyses of Pleistocene lithic technologies using methods from the cognitive and information sciences (e.g., Guilmet 1977; Holloway Jr 1969; Wynn 1979). Researchers in ECA analyze the archaeological record for evidence of the course, timing, and factors driving hominin cognitive evolution. Studies in ECA have proliferated, providing an increasingly precise model of the cognitive foundations of stoneknapping as well as clarifying what it might be able to tell us about the evolution of the hominin mind.

However, results from one study are difficult to relate to those from other studies due the lack of an overall framework for organizing our thinking about the cognitive foundations of lithic technology. By framework, I am referring to a set of heuristics that will define what kinds of things cognitive archaeologists are investigating and how these things relate to each other. Such a framework would include tools for describing technical knowledge, the neurocognitive systems that generate that knowledge, and the different levels at which to analyze this system. The ultimate goal of this paper is to generate discussion about these fundamental topics amongst cognitive archaeologists.

In this paper, I will perform selective review of the current state of knowledge in ECA of lithic technology, focusing on work from researchers engaging in sustained programs of research. First, we must distinguish between the technical knowledge and the brain systems that make that knowledge possible. The contribution of the *chaîne opératoire* approach to a model of the knowledge system subserving stoneknapping will be briefly described. Then I will describe Wynn's Three Layer heuristic of the neurocogntive dimension of tool behavior (Wynn 1993), placing recent research within this framework. Most of the research reviewed explicitly compares Oldowan (2.6 to 1.1 million years ago) to Late Acheulean (~0.7 to 0.25 million years ago) technologies, comparing a simple debitage technology to a shaped tool technology.

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Contributions of the *Chaîne Opératoire* approach to a cognitive model of stoneknapping: chains and recipes

Most, if not all, archaeological research contains implicit cognitive theories. Some traditions of analysis have elaborated explicit cognitive models of how people make decisions about foraging, manage social relationships, or structure technology. The assumption undergirding ECA is the link between technology and knowledge. Schiffer and Skibo (1987) defined technology in these terms:

> A technology is a corpus of artifacts, behaviors, and knowledge for creating and using products that is transmitted intergenerationally (adapted from Merrill 1965: 576; see also Richter 1982: 8). Traditionally, emphasis has been placed on inferring the specific sequence of activities employed by ancient artisans to produce a given form (p. 595).

Initiated in early to mid-twentieth century by Mauss (Mauss and Schlanger 2006) and Leroi-Gourhan (1993), the *chaîne opératoire* approach has attempted to use the analysis of technologies to understand the behaviors and social groups of archaeological documented cultures. In the 1980s and 1990s, the approach was widely used in lithic analyses (e.g., Boëda 1988a, 1988b, 1995; Boëda et al. 1990; Geneste 1985; Inizan et al. 1999; Pelegrin 1990; Pigeot 1990, 1991; Schlanger 1996). Based in the empirical replication of archaeologically documented technologies, researchers attempt to determine the system of knowledge underlying the process by which the technology is produced, used, and discarded (Desrosiers and Sørensen 2008). There are usually a number of methods available to make an artifact of a particular type, so the choices exhibited in the reconstructed operational chain can ultimately provide some information about the economic, social, and cultural lives of the people who deposited the artifacts (Lemmonier 1992; Leroi-Gourhan 1943; Mauss and Schlanger 2006).

The most significant contribution of the *chaîne opératoire* approach to our understanding of the cognitive foundations of stoneknapping lay in its model of the knowledge systems instantiated in a technology. Figure 1 reproduces a diagram by Desrosiers and Sørensen (2008: 10) detailing the basic structure of this theoretical knowledge

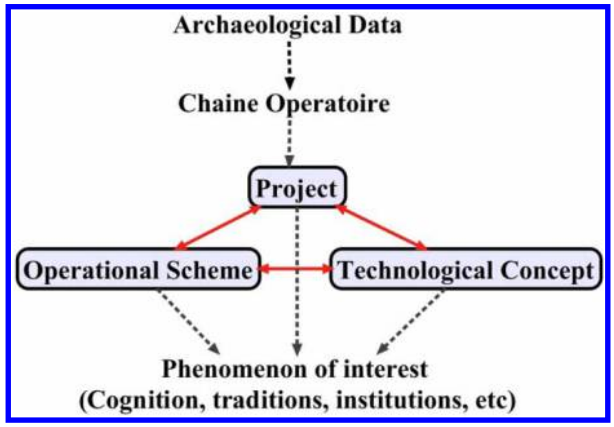

Figure 1. *Chaîne opératoire* model of technological knowledge. After Desrosiers and Sørensen (2008: 10).

system. It should be noted that the diagram shows how archaeologists infer features of anthropological interest on the basis of archaeological data. It assumes that archaeologist participate in the same process as ancient people when they experimentally replicate technologies (Schiffer and Skibo 1987; Schiffer et al. 2001).

Central to the *chaîne opératoire* approach are three notions: the operational scheme (*schema operatiore*), the technological concept, and the project. The operational scheme refers to the mental representations of the toolmaking process. A technological concept refers to how the stoneknapper imagines the object, typically in terms of volume, affordances, and "tricks" for achieveing desired results (Moore 2010). Finally, the project refers the real-world goals that stoneknapper is trying to achieve such as to hunt ibex in a mountain valley 13 km distant from the nearest quarry, for example. The project motivates and organizes toolmaking, selecting schemas and concepts and guiding decisions in relation to the phsyical and social environments. Finally, stoneknapping requires the interaction of emplicit semantic knoweldge (know-that) and implicit procedural memory (know-how) (Pelegrin 2005). Personal experience indicates the primacy of know-how while knapping, while know-that provides analogies for shapes and actions allowing novices to identifiy relevant features of the core as they learn.

Analyzing both the structure of practical technical behavior and how it is learned and transmitted across generations, Mesoudi and O'Brien (2008) described these representations as cultural recipes, "a unit of cultural transmission that combines raw materials and the various behaviors that constitute a person's knowledge regarding how tool is made and used" (p. 64). As with a recipe from a cookbook, these cultural recipes are constructed from knowledge about the acquisition and use of raw materials as well as the procedures for the construction, use, and repair of the tools. While these authors do not explicitly use the *chaîne opératoire* approach, the concepts of a cultural recipe and an operational scheme are homologous.

Other non- *chaîne opératoire* approaches to technology have generated similar conceptual frameworks. For example, this interaction of knowledge, practice, and the project appears independently in the work of cognitive anthropologists Keller and Keller (1996). According to them, skill is comprised of knowledge and practice. Knowledge is the "disparate and dynamic conceptual entities that individuals use in their various activities" (p. 15). Practice is "the observable behaviors performed in the production of an artifact, the sequences of observations in which individuals engage" (p. 16). Skilled action is an emergent, dynamic activity as it unfolds in the world.

Learning complex, multivariate skills such as stoneknapping is aided by the hierarchical structure of the cultural recipes that a social group transmits generationally (Kempe et al. 2012; Mesoudi and O'Brien 2008). In a hierarchical structure, there are higher-level goals or intentions guiding lower level subroutines composed of individual actions (Figure 2). It is easy to see a similar structure in language. Higher-level structures, like a story's narrative, organize a series of sentences that in turn organize individual words. Mesoudi and O'Brien (2008) found a typical pattern of learning cultural recipes as people progress from the status of novices to expertise. Novices tend to perform unconnected and unorganized actions while experts tend to organize actions into distinct subroutines. Over time, subroutines are constructed. Then, instead of attending to individual actions, they focus on and organize the relationships of chunked sequences of actions. Such hierarchically recipes are less vulnerable to error, more easily executed, and learned.

Wynn's Three Layer Model

The *chaîne opératoire* model of technological knowledge discussed above focuses primarily on knowledge. In this sense, it is very much in line with Schiffer's definition of technology. While there is increasing contact with the cognitive and psychological sciences in this approach (e.g., Haidle 2006, 2007, 2009, 2010, 2011; Lombard and Haidle 2012), it views technological behavior very much from a traditional archaeological perspective. It describes the knowledge or recipes needed to make a particular lithic artifact, but it does not describe how this knowledge is possible i.e., what kind of cognitive (information processing) system makes this knowledge possible. It does not explain why the makers of Oldowan tools did not use — and presumably could not use — the classic Levallois technique but Neanderthals were capable of a much wider technological repertoire. As noted by Bar-Yosef and Van Peer (2009), this descriptive bias can leave these analyses as being classificatory and not explanatory.

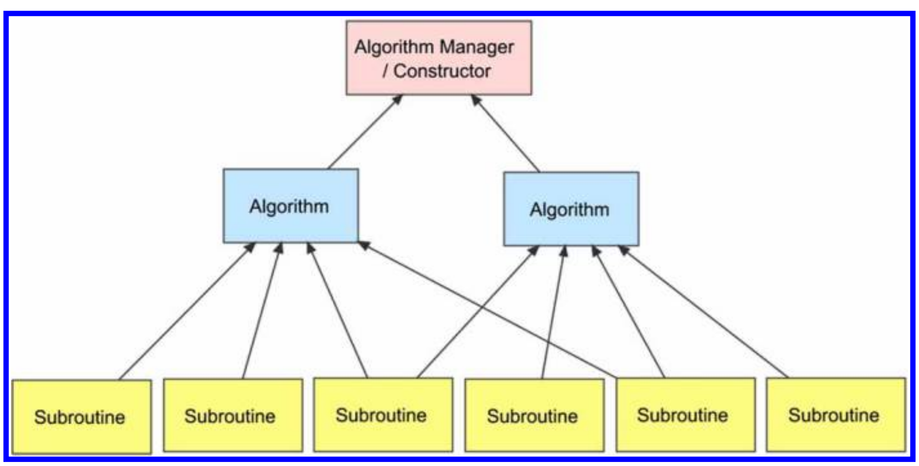

FIGURE 2. Example of a hierarchically-structured system composed of subroutines organized into algorithms. Guiding the entire system are high-level processes constructting algorithms, initating their execution, and matching them to behavioral contexts.

A complementary approach mobilizing the theories and methods of psychology and the cognitive sciences has been more productive at approaching evolutionary explanations of differences between Pleistocene lithic technologies. Archaeologist Thomas Wynn has been at the forefront of this approach. As a heuristic and nascent theory to address how knowledge is instantiated in the brain and intentional activity, Wynn (1993) has proposed a "general structure of tool behavior" (p. 390) with three layers: (1) Biomechanical, (2) Sequence Construction, and (3) Problem-Solving/ Cognitive Control (Figure 3). This partitioning of the cognitive processes involved in stoneknapping is derived from psychological theory and supported by neuroimaging studies of modern knappers contrasting Oldowan and Acheulean replication (Stout and Chaminade 2007; Stout et al. 2000, 2008).

The biomechanical layer refers to the affordances and the constraints of the anatomy of the stoneknapper as well as the cognitive systems that guides simple behaviors. The "three-jaw" chuck grip characteristic of hominids (e.g., Marzke 1997), handedness (e.g., Steele and Uomini 2005; Uomini 2008, 2009), and bimanual coordination (e.g., Faisal et al. 2010) can all be discussed at this level. In addition, the production of the individual actions used by the stoneknapper during lithic reduction is also analyzed as a phenomenon of this layer, most notably the ballistic knapping gesture (e.g., Calvin 1993). As we will see when we discuss the research of Blandine Bril and collaborators, placing the knapping at this lowest level is not meant to imply that this is a trivial skill for the stoneknapper to master. In fact, it may be the most complex and subtle aspect of the entire process. However, it is guided by operations at the higher layers of the process when the knapper creates a shaped tool.

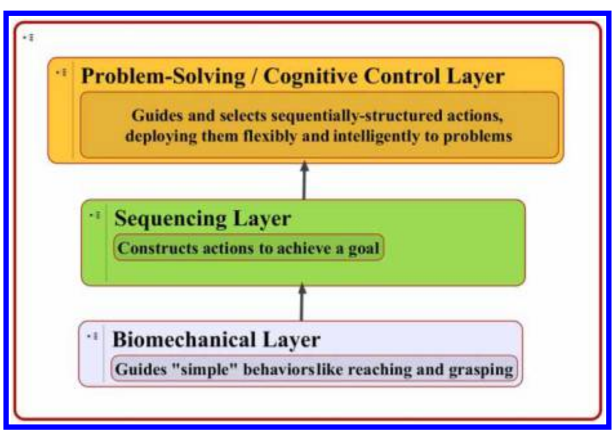

FIGURE 3. Thomas Wynn's Three-Layer Heuristic for the cognitive analysis of stoneknapping and lithic technology.

Following Wynn, the next layer is that of sequence construction or the process of concatenating actions in order to achieve a goal. The ability to construct sequences is a widespread synapomorphy ("shared trait") among primates. Parker and Gibson (1977) have argued that primates specialize in various forms of extractive foraging. Extractive foraging refers to the process by which a primate accesses a hidden or defended resource such as nut-cracking (Boesch and Boesch 1982; Carvalho et al. 2008, 2009; Fragaszy et al. 2004; Visalberghi et al. 2009), probing (Van Lawick-Goodall 1970), or digging (Mannu and Ottoni 2009; Yamagiwa et al. 1988) by chimpanzees and capuchin monkeys (Cebus). In case of the aye-aye (*Daubentonia madagascariensis*), a strepsirhine primate, this involves physical adaptations such as long probing fingers and rodent-like incisors (Fleagle 2013). However, most primates utilize variously flexible, learned strategies for accessing hidden resources.

From this evolutionary perspective, this stringing together of actions provides a possible preadaptation for syntax in language. In cognitive lithic analyses, it is often seen as a homologue of syntactic abilities, indicating the emergence of language at some point during the Pleistocene (Holloway 1967; Moore 2010, 2011; Stout and Chaminade 2012). This proposal that an important aspect of grammar is an exaptation of a wider primate characteristic is intuitively appealing and evolutionarily plausible. Language no longer would seem qualitatively novel, as proposed by Pinker (1994) but instead a development at one end of a spectrum allowing for meaningful comparisons of similarities and differences in the order *Primates* as variously envisaged by Greenfield (1998, 1991), Chomsky and collaborators (Fitch et al. 2005; Hauser et al. 2002), or Schoenemann (Beckner et al. 2009; Schoenemann 2009).

"Above" these two layers is the problem solving layer. Processes operating at this level guide and select sequentially structured actions, deploying them flexibly and intelligently to problems. In stoneknapping, the choice of a tool-type based on the goals of the knapper and available raw materials would be governed by processes in this layer. As stoneknappers work, flaws in the material or the emergence of other contingencies force modifications to anticipated plans. It is this layer that is coordinating the actions within cultural recipes, leading to the replication of functional forms with imposed design in the sense of Deetz (1967), Crompton and Gowlett (1993), or Holloway Jr (1969).

During the Pleistocene, the overall increase in absolute brain size, an increase in the size of prefrontal (Schoenemann et al. 2005) and parietal (Bruner 2003) cortices relative to the rest of the brain, and possible changes to connectivity patterns (Glasser and Rilling 2008; Ramayya et al. 2010; Rilling et al. 2012) would have affected processes occurring at this problem-solving level. Such processes would include executive functions (Elliott 2003) and working memory (Baddeley 1992), leading to an increase in cognitive control (Stout 2010). Shipton (2013) reports a relationship between absolute brain size and biface refinement over the course of the Acheulean that corresponds with a general trend towards more finely made, increasingly symmetrical artifacts (Wynn 2002). These patterns may correspond to the increasing role of cognitive control during stoneknapping over the course of the Pleistocene after 1.8 million years ago.

Biomechanical Layer

In this heuristic, the lowest level component of stoneknapping a Late Acheulean handaxe involves the removal of a single flake using an aimed knapping gesture. However, "lowest" should not be confused for simplest. As observed by the roboticist Hans Moravec (1988), "it is comparatively easy to make computers exhibit adult level performance on intelligence tests or playing checkers, and difficult or impossible to give them the skills of a one-year-old when it comes to perception and mobility" (p. 15). The evolution of perceptual and motor processes took hundreds of millions of years while higher-cognition has appeared relatively recently.

In this section, I will review the work of Bril and associates (Bril et al. 1996, 2010; Nonaka and Bril 2012; Nonaka et al. 2010; Rein et al. 2013; Roux et al. 1995) in which they analyze the factors involved in the knapping gesture. Their results demonstrate that the performance of the knapping gesture is a complex, dynamic phenomenon.

As noted above, the importance of the ballistic gesture was first noted by the neurologist William Calvin. In a series of articles (Calvin 1983, 1993), he argued that aimed throwing is more challenging than simpler actions such as reaching for an object. During reaching, the agent can correct the action as they perform it. However, during throwing, the action occurs too quickly for a signal to travel from the limb to the spine and brain, then back. The blow had to be precisely calibrated before execution, taking into account a number of factors. Especially when at a distance from raw material sources, here would have been a cost to a misjudged blow for hominid knappers who might render a core unusable.

That this skill is not simple is indicated by the rarity of aimed throwing among modern apes who otherwise demonstrate all of the requisite cognitive capacities necessary to flake stone (Byrne 2004). However, this does not mean that modern apes lack the capacity. When he was being trained to knap flakes in order to access a box for a food reward, the language-trained bonobo (P. paniscus) Kanzi did become adept at removing flakes by aimed throwing of one rock at another (Schick et al. 1999). In fact, it was only after becoming skilled at this technique that he had a "moment of insight" and was able to engage in simple freehand knapping (Savage-Rumbaugh and Fields 2006). Modern apes appear to the capacity for aimed throwing, but do not exhibit it often. This is either due to the lack of ecological motivations or to the relative difficulty of acquiring the skill.

Inspired by the dynamic view of ecological cognition proposed by Gibson (Gibson 1979), Bril and associates have initiated a research program in which they analyzed the differences in how novice, intermediate, and expert knappers in the UK (Bril et al. 2010; Nonaka et al. 2010) and stone beadmakers in Gujurat, India (Bril et al. 1996; Roux et al. 1995) performed knapping gestures. Gibsonian ecological cognition proposes that the mind does not represent the world but instead is immersed in the world. According to this theoretical perspective, the brain, body, and objects form a single dynamic system in direct contact with each other unmediated by a model of the world in the brain.

Using motion-capture, they attended to factors such as the weight of the hammer, the height to which it is raised, the force with which it is driven, the accuracy of the strike, the size of the platform, the size of the flake, the success rate of removal, and the ability to accurately predict the size of the anticipated flake.

Development in the knapping gesture with increasing skill provide an indication of which parameters of the task are technically relevant to the knapper i.e., which features the brain is attending to and, in some way, representing. This is seen in how knappers manage the threshold effect in flake removal (Dibble and Pelcin 1995; Pelcin 1998). A flake will not detach unless a certain loading is reached, but additional force beyond this threshold is unnecessary. In fact, it may lead to negative outcomes like the crushing of platforms, splitting of flakes, etc. There is also a speed/accuracy tradeoff (Fitts 1954). The most skillful, and efficient, gesture in stoneknapping balances tasks parameters to approximate the removal threshold.

In one study, Bril et al. (2010) participants were given two hammers of different sizes, and then asked to reproduce either a larger or a smaller flake presented to them. Participants were novices, intermediates, or experts (20+ years). Interestingly, experts produced the roughly the same level of kinetic energy with both larger and smaller hammerstones. All knappers increased the path length of the strike (increasing potential energy) when using a lighter hammerstone, but novices and intermediates relied on an increase in muscular force to generate adequate kinetic energy. Even though experts removed larger flakes on average, they did not increase force through muscular exertion but instead through strategy of manipulating potential energy. In other words, their actions were more efficient.

Expert knappers are also able to anticipate the size and shape of the flake that they are attempting to remove. Nonaka et al. (2010) had novice, intermediate, and expert knappers draw an anticipated flake with a felt-tip marker before striking a standardized flint core. Experts produced flakes most similar to those anticipated. They also consistently selected platforms with large exterior platform angles adjacent to convexities on the core. As in the earlier study, experts efficiently approximated flake detachment thresholds. In other words, experts considered "higher-order functional relationship among platform variables, intended flake size, and the required kinetic energy determined by these platform variables" (p. 164).

Based on these results, Bril et al. (2010) have proposed a model of 4 sets of components interacting during the performance of the knapping gesture: Functional, control, regulatory, and movement parameters (Figure 4). Functional parameters are not under the control of the knapper but are instead determined by the material properties of stone. These include the kinetic energy required to detach a flake, the angle of the blow, and the point of percussion. Control parameters include velocity and the mass of the hammer, which is modulated by the regulatory parameters of potential energy, muscular effort, and the trajectory of the strike. This in turn is modulated by movement parameters involving the coordination of muscle activity and other kinematic factors.

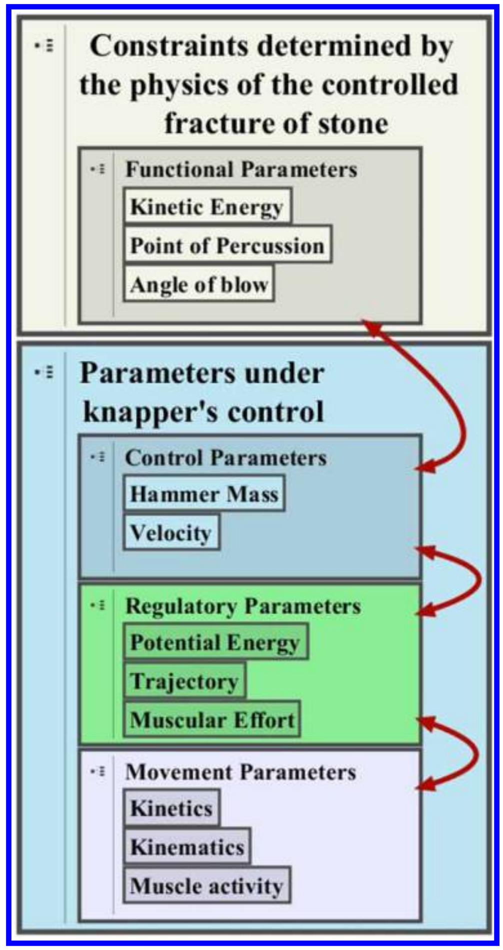

FIGURE 4. Four-parameter model of the knapping gesture. After Bril et al. (2010: 61).

While the knapping gesture may not seem like a complex phenomenon, the development of the skill over time indicates otherwise. As a novice learns to make a stone tool, they are exploring a parameter space containing a theoretically infinite number of combinations of the control, regulatory, and movement parameters. Over time, they identify the areas of this space that optimize the success of a flake removal at or near the removal threshold. Skill can be defined as the efficient performance of the knapping gesture across a wide variety of circumstances. In these studies, expert knappers were defined as skilled artisans with at least 20 years' experience (Roux et al. 1995). This provides some sense of how much experience is required to become skilled at "throwing the ball over the plate."

Sequencing Layer

Since paleoneurologist Ralph Holloway (1969) proposed an homology between stoneknapping and aspects of language including syntax, much attention has been focused on how knappers sequence actions. Holloway compared the design features of language identified by Hockett (1959, 1960) with the manner in which knappers flexibly sequence technical gestures as they work: traditional transmission, productivity, duality of patterning, and arbitrariness. According to Holloway:

> Elements of a basic "vocabulary" of motor operations — flake detachment, rotation, preparation of striking platform, etc. — are used in different combinations to produce dissimilar tools, with different forms, and supposedly, different uses. (p. 55)

Drawing on the work in serial action by psychologists Lashley (Lashley 1951) and Bruner and Bruner (Bruner and Bruner 1968) as well as her own work with apes and children (Greenfield and Savage-Rumbaugh 1993; Johnson-Pynn et al. 1999), Patricia Greenfield (Greenfield 1998, 1991) drew explicit parallels between proposed action grammars in tool use, stages of infant development, and language in humans and non-human primates. She designed a cross-species experiment to test how participants organized a sequence of actions using pots, specifically nesting these pots into each other (Figure 5). Different strategies were used at different ages in humans (11 to 36 months). The youngest children could perform the "pairing strategy" in which they related one active object with one static object (nesting a single pot in a larger pot, for example). Slightly older children used the "pot strategy," by which they related multiple active objects with a static object (nesting an intermediate pot in a larger pot, then placing a third smaller pot within these). The oldest children used a slightly more complex "subassembly" strategy in which two objects are combined as a higher-level unit, and then used a single active unit in relation to a static object (nesting the smallest pot in the medium pot, and then placing them in a larger pot). Non-human primates tested with a similar experiment produced both the pairing and pot strategies, but not the subassembly strategy. However, there may be an issue with ecological validity in this experiment. When manipulating wild foods gorillas and chimpanzees do seem to use sequences with a subassembly structure (Byrne and Russon 1998; Stokes and Byrne 2001). As with aimed throwing, comparisons between modern apes and *H. sapiens* tend to be a matter of degree, not kind.

Both pairing and pot strategies related the objects together using a chain-like series of actions while the later developing subassembly method presumably requires an organizational process capable of managing a higher-level combined unit. Such a structure mirrors the phrase

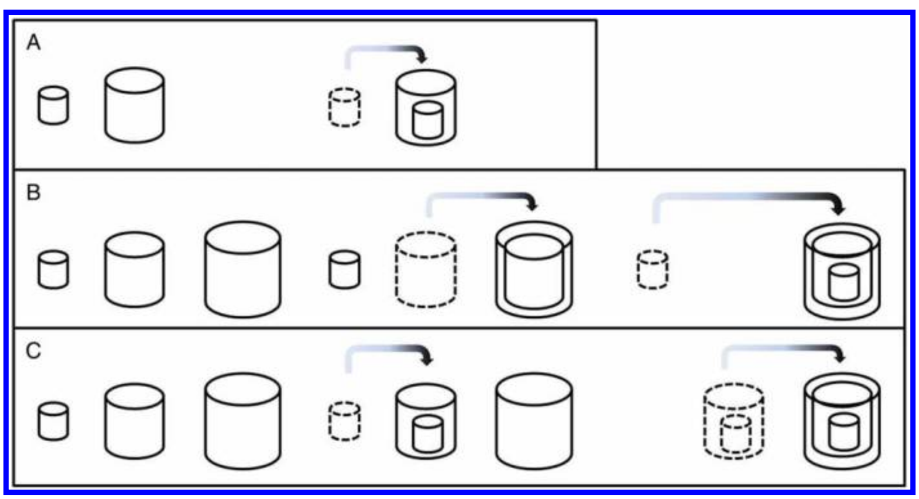

Figure 5. Greenfield's nesting strategies. (A) Pairing strategy. (B) Pot strategy. (C) Sub-assembly strategy. After Greenfield (1991: 532).

structure of language, suggesting that the proposed action grammars are homologous with processes in language production. In the realm of cognitive lithic analysis, Holloway and Greenfield's ideas have been influential but there is no consensus regarding the proposed homology. There are theoretical reasons to believe that the surface similarities between sequencing action in stoneknapping and grammar in language may not represent the same underlying processes (Linz 2011; Revesz 1991; Wynn 1991).

Archaeologist Mark Moore (Moore 2010, 2011) has focused on this question, analyzing stoneknapping in terms of the underlying logic or grammar organizing it. This action grammar unfolds in a design space constrained by the functional parameters of stoneknapping:

> "The design space of stoneworking is composed of the leeway available for stoneworkers to successfully articulate motor actions ('gestures') with the physics of stone fracture. Certain stoneworking gestures are irreducible in the sense that they must be done in combination or controlled stone flaking will not occur" (Moore 2011: 703)

According to Moore, stoneknapping is "cellular" in structure. Each cell contains all of the movements — rotation, placement, tilting, striking the stone — required for the removal of a flake. Such a cell is termed a basic flake unit and it is performed to remove a flake. Many lithic technologies require the removal of a series of anticipatory flakes to prepare an optimal platform and core morphology for the eventual removal of the objective flake. A cell concatenating both anticipatory and objective flake units is a complex flake unit. Finally, knappers often also rub or grind platforms with a stone percussor to further alter the platform to improve control over the fracture. Cells containing anticipatory flake units, grinding, and an objective flake unit are referred to as an elaborated flake unit.

The basic flake unit could be produced by the following algorithm (Moore 2010, 23):

identify high mass → apply the flake

These algorithms can be concatenated into long chains, producing sequences (Moore 2010, 23):

(identify high mass → apply the flake) →(identify high mass → apply the flake) →

(identify high mass → apply the flake) →(identify high mass → apply the flake)…

As described by Moore, the basic flake unit has the same structure as Greenfield's pairing strategy while the concatenated string has the structure of the pot strategy. The subassembly strategy is not needed to make a tool like an Acheulean biface. These concatenated chains can be assembled into seven "tricks" or strategies to achieve simple solutions to problems that emerge during stoneknapping. For instance, if the knapper is attempting to create a continuous edge in a slightly rounded stone she will take advantage of the simple properties of controlled stone fracture. When a flake is removed from an area of high mass, it leaves a concave scar that terminates in a slightly raised edge on its perimeter. This ridge provides an optimal location for the removal of two additional flakes on either side of the initial scar that repeat this advantageous morphology. By simply taking advantage of these scars and ridges, a knapper can reduce an area of high mass and create a continuous edge centered in the overall mass of the stone.

For Moore, the stringing together of flake units into a series of simple strategies indicates a lack of cognitive control over the process. Knapping both Oldowan flake tools and Acheulean bifaces only requires a "mindless algorithm" utilizing the simple mapping of stimulus (perception of the core) onto response (evoked action). While more complicated, hierarchically organized systems may have been capable of producing Acheulean bifaces, he argues that it is more parsimonious to assume that his model approximates the actual process at work. It is only later in time that archaeologists have the epistemological security to assume a more complicated cognitive architecture.

While Moore's model appeals to good archaeological practice in terms of Isaac's (1989) "method of residuals," it oversimplifies the cognitive requirements of stoneknapping by using terms that render complex processes unrealistically shallow. Bril and colleagues' research indicates that "*identify mass*" and "*applying the flake*" are relatively complex perceptual and motor skills already. Why it is true that experts do not require effortful thought to perform a skill, it is also true that most skills require a period of effortful thought and experimentation (Haier et al. 1992; Jenkins et al. 1994; Raichle et al. 1994; Seitz et al. 1990).

Problem-Solving/Cognitive Control Layer

What aspects of a making a stone tool is similar to the structure that is apparent when we watch a pitcher at work in a baseball game? According to Thomas Wynn and John Gowlett, imposed form is apparent in particular types of artifacts appearing after 1.8 million years ago in the Acheulean technocomplex. This would require the organization of lower level actions into a higher-level recipe. The earlier Oldowan technologies were the equivalent of eating an apple. It has to be pulled down from a tree and perhaps a little bit of work would go into preparing it (cutting a portion eaten by worms, for example), but it is a fairly direct and simple technology. Making a Late Acheulean handaxe is more like baking an apple pie. The knapper has to collect together a wider range of resources and deploy them following a particular recipe (Rugg 2011).

This claim remains controversial in archaeology. Starting from a healthy skeptical empiricism, Davidson (Davidson 2002; Davidson et al. 1989; Noble and Davidson 1996) argues that this represents the "finished artifact fallacy." Typically, it is naïve to assume that a recovered artifact represents the fossilized intentions of the people that made and used it. Davidson argues that the recurrent forms of handaxes and cleavers in Acheulean assemblages may simply be the byproduct of a simpler process, such as the opportunistic removal of sharp flakes.

However, in the context of Acheulean technology there are fatal weaknesses with this argument. First, it makes little statistical or behavioral sense. There is no apparent reason for hominins to consistently abandon cores when they achieved the range of forms associated with handaxes and cleavers. It surely would have been possible to remove additional flakes, so why abandon them at that stage? In Toth's (1985) classic replication study of the Oldowan, he found that opportunistic debitage on a cobble blank produces chopper and polyhedral forms. A similar approach with flake blanks resulted in the production of discoidal forms. Proto-facial forms only emerged rarely. This study implies that opportunistic debitage should not produce the artifact distributions seen in Acheulean assemblages. Finally, flakes appear to be removed in patterns that indicate intentional artifact shaping (Shipton 2013; Wynn 1989). The conclusion that these artifacts represent imposed form related to a specific, if wide, range of functions is simply a more parsimonious explanation of these patterns.

Acheulean tools are of particular importance to archaeologists in what they can tell us about how hominids integrated operational schemes and technological concepts into pragmatic projects. Compared with unretouched stone flakes, bifacially worked Acheulean tools are easier to hold and use while butchering a carcass (Jones 1980, 1981) and they retain their working edges longer (Machin et al. 2007; Toth and Schick 2009). Furthermore, edges can be easily resharpened. There has been little cognitive analysis of the functional organization of shaped tools. It may represent the solution to multiple practical problems faced by early hominids, so it may provide some information about their problem-solving capacities concerning foraging.

A number of studies have analyzed an interesting morphological property of Acheulean tools, in particular handaxes. They are remarkably symmetrical, with both planform and cross-sectional symmetry increasing through time (McNabb et al. 2004; Saragusti et al. 1998; Wynn 1979). While handaxe form and refinement is influenced by the effects of raw material (Jones 1979), it appears that symmetry was intentionally selected for across widely distributed Acheulean assemblages (Lycett 2008). Patterns of flake removal in widely separated assemblages also suggest that the imposition of symmetrical form was intentional (Shipton 2013; Wynn 1989).

Comparing Oldowan and Acheulean tools, Wynn (1989, 2002) has analyzed artifact symmetry in terms of spatial cognition. Based in (Piagetian) developmental psychology, the notion of spatial cognition refers to both how object volumes are conceptualized as well as how actions are organized within this spatial framework. As the source of usable flakes, the knapping of Oldowan cores was organized simply along the edge. Knappers utilized natural platforms or platforms created by past removals, but they did not intentionally modify platforms. Removals were placed near each other, sometimes ordered so that their proximity and separation maintained flakeable geometries. The volume of the stone was conceptualized in terms of the flakeable edge, neglecting relationships between these edges and the rest of the stone.

The bilateral symmetry of handaxes or directional asymmetry of cleavers requires the ability to relate the part of the blank the knapper is working on to the overall geometry of the object. In other words, symmetry will only be approximated if the results of a removal of mass on one side mirror the profile of the other side of the object. In a sense, the knapper is taking a "step back" from the edge perceptually, observing its relationship with the rest of the piece. The knapper can then use these part-whole relationship to choose between the alternative courses of action available to them.

Gowlett has provided some additional evidence from Kariandusi, Kenya (approximately 1 million years ago) about how Acheulean knappers were able to manage these relationships at multiple levels (Crompton and Gowlett 1993). Morphometric analyses of the different regions of the handaxe — the butt, the edges, the tip — display different allometric trends as artifacts increase in size. Gowlett argues that the results of a principle components analysis define units of the tools that correspond both to the underlying volumetric technological concept as well as the factors that guide the operational scheme (Figure 6) (Gowlett 2006). These components include the butt, which centers the mass and provides a grip. The forward extension of the handaxe provides a support for working edges. Small changes to lateral extension and thickness help the knapper allows for the alteration of the angles of working edges.

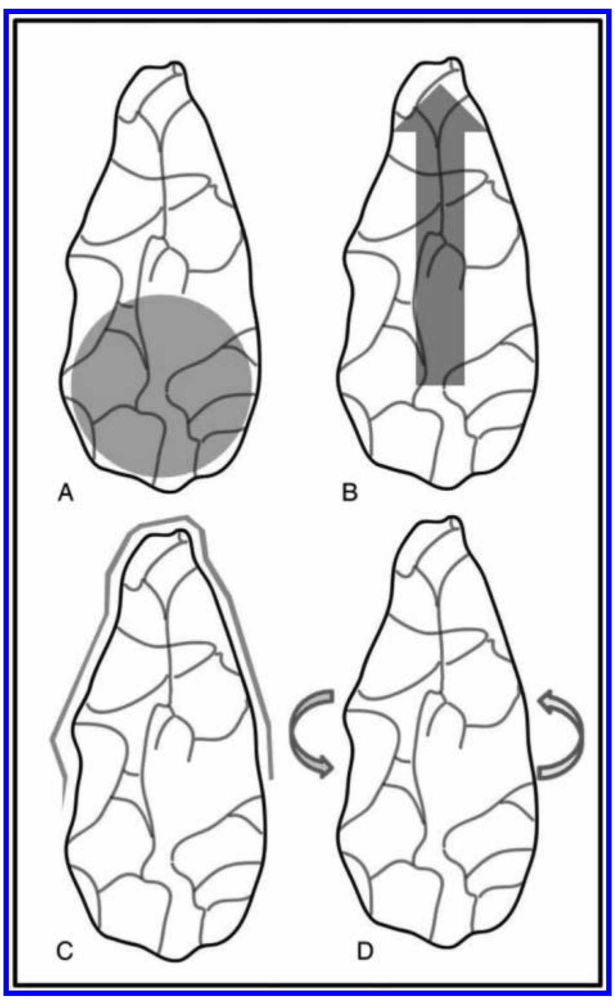

FIGURE 6. Gowlett's variables of handaxe volume managed by the knapper. (A) Globular butt. (B) Forward Extension. (C) Support for working edges. (D) Lateral shift. After Gowlett (2006: 8).

Decisions about how to distribute actions across the core have to take account of tradeoffs between thickness and breadth on the one hand and overall weight on the other. As handaxes get larger, they get relatively thinner and the forward extension and edges increase in size at a greater rate than the rest of the artifact. Balancing these variables, as well as the necessity to maintain three-dimensional part-whole relations is a challenging skill. Partially to simplify these multivariate relationships, Acheulean tools are organized along two planes (Roche 2005).

An analogy of another technology may provide additional insights into the problem-solving layer. Cognitive anthropologists Keller and Keller's (1996) spent two decades studying how blacksmiths become skilled. Blacksmiths are faced with a project, such as making a scrolled piece of wrought iron. To achieve this goal, smiths assemble techniques, tools, and facilities to form a "constellation" that "enables action with reproductive and transformative potential for the constellation itself, for the materials at issue, and for the umbrella plan and stock of knowledge form which the constellation is derived" (p. 23). An umbrella plan "defines a goal for production, and further, of a construct for that is in essence both mental and material and enables the enactment of the plan" (p. 23).This concept of an umbrella plan is essentially a cultural recipe adapted to the materials and context in which the smith is working. The blacksmith adjusts portion of the umbrella plan flexibly, altering techniques and tools as necessary.

The evocative analogies of "constellations" and "umbrellas" highlight the fact that the process of making a piece of wrought iron or a large bifacial stone tool is dynamic. Unforeseen events may emerge during performance that may require reconceptualization of the task and modification of intent.

Keller and Keller themselves do not engage deeply with the conceptual world of the cognitive sciences and concepts such as memory, concepts, information, etc. However, Wynn (1993) has attempted to map their analogies onto cognitive mechanisms. A constellation is a plan of action. Plans of action can either proceed by trial and error, with an artisan working until reaching a dead end and then backtracking and trying again. Alternatively, the artisan can simulate a course of action and its probable consequences in thought. Doing so requires reversibility, defined by Wynn as "a characteristic of thinking used in contingency planning, where failures are anticipated and alternative procedures prepared for ahead of time" (p. 400). Reversibility and contingency planning require higher-level cognition in the same way that the pitcher does when attempting to strike out a batter or a baker does when faced with missing or atypical ingredients. Of course, the concepts of a plan of action or constellation are homologous with the ideas of the operational scheme and the cultural recipe.

To make an Acheulean tool, especially a Late Acheulean tool, requires that a knapper be able to guide a dynamic, multivariate process in order to realize the project. They need to have the cognitive resources to manage technological concepts of volume and operational schemes of action distributed across that changing volume in relation to constraints on time, resources, and skill. While much of this process is procedural and non-verbal, it certainly is not mindless.

Neuroimaging Studies

"Changing gears," linking these three cognitive layers to functional anatomy and neurophysiology is the next step in understanding the cognitive foundations of stoneknapping. Functional brain imaging present participants with a systematically varying task to determine how cognition is actually instantiated in the brain. Typically, the task represents the concrete operationalization of a theoretical entity like "executive functions" or "working-memory." Replicative studies in neuroarchaeology, the study of the neurological systems involved in archaeologically documented behaviors (Malafouris 2009), are structured somewhat differently. They take a real-world task, determine which region of the brain are involved in it, then attempt to link these activated networks with well-known tasks and hypothetical cognitive processes. Ultimately, it represents the same pattern of analogical reasoning present in most archaeological inferences (Wylie 2002).

In a small but growing number of studies, Wynn's three-layers are being functionally mapped onto the brain of modern people. All of these studies have focused on the contrast between Oldowan and Late Acheulean technologies in an attempt to understand what they can tell us about trends in cognitive evolution during the Pleistocene. They indicate that Oldowan technology activates a network of areas especially in the left hemisphere (all knappers were right handed) (Stout et al. 2000). Acheulean technologies activate these regions as well as more extensive areas in the right hemisphere (Stout et al. 2008). As in the example of the pitching machine above, it is necessary to "build" additional capacities onto the system in order to knap a Late Acheulean tool.

Stout and his collaborators have presented a model of stoneknapping in several publications based on results from a series of positron emission tomography (PET) and functional Magnetic Resonance Imaging (fMRI) studies (Figure 7) (Faisal et al. 2010; Stout and Chaminade 2007, 2009; Stout et al. 2000, 2008, 2011;). At the biomechanical layer, the knapper synthesizes an "internal model" of the space and objects relevant to the project that they are engaged in. These include the transformation of visual information (V1) into a spatial framework defined in relation to the performance of action. This occurs in the higher-level visual areas and the posterior parietal lobe (A1, S1, PTC, IPS). This model is further enriched with auditory, tactile, proprioceptive (sense of the body in an egocentric, bodily defined-space), and even possibly nocioreceptive (pain) information the anterior intraparietal sulcus

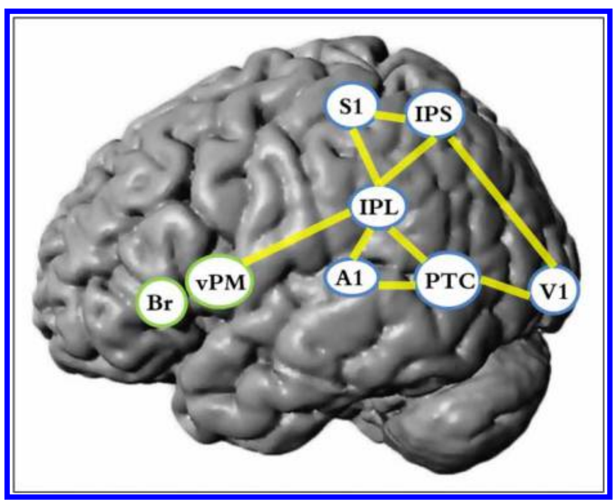

Figure 7. Regions of the brain involved in stoneknapping as identified by Stout and colleagues. Left hemisphere pictured. A1 Auditory, Br Broca's Area, IPL interparietal lobule, IPS interparietal sulcus, PTC posterior temporal cortex, S1 somatosensory, V1 primary visual cortex, vPM ventral premotor cortex. After Stout and Chaminade (2012: 77).

(IPS). Finally, there is an integration of this changing model and performed actions over time in the right inferior parietal (IPL).

The sequencing layer involves the left inferior premotor cortex. This region is involved in the planning of either simple or over-learned actions. It would be expected that novel or morefr complex actions would activate areas of the left inferior frontal cortex, Broca's area (Br). It may be that action sequencing in Acheulean knapping may be less complex than that seen in modern language. It should be noted that the left premotor (vPM) does play a role in grammar, particularly of simpler sentence structures. A Transcranial Doppler study performed by Uomini and Meyer (2013) found a similar pattern in blood flow between in Acheulean replication and language use.

The previous areas are active during Oldowan replication. The right inferior frontal (Broca's area homologue) (Br) is activated during only during Acheulean replication. Stout et al. (2008) have hypothesized that this is analogous with the role that the region plays in the discursive level of language. To engage with someone in conversation or tell a story, both the speaker and listener must be able to maintain information across sentences. Similarly, in stoneknapping the knapper must be able to track how past, current, and possible future actions relate to one another in the performance of a cultural recipe.

Stout's work has made extensive use of contemporary hierarchical models of brain function (Badre 2008; Badre and D'Esposito 2009; Koechlin and Jubault 2006; Koechlin and Summerfield 2007). In fact, Stout hypothesizes that the shift from simpler to more complex lithic technologies indicates an increase in the cognitive control of the behavior (Stout 2010) (Figure 2). This implies top-down activation of the problem-solving layer influencing decisions about which lower level chunks of action to deploy in a manner consistent with the overall project.

In Stout et al.'s (2011) study of the social learning dimension of stoneknapping, this dynamic aspect was on display as well as the involvement of additional regions not seen in earlier studies. Novices with no knapping experience, trained novices, and expert knappers all watched videos of knapper at work. Naïve subjects were unfamiliar with the task, but they had a familiarity with the motor primitives that it was constructed from. Their brains showed unique activations in the left inferior frontal cortex, or Broca's area (Br), in a pattern of activity associated with mirror neurons. Mirror neurons are active when a person is performing an action or when they observe someone else performing the same action. This creates a "motor resonance" circuit allowing novices to map novel observed actions onto representations of actions they already have encoded, providing scaffolding for imitation. Trained novices, on the other hand, showed unique activations in the frontal eye fields associated with sustained attention. Experts, on the other hand, exhibited activations in the right inferior frontal, medial frontal, and anterior parietal cortices. These areas are involved in aspects of social cognition, primarily inferences about the intent of another person as they perform an action. Motor resonance, attention, and social inference are all complex metaprocesses involving the dynamic interplay of top-down and bottom-up processes.

Outside of social learning, the rich dynamics of cognition during knapping are not well understood. Most neuroimaging techniques have excellent spatial resolution, but poor temporal resolution. Near Infrared Imaging (NII) and Transcranial Doppler (TCD) have better temporal resolution, but lose spatial resolution. Electroencephalography (EEG) can make even finer temporal distinctions, but has poor spatial localization unless paired with other techniques. Future studies acquiring information about how the brain acts in real time would enrich and clarify our increasingly sophisticated model of the cognitive foundations of stoneknapping.

Conclusion: The Ultimate Goal of the Cognitive Analysis of Stoneknapping

Evolutionary cognitive archaeology is in need of a general theoretical framework with which to approach lithic technology. It is fortunate that the needed tools are at hand. The *chaîne opératoire* approach provides a number of rich conceptual tools for describing and analyzing one aspect of cognition; technical knowledge. These concepts were briefly reviewed earlier. Wynn's Three-Layer Heuristic provides a simple, useful organizing scheme for the results of past and future studies. Its primary usefulness is the reminder that what occurs at one level or domain of the neurocognitive system is not independent of the other levels or domains. If these tools are available, one might ask what is new about this paper. What I am arguing for is self-consciousness in the use of these resources.

Of the studies that reviewed, there are conflicting theoretical perspectives that would radically affect our understanding of the results. Both Moore and the researchers working with Bril assume that the Acheulean stoneknappers were not guided by mental representations as they made tools. However, they do so for very different reasons. Moore assumes that it is simpler to assume that a "mindless algorithm" made these artifacts. Bril and colleagues follow Gibsonian ecological cognition, which argues that the world "represents itself" to the agent who has certain faculties by which to perceive it. From this perspective, the brain is not like a computer taking in information, processing it, and spitting out a result. Instead it forms a single, dynamic system with objects. These perspectives stand in stark contrast to the work of Wynn and Gowlett, who interpret their results to indicate that the knapper has a "mental template" in mind that they intentionally impose on the stone as they work. Obviously, these perspectives conflict with one another. How can a system be mindless and mindful at the same time? Does this apparent conflict arise do to description at different levels? Alternatively, is it attributable to a myopic focus on one aspect to the problem?

But how do cognitive archaeologists begin to use this tension to generate productive hypotheses that move the ECA forward? I suggest that a general theoretical framework such as that proposed in this paper may help. Currently, research at different levels is occurring in isolation. However, if hypotheses examining different aspects (knowledge vs. neurocognitive systems) or levels (biomechanical, sequential, or decision-making) are being formulated with other aspects and the levels in mind, they should gain in explanatory power and productivity.

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