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RESEARCH ARTICLE

Modularity and Recombination in Technological Evolution

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Abstract Cultural evolutionists typically emphasize the informational aspect of social transmission, that of the learning, stabilizing, and transformation of mental representations along cultural lineages. Social transmission also depends on the production of public displays such as utterances, behaviors, and artifacts, as these displays are what social learners learn from. However, the generative processes involved in the production of public displays are usually abstracted away in both theoretical assessments and formal models. The aim of this paper is to complement the informational view with a generative dimension, emphasizing how the production of public displays both enable and constrain the production of modular cultural recipes through the process of innovation by recombination. In order to avoid a circular understanding of cultural recombination and cultural modularity, we need to take seriously the nature and structure of the generative processes involved in the maintenance of cultural traditions. A preliminary analysis of what recombination and modularity consist of is offered. It is shown how the study of recombination and modularity depends on a finer understanding of the generative processes involved in the production phase of social transmission. Finally, it is argued that the recombination process depends on the inventive production of an interface between modules and the complex recipes in which they figure, and that such interfaces are the direct result of the generative processes involved in the production of these recipes. The analysis is supported by the case study of the transition from the Oldowan to the Early Acheulean flake detachment techniques.

Keywords Cultural evolution · Recombination · Modularity · Innovation · Stone-tool technology

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1 Introduction

A central mechanism involved in the generation of cultural variation, and one often described as humans' special ability to produce cumulative culture, is that of cultural recombination (or "combination"; Basalla 1988; Enquist et al. 2011; Lewis and Laland 2012; Mesoudi 2011; Mesoudi and O'Brien 2008). The recombination process can be understood as the bringing together of existing cultural traditions or of existing cultural traditions' sub-components into novel, complex cultural composites. Central to the mechanism of recombination is the capacity for cultural traditions to possess modular structures. Indeed, as the recombination process can decompose old cultural traditions and recompose them into new ones, the recombined sub-components must be relatively independent of the traditions of which they are part.

Most work on cultural recombination and cultural modularity consists of simulations and models exploring their evolutionary impacts on cultural traditions (e.g., Enquist et al. 2011; Lewis and Laland 2012; Mesoudi and O'Brien 2008). There are also some more general discussions of cultural modularity to be found in the cultural evolutionary literature (e.g., Mesoudi 2011; Mesoudi and O'Brien 2008; Mesoudi et al. 2006; O'Brien et al. 2010; Reader 2006; Wimsatt 2006, 2013). These discussions generally offer some intuitive examples illustrating the recombination process and modular cultural traits. The Swiss army knife is one example that comes to mind (Mesoudi 2011). We are told that this tool is modular because it is the result of a combination of previously existing technologies, such as knives, screwdrivers, and saws. However, examples such as this one offer no real explanations of what a cultural module consists of, how it works, and how to identify one in an empirical system. For instance, we are not told why knives and saws could be recombined into novel technologies in the first place. Merely specifying that modules are combined together leaves unaddressed just how this is done.

Moreover, it is unclear what the innovative process of joining modules into novel, functional traditions amounts to. While formal models typically assume that modules just naturally fit with one another, this assumption is far from being obvious. For instance, the Swiss army knife is not just the combination of blades, saws, and screwdrivers. The component tools are combined into a single pocket size tool, a process that involves the miniaturization of the components and the designing of a system to pack and unpack them in a functional way. A theory of cultural recombination and modularity should thus offer us an understanding of the functional interfaces the recombination process creates so that modules can be articulated together into new meaningful, functional traditions. Leaving these questions unanswered leads to the circular conclusion that cultural modules are the units of recombination, and that recombination deals with cultural modules.

Cultural evolutionists typically emphasize the informational aspect of social transmission, i.e., the learning, stabilization, and transformation of mental representations along cultural lineages. But mental representations also need to be expressed publicly—e.g., through utterances, actions, and/or tools—so that they are accessible for learning by others (Charbonneau 2015a; Sperber 2006). These public representations are material entities, be they sound waves, observable behaviors, or actual physical objects. This implies that individuals need to know how to publicly produce such displays and do so in the right way if learners are to grasp what must be learned. An informational approach, concerned primarily with the acquisition of mental representations from public displays, is a necessary part of a theory of cultural evolution. However, it is insufficient. The inescapable material and generative dimensions of social transmission must also be seriously addressed for cultural evolutionary theory to serve as a successful research program of the workings of cultural change, diversity, and persistence.

In this paper, it is argued that the study of innovation through recombination and its complementary notion of cultural modularity both depend on a deeper understanding of the generative processes involved in social transmission. More specifically, the hierarchical and functional structures of these generative processes play a key role in structuring modular cultural traditions. A strictly informational account is bound to fail to make sense of the recombination process and of modular traditions because both phenomena depend on the capacity of an individual to enact, alter, and learn how to produce public displays. In continuity with existing work on cultural modularity, especially Mesoudi and O'Brien (2008), this paper develops the concepts of recombination and of cultural modularity by grounding them in terms of the operations and structural properties of cultural recipes. The argument is supported with the case study of the transition between the simple flaking technique characteristic of the Oldowan industry and the more complex ones of the Early Acheulean (Stout 2011; Moore 2007, 2010), a paradigmatic cultural module, and arguably the oldest one.

2 A Black-box in Cultural Evolutionary Theory

2.1 The Structure of Social Transmission

Social transmission is at the core of cultural evolutionary theory (Boyd and Richerson 1985; Cavalli-Sforza and Feldman 1981; Claidière et al. 2014; Claidière and Sperber 2010; Durham 1991; Heintz and Claidière 2015; Mesoudi 2011; Mesoudi et al. 2006; Morin 2016; Sperber 1996, 2006; Richerson and Boyd 2005) and it is also a complex process (Charbonneau 2015a; Hoppitt and Laland 2013; Sperber 2006). Social transmission is central for cultural evolutionists because it is one of the key mechanisms participating in the maintenance and diffusion of cultural traditions, i.e., the reproduction of chains of similar mental representations and similar public displays.[1] The key insight of an evolutionary approach to cultural change is the adoption of a population-level perspective on the effects of the social transmission of *variant cultural information* (Richerson and Boyd 2005; Claidière et al. 2014). Cultural evolutionists study how variation in socially transmitted information leads to variation in social traditions and how cultural traditions are sustained, transformed, and diffused through and among populations, from one generation to the next.

Social transmission can minimally be understood as a two-step process. First, one produces some public display (an utterance, a behavior, and/or a tool) from some

[1] Mechanisms other than social transmission participate in maintaining traditions, such as a rich shared learning environment (Sterelny 2012), common cognitive biases (Sperber and Hirschfeld 2004), and motivational factors (Morin 2016), to name a few.

mental representation. For instance, knowing a recipe for the production of an adhesive from a set of ingredients and operations on these ingredients, you go on to produce such an adhesive. Whereas others may not directly access your knowledge of the adhesive recipe, by enacting the recipe and producing it effectively, your private knowledge now becomes publicly available as others can observe you producing the adhesive. This knowledge can be expressed differently, for instance by giving instructions on how to produce the adhesive. Yet again, the public display (in the latter case, the linguistic production of instructions) remains an overt expression of private knowledge. The second step consists of another individual perceiving and acquiring from the public display (or multiple instances of the public display) its very own private mental representation of the adhesive recipe. In future instances, the social learner will be able to reproduce the recipe (or explain it, or both), which in turn will make it publicly available for another person to learn, thus sustaining a tradition of adhesive making. These two steps are referred to here as production and acquisition, respectively (see Fig. 1).

2.2 The Production Phase as a Generative Process

Whereas the acquisition phase of social transmission concerns how individuals learn from public displays, the production phase consists of the means individuals employ to generate public displays from socially acquired mental representations. Cultural evolutionists typically focus their work on the cognitive, demographic, and environmental processes involved in the acquisition phase of social transmission, thus concentrating their research efforts on the informational content, the learning biases, the channels of transmission, and the networks of social learning. For instance, when investigating the possible patterning of cultural evolution, many emphasize the importance of the structure of the channels of transmission and the different biases in selecting which available cultural variants individuals will learn (e.g., Boyd and Richerson 1985; Richerson and Boyd 2005). Others investigate how the cognitive mechanisms and reconstructive biases involved in social learning induce ampliative, corrective, and transformative changes and how these shape cultural traditions (e.g., Boyer 1999; Griffiths et al. 2008; Sperber and Hirschfeld 2004).

In contrast to the acquisition phase of social transmission, the production phase is generally left unaddressed by cultural evolutionists. The production phase of social

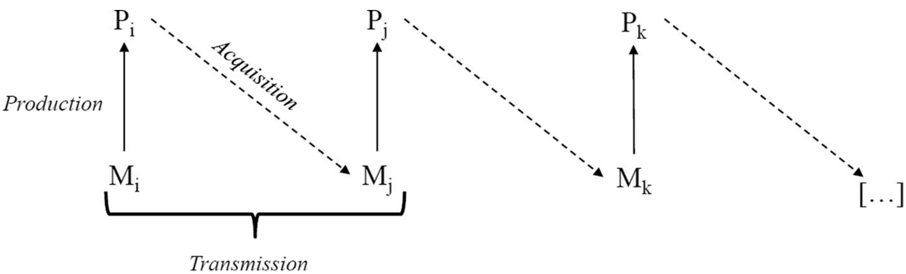

Fig. 1 Social transmission as a multistep process. A demonstrator's mental representation M_x is used to produce (production) some public display P_x (e.g., utterances, behaviors, tools, etc.). For a tradition to be perpetuated, the learner acquires a similar mental representation M_{x+1} by observing the demonstrator's public display P_x and so on and so forth

transmission consists of the generative processes involved in the production of some public display. These processes link the information encoded into an individual's brain to the relevant information contained in the public displays. Given that there are many ways to encode such information—for instance, through linguistic expressions, behavioral performances, or even through the actual production of a tool—we should expect some variability in the specific generative processes employed to produce different kinds of public displays. The production of utterances from mental representations will not exploit the same cognitive, bodily, and material processes as those exploited by the production of a stone tool or of a dancing routine. Following Charbonneau (2015a), we can broadly identify four sets of mechanisms and factors involved in the production of public displays:

(1) the cognitive processes and biases participating in the generation of public displays from mental representations (e.g., decision-making processes, mental imagery, motor control, etc.);
(2) the external actions recruited in the production of the public displays (e.g., locomotion, prehension, manipulation, pronunciation, etc.), including the affordances and constraints set by the particular body of the demonstrator (e.g., opposable thumb, flexibility, dexterity, body size and mass, etc.);
(3) the specific tools and materials used to produce the public displays (if any);
(4) the ecological processes engaged in the production of the public displays (e.g., chemical reactions, percussion effects, sound-wave propagation, etc.).

These factors relate to the generative processes involved in the production of a public display. This means that they impose constraints on what sorts of public displays are producible and which ones are not. Indeed, not every imaginable cultural trait is producible. Our cognitive capacities, body shapes, and the nature of the material world will constrain which public displays can and cannot be produced and thus which traditions are possible and which ones are not. However, these factors do not give us an understanding of how the generative processes insure the repetition of stable cultural traditions. The generative processes need to be structured in the right way for a tradition to be perpetuated from one generation to the next. It is thus imperative that cultural evolutionists integrate an understanding of the generative processes involved in the production of public displays for a fuller, richer theory of cultural change.

3 The Structure of Cultural Generative Processes

As mental representations need to be expressed publicly if they are to be transmitted, the production of public displays encompasses both cognitive and behavioral processes. Paleoarcheologists have studied the structure of the generative processes involved in the production of stone tools through the analytical frameworks of *chaînes opératoires* (Inizan et al. 1999; Schlanger 2005; Soressi and Geneste 2011) and of *cultural recipes* (Mesoudi and O'Brien 2008, 2009; Lyman and O'Brien 2003; Neff 1992; O'Brien et al. 2010; Pelegrin 1990, 1993; Stout 2011), i.e., the list of materials, actions, and instructions to be followed in order to produce and maintain some tool. Some archeology-minded cultural evolutionists have adopted and generalized the recipe construct to serve as a general characterization of the steps involved in producing some tool. Unfortunately, exactly what the notion of cultural recipe refers to varies from one account to the other. In some cases, it refers to the causal sequence of the production of complex cultural traits (e.g., Mesoudi and O'Brien 2009). In others, cultural recipes are the set of transmissible instructions contained in the mental representations (e.g., Charbonneau 2015a; Mesoudi and O'Brien 2008; O'Brien et al. 2010). Finally, sometimes it refers to both the instructions and the actual production of the public display (Charbonneau 2015b; Lyman and O'Brien 2003). Here, the concept of cultural recipe is used to refer to the actual generative processes constituting the enactment of instructions towards an intended end result, i.e., a public display, whether it is a tool or not. For convenience of discussion, it is assumed that the structure of the generative processes leading to the production of a public display is represented in the set of instructions contained in the relevant mental representations.

A cultural recipe is understood here as the hierarchically organized set of actions and decisions leading to the satisfaction of a specific, intended goal.[2] In this sense, recipes are the means to an end. The hierarchical structure of recipes can be decomposed into assemblies of actions serving some subgoal that must be satisfied on the road to the intended end product. A subgoal consists of a measure of what conditions needs to be satisfied and what to do next if the conditions are perceived as being satisfied (but also what to do when they are not). These subgoals can also be nested as intermediary steps in the realization of some other subgoals, thus generating a potentially complex structure of dependencies between action and decision assemblies. Ultimately, all subgoals are ruled by a single master goal, that of the final intended end result of the recipe. The hierarchical structure of recipes is a functional structure, one typically depicted as a tree-like structure (as in Fig. 2) (e.g., Mesoudi and O'Brien 2008).

Consider, for instance, the very simple recipe of cracking an egg. There are two action components and one decision here: action 1—hit the egg on the side of the bowl, action 2—empty the egg's yolk into the bowl, and decision—Do action 1 until egg is cracked, then do action 2 until egg yolk is in bowl. This is a very simple recipe. Obviously, we could identify an even deeper structure if we are interested in including all the actual manipulations involved (e.g., grab the egg, hold the bowl, reach opposite side of cracked egg to open, pull in opposite direction to empty content, etc.) or a more precise degree of cognitive decisions (e.g., identify an egg object, orient hand to grab egg, identify bowl, etc.) and states satisfying these decisions. This can go down a long way until we identify some basic action units and their related decision-structure, assuming of course we agree on how to go downwards and where to stop.[3]

[2] There is a vast scientific literature concerned with the structure of behaviors. One general point of consensus among cognitive psychologists, neuroscientists, linguists, paleoarcheologists, anthropologists, primatologists, and artificial intelligence researchers is that behaviors are hierarchically organized (Botvinick 2008; Byrne 2003; Byrne and Russon 1998; Chomsky 1957; Greenfield 1991; Guerra-Filho and Aloimonos 2012; Lashley 1951; Mesoudi and Whiten 2004; Miller et al. 1960; Pastra and Aloimonos 2012; Schank and Abelson 1977; Simon 1962; Stout 2011; Whiten 2002). Cultural evolutionists have also noted that complex cultural recipes are hierarchically organized and have studied some of the evolutionary implications of these structures (Enquist et al. 2011; Mesoudi and O'Brien 2008; Mesoudi and Whiten 2004).

[3] Just how we decide what constitutes a basic action unit will not be addressed here in any detail. There has been debates on just what the appropriate level of description is and whether there exists such thing as an atomic action (e.g., Lombard and Haidle 2012; Perreault et al. 2013). For the remainder, we can assume that all agree on the right granularity of description, as what is of interest here is not the proper grain of description for complex behaviors but the implications of their hierarchical structures having different degrees of integration.

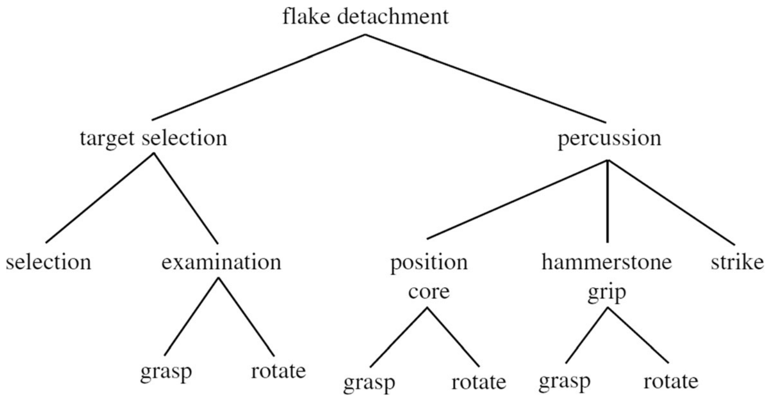

Fig. 2 The hierarchical structure of the basic flaking unit. Flake detachment consists of two main sub-components, that of target selection and that of percussion. Target selection consists in choosing a specific point on a core to hit with a hammerstone. The percussion sub-component consists in positioning the core and appropriately grasping the hammerstone so as to strike the core on its target platform (adapted from Stout 2011, p. 1052)

When enacted successfully, a recipe yields its intended end result. The successful enactment of a recipe thus depends on producing the right changes in the individual's environment so that the recipe's success conditions are met. As mentioned above, the four types of factors identified above will serve as constraints on the space of successfully enactable recipes. The impact of these factors on the functionality of a recipe are discussed in more detail in Section 1.5 below.

Consider the technique for producing Oldowan flakes as a paradigmatic case of a cultural recipe (Fig. 2). Tool assemblages of the Oldowan industry, typically dated from around 2.6 to 1.4 million years ago, mainly consist of detached stone flakes, the cores from which the flakes were removed, and the hammerstones used to strike the cores (de la Torre 2011; Schick and Toth 2006; Fig. 3). The basic knapping technique consists of using a hammerstone in order to hit a core (made of brittle material) on one of its sides (the platform). The intention is to produce a fracture (a conchoidal cone-shaped shock wave) that will detach a flake from the core. The basic flaking technique considered here is one of debitage, i.e., the sharp-edged flakes detached from the core are the intended functional end products, whereas the reduced cores are residual by-products (Inizan et al. 1999; Stout 2011).

Producing Oldowan flakes is a process requiring a certain level of expertise, both in terms of the control of the striking gesture and of a tacit understanding of the material properties of the cores (Delagnes and Roche 2005; Pelegrin 1993; Roux and Bril 2005). This means that for an individual to successfully enact the recipe (i.e., produce a functional flake), she needs to both learn the structure of the recipe and gain sufficient skill to reliably enact the technique. For instance, a strike above 90° of incidence to the platform will fail to produce a functional flake. It also runs the risk of crushing the core and wasting it for further flaking (Pelegrin 2005; Whittaker 1994). Moreover, the blow must be delivered with a strength proportional to the resistance of the core's material (Braun et al. 2009). These cognitive factors (hand-eye coordination, tacit knowledge about the material), ecological factors (type of material, physics of conchoidal fractures) and

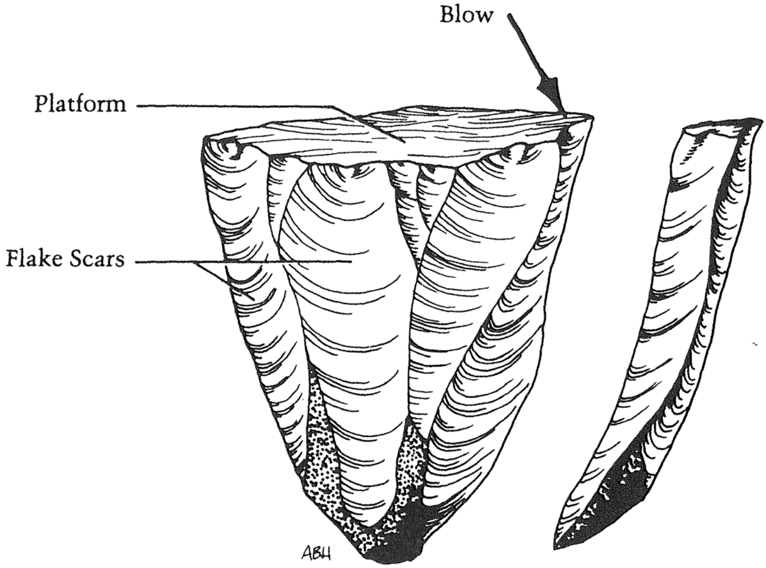

Fig. 3 The core (left) is the piece being stroke on its platform. Striking the core with a hammerstone in order to produce a conchoidal fracture will lead to part of the transversal side under the blow to detach and form a flake (right) (from Whittaker 1994, p. 15)

body factors (strength and hand used for grip) illustrate some of the different processes and constraints that are integral to the generation of lithic flakes through hardhammer percussion. These constraints relate to the production phase of the social transmission process. So for instance, transmitting a flaking recipe with a striking angle above 90° of incidence will fail to produce a functional flake, which will likely result in the abandonment of the recipe by potential learners.

The successful production of Oldowan flakes depends on a hierarchically structured recipe. Following Stout (2011), we can understand such recipe as consisting of two general steps – gathering materials and detaching a flake (Fig. 4a). Of special interest for the present discussion is the basic flaking unit,[4] the subassembly of actions and goals subsumed under the second step (of which Fig. 2 offers a zoomed-in view). The basic flaking unit itself consists of two action subassemblies subsumed under a single decision node: selecting a target platform to strike and the effective percussion of the core, leading to the detachment of a functional, sharp flake. Each subassembly is in turn composed of lower level subgoals and ultimately of specific actions (grasp, rotate, etc.) that will have to be enacted appropriately in order to satisfy the goals under which they fall. If successful, the enactment of the flaking unit will lead to the detachment of a functional, sharp-edged flake. See Stout (2011) and Moore (2007, 2010) for more detailed discussions.

[4] The expression is mine, but it is adapted from Moore (2007, 2010) who also develops a hierarchical description of the recipe's functional structure. However, Moore writes about a "basic flake unit," which suggests a static view, an object. The active form "flaking" is preferred here as it makes it clearer that the unit is a behavioral/cognitive process and not a material end-result.

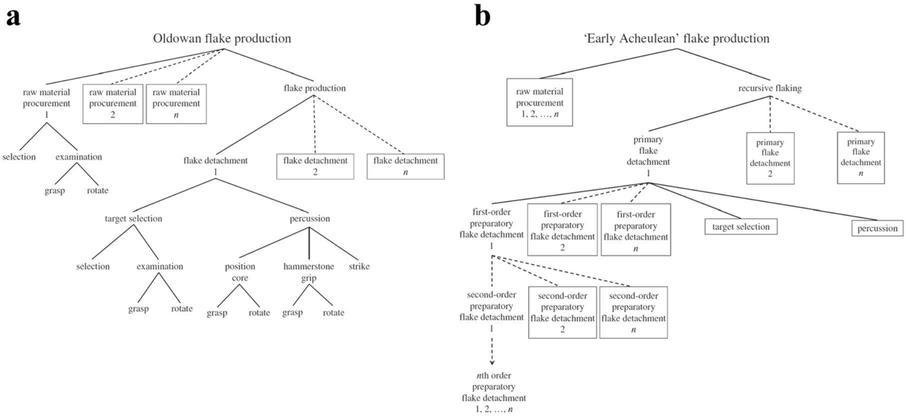

Fig. 4 Lower Paleolithic action hierarchies. Lines connect subordinate elements with the superordinate element they instantiate. *Dashed lines* indicate optional elements, *numbers* indicate duplications of action elements, and *boxes* enclose "collapsed" action chunks whose subordinate elements have been omitted to avoid crowding (from Stout 2011, p. 1052)

4 Innovation by Recombination

With a clearer understanding of what a cultural recipe consists of, we can now turn to the problem of defining the recombination process and, in the next section, cultural modularity. For the remainder of the paper, the discussion will be restricted to the recombination and modularity of complex behaviors, which may or may not result in the production or modification of a tool. Other forms of recombination and modularity are discussed in Section 5 below.

Recombination is the bringing together of existing recipes or of existing recipes' sub-components into novel, complex recipes. Combining together (parts of) two recipes can take many forms. For example, the same sub-component can be duplicated (repeated and reinserted in the original recipe), added to a different recipe, replace a sub-component of another recipe, or two recipes can be joined together under a new master goal (rearticulating to a more or less important degree the hierarchical structures of the two combined recipes), etc. The recombination process thus mainly manipulates the hierarchical structure of complex recipes rather than the specific actions from which the recipes and their sub-components are made of (Charbonneau 2015b; Mesoudi and O'Brien 2008).

A good example of the recombination process can be found in the modification of the Oldowan flake detachment technique into that of the Early Acheulean (Moore 2007, 2010; Stout 2011).[5] The key difference between the Oldowan and Early Acheulean flaking processes is the introduction of a new step, that of detaching preparatory flakes preliminary to the detachment of a final, functional flake, i.e., the Early Acheulean's technique intended end result (Fig. 4). Preparatory flake detachment is an important technical innovation as the knapper first detaches flakes not specifically to use them as tools (although they may accidentally be found to be useful). Rather, preparatory flaking is a process intending to preform the core's morphology so

[5] Although technically the Early Acheulean technique examined here is not a part of the Acheulean industry, it is nevertheless generally considered part of the transition leading to the Acheulean. See Stout (2011) for discussion.

that the knapper can detach a flake with a specific, intended shape—the primary flake. Preparatory detachment is mainly a shaping process—where the shape of the core becomes the intended result and the detached flakes the by-products—whereas primary flake detachment remains, as in the Oldowan technique, a debitage process—the detached flakes are the intended results and the remaining core the by-product (Inizan et al. 1999).

Although introducing a new function—that of shaping a core—the Early Acheulean technique is in fact a recombination of the basic flaking unit with the Oldowan technique. The innovation in the Early Acheulean technique is one where the basic flaking unit is duplicated and inserted under a new function node, that of preparatory flake detachment (Fig. 4b; Stout 2011). Preparatory flaking is composed of the basic flaking unit but with a different intended end result in mind. The duplicated units have been coopted to serve a shaping function (preparatory detachment) instead of the ancestral role of debitage, the latter being retained in the use of the basic flaking unit for primary detachment. Nevertheless, the procedure is basically the same, i.e., flakes are detached through hardhammer percussion on a selected platform. The shaping function is in fact insured through the repetitive use of preparatory flaking allowing the knapper to shape the core until the specific morphology necessary for a controlled, primary flake detachment is reached. Both preparatory and primary flaking are composed of the basic flaking unit.

In addition to serving as a case of recombination, the transition to the Early Acheulean technique also shows the importance of the addition of an interface between the two combined components. Modules are not necessarily pre-organized to fit together in a new functional structure. The recombination process may require the addition of an interface between the combined components. In our case study, the recombination of the basic flaking unit with the Oldowan recipe necessitated the addition of a new subassembly in the basic flaking unit to allow recursive flaking. This is illustrated in Fig. 4b by the additional node preceding the target selection and percussion subassemblies in primary flake detachment. The shaping of a core is not just a sequence of flake detachment on a same core. It is an organized, *conditional* sequence of reduction aiming at shaping the core in a specific, intentional way. This means that each preliminary flake detachment will determine where the next detachment will be done, until the core is ready for the detachment of a functional flake.

The interface introduced in the Early Acheulean technique brings with it the use of different cognitive and material processes, even though the basic way of detaching a flake remains the same – i.e., select target and strike it with a hammerstone. For instance, the knapper must now hold in her working memory a mental image of the desired core shape to guide preparatory flaking (Pelegrin 1993). Moreover, given that there are no two cores with the exact same morphology and material structure, the preparatory flaking subassembly needs to allow some redundancy and recursivity in detachment so as to adapt to the core's idiosyncrasies (and possibly correct knapping mistakes). The new recipe thus also depends on the capacity of the flaker to understand, organize, and produce recursive actions (which was not necessary in the Oldowan technique).[6]

[6] Some argue that the ability to manipulate the complex hierarchical structure of structured behaviors is based on the same neurological substrates used to manipulate linguistic structures (e.g., Greenfield 1991; Stout and Chaminade 2009; Stout et al. 2008).

In contrast, the few formal treatments of the recombination process typically assume that the components being recombined simply sit next to one another without requiring an additional interface to insure the functionality of the novel tradition (e.g., Enquist et al. 2011; Lewis and Laland 2012; Mesoudi and O'Brien 2008). This simplification, however, abstracts away from the necessity imposed by the material nature of cultural traditions to adapt the recombined traits so that they fit together in a complex, functioning recipe. The transition between the Oldowan flake detachment technique and its Early Acheulean derivative demonstrates that the recombination process is not just sequencing old steps next to one another, thus producing a series of independent actions. Recombination also implies a fair amount of addition in order for the recombined elements to be integrated into a coherent whole. This added "interface" makes sure that the modules can be coordinated with one another into a viable, functional recipe.

5 Individuating Cultural Modules of Recombination

The recombination process joins parts of existing recipes together into new recipes. Recombination also depends on the singling out and "detachment" of *coherent* sub-components from their original context. The aim of this section is to characterize more precisely what makes a recipe modular and to offer means to identify modules capable of recombination into novel recipes. Such modules are referred to here as *cultural modules of recombination* (or CMR) so that they can be differentiated from other possible kinds of cultural modules, such as linguistic modules, interchangeable parts in tools, etc. (see Section 5 below).

A CMR is a sub-component of a complex recipe that satisfies three roles. First, the module is a recipe's sub-component possessing a unitary function. Second, the module can maintain its function relatively independently from the rest of the recipe of which it is part. Third, the module can be learned separately from the rest of the complex of which it is part. All three roles—having a unitary function, being functionally integrated, and being separately learnable—depend on the cognitive and material nature of the generative processes. This is true because they characterize sub-components of cultural recipes. For instance, the fact that a sub-component of a recipe possesses a function at all relies on the structure of the production procedure and its interactions with the cognitive capacities and body of the individual producing a public display, in addition to the environment in which it is produced. In this minimal sense, generative processes play a major role in shaping CMRs since the recipes are themselves constitutive of the production phase of social transmission. However, the case made here is stronger. It is argued that the individuation of CMRs—which sub-component of a cultural recipe can serve as a CMR and which ones cannot—is itself determined by the nature of the generative processes involved in producing the relevant public displays.

5.1 CMRs Have Unitary Functions

A CMR is a subassembly of a cultural recipe possessing a unitary function, meaning that the sub-component, taken as a unit, serves some function (Brandon 2005). Indeed, for a sub-component to make sense as a modular unit, it needs to possess a basic function that is exploitable in novel recipes. The basic flaking unit certainly possesses a unitary function in this sense, i.e., it is used to detach sharp flakes from a core. Of course, the sub-component can partake into more than one function, as it can fall under higher level subgoals, and it can be composed of lower subassemblies with their own unitary functions. For instance, the basic flaking unit serves a debitage function in the Oldowan recipe whereas it serves a shaping function in the Early Acheulean one. However, both these higher level function depend on the intended end result of the overall technique, not specifically on the structure of the basic flaking unit. Moreover, the target selection and percussion subassemblies each have their own unitary function, i.e., selecting a point to hit on the core and hitting a core with a hammerstone respectively. However, it is only by combining the percussion action with a specific aim on the core (and in the right order) that one can reliably produce a functional flake.

Given that recipes' structures are defined as functional hierarchies, we can understand a recipe's sub-component as possessing a unitary function if it consists of the full subassembly of actions and decisions under a specific subgoal node. This means that partial subassemblies or subassemblies with no common subgoal do not possess unitary functions. For instance, in the Oldowan technique, the subassemblies under the raw material procurement node and the one under the target selection node do not conjointly share a common function. In contrast, the subassembly of actions and decisions falling under the subgoal of the basic flaking unit – target selection followed by percussion – possesses a unitary function. The reason that some parts of a recipe do or do not have a unitary function has little to do with the nature of the information transmitted through the public display. Rather, it is the cognitive/behavioral structure of the sub-component that gives it a unitary function, i.e., in terms of the practical effects of the cognitive decisions and sequence of actions they command, and how these effects satisfy the intentions of the individual.

5.2 CMRs Are Functionally Integrated

Having a unitary function is not sufficient for a subassembly to serve as a CMR. In addition, the recombined module must remain functional in the new recipe. Indeed, it makes little sense to talk of modularity and recombination at all if what is being "recombined" fails to function appropriately in any other tradition than the one it originated from. In order to serve as a CMR, a recipe's sub-component must be apt to insure its functioning relatively independently from the recipe of which it was originally part. A CMR is a functionally integrated subassembly, meaning that its functioning depends more closely on the subassembly's constituent parts than it does on the other parts of the recipe. A subassembly that fails to be functionally integrated will generally fail to be recombined as the new recipe may not offer the functional support required by the sub-component to be successfully enacted.

The functional integration of a cultural module needs not be an all or nothing affair. Following Simon (1962), we can decompose a complex system into component subsystems (or modules) that are relatively independent as the functional interactions among the constituent parts of the sub-systems are denser than the functional interactions between the sub-systems. The more a sub-component depends on the recipe of which it is part to satisfy its intended end result, the more difficult it will be to detach the sub-component from its original context. This is because not all novel recipes obtained by recombination will be able to compensate from the loss of functional support offered by the original recipe. Inversely, a functionally encapsulated subcomponent—one that depends very little if at all on the rest of the recipe to satisfy its function—will be much more capable of recombination as it is much more plastic in terms of the recipe structures in which it can function. Just how functionally integrated a subassembly must be to serve as a CMR is an open empirical question that will not be tackled here.

The basic flaking unit appears to be well integrated functionally. The successful detachment of a flake from a core depends more on the proper selection of a target platform and the appropriate percussion gesture than it depends on the specific methods of material procurement. Changes in the angle of percussion or the type of grip used to hold the core and/ or the hammerstone will have important functional impacts on the production of a sharp flake, much more than the choice of carrying cores to a selected site or of directly knapping in the quarry. Of course, detaching a flake depends on the type of materials that are being used (Pelegrin 1993) and material procurement methods may constrain what sorts of materials are available to the knapper. However, the successful enactment of a flaking episode does not intrinsically depend on the success or idiosyncrasies of the method used to gather materials (e.g., someone else could provide the knapper with the material if she failed to find promising cores to flake). As long as a potent core is available, the basic flaking unit can be enacted, disregarding where from and how the core was procured.

Although conceptually different, it may seem that possessing a unitary function and being functionally integrated are but two sides of a same coin such that all subcomponents with a unitary function are also functionally integrated. A closer look at the basic flaking unit shows that this is not always case. Consider the two constitutive subassemblies of the basic flaking unit, i.e., target selection and percussion. Although each subassembly has its own unitary function, the target selection assembly appears to be functionally independent of the percussion subassemblies, whereas the reverse is not true. Indeed, successfully identifying a promising platform does not depend on the knapper effectively detaching a flake from it. However, in order to produce a percussion, one needs to properly select a viable target platform. This is not to say that one needs to select a target to produce a percussion in general. Indeed, one can just take two rocks and hit them with one another. However, the percussion subassembly is more sophisticated than merely banging two rocks together. One rock is used to hammer another, with a flake being detached from the core but not from the hammerstone. It is the selection of a target that indicates to the knapper which rock serves as the core—the rock being hit upon—and thus how to stabilize it in one hand, and which other rock will serve as the hammerstone—the rock that is to be used to strike the stabilized core. Without the selection of a target, the decisions involved in the percussion subassembly cannot be adequately processed as the percussion subassemblies does not itself determine which rock will serve the functional role of a core. It depends on the functional decisions made during the selection of a target. The choice of a target also guides how the core and hammerstone will be held—e.g., you do not grab the core so that the target happens to be under your fingers—and how the strike movement will be processed, as it needs to hit the core on the selected target. Thus, although the percussion subassembly does possess a unitary function—i.e., hitting a core with a hammerstone to detach a flake—it fails to satisfy this function independently of the preselection of a target. Consequently, functional unity and functional integration are neither conceptually nor empirically equivalents. Moreover, only through a close examination of the structure of the basic flaking unit and the generative processes involved in can it be determined whether any of its subassemblies are functionally integrated.

5.3 CMRs can be Learned Separately

Possessing a unitary function and being functionally integrated are still not sufficient conditions for a recipe's subassembly to serve as a CMR. The modular subassembly must also be capable of persisting into novel cultural lineages independently of the original recipe of which it was a part such that even if the original recipe was to be lost, the module would survive in its recombined context. This means that if a CMR is to be recombined into a novel tradition, learners must be capable of acquiring it separately from the recipe of which it was originally a part of. Whereas the functional integration condition concerns the relative functional autonomy of a recipe's sub-components, the separability condition pertains to the transmission of traditions formed through recombination. This conceptual distinction has empirical consequences. Most importantly, we should not expect all the functionally integrated sub-components of a recipe to be learnable separately from one another.

Clearly, the basic flaking unit can be learned separately from the rest of Oldowan technique.[7] There are no reasons to assume that in order to master the basic flaking unit, one must also know how to gather the materials for the task. Someone else could procure the materials and that someone else might not even know how to detach a functional flake. Paleoarcheologists are often trained to knap Oldowan flakes but are generally not taught how to gather materials the way Oldowan knappers did more than 2 million years ago. In addition to having a unitary function that is well integrated, the basic flaking unit is also learnable separately from the Oldowan technique (e.g., it figures in other stone knapping techniques).

In contrast, consider the two subassemblies comprised in the basic flaking unit, that of target selection and of percussion. It was shown above that the percussion subassembly is not functionally integrated as it is highly dependent on the target selection subassembly to function. In contrast, the target selection subassembly has well-integrated unitary function. However, the target selection subassembly is not learnable separately from the percussion subassembly. Indeed, in order to learn how to properly select a viable target on a core so that it produces a functional flake, one must first know *how a core will react to percussions*. Learning how to choose a promising platform on a core depends on the capacity of the individual to read the material and geometrical structure of the core. This can only be achieved by acquiring a tacit understanding of the physics of conchoidal fracture so as to identify the flaking affordances of a core. Without this prior know-how, an individual will not be able to reliably identify a promising platform.

[7] Following most paleoarcheologists, it is assumed here that the transition from the Oldowan to the Early Acheulean techniques is a cultural (technological) one, made possible (at least in part) by the cultural transmission of the flaking techniques. Some doubts have been raised about this possibility (see Richerson and Boyd 2005; Corbey et al. 2016). Even if it was shown that the Oldowan-Early Acheulean transition was not cultural, the general conceptual analysis developed her would still stand on its own. Moreover, the basic flaking unit is known to be transmissible through social learning as even more sophisticated, clearly cultural techniques employ it (Whittaker 1994).

As years of actualistic research have shown, learning how to read a core and finding a promising platform depends on developing one's skill in percussion through a process of trial-and-error learning (Pelegrin 1993; Roux and Bril 2005; Whittaker 1994).

As it relates to the acquisition phase of social transmission (see Section 1.1 above), learning separability suggests that it should reduce to the informational dimension of the cultural trait. Indeed, the informational structure of a complex trait is important for assessing its learnability as a cohesive unit. However, social learning can often depend on the generative processes and material nature of the recipe, as mastering the basic flaking unit nicely illustrates. For instance, one may know the theory behind the Oldowan technique, but that does not mean one knows how to actually select a proper target on a stone core. One must first familiarize oneself with the materials, a learning process in which the body and the environmental processes (such as the physics of conchoidal fracture) play a crucial structuring role. In other words, one needs to try to detach flakes in order to learn how the material properties of a core reacts to specific strikes and eventually master precision striking. Practice is paramount to choosing where to strike a core to produce a viable flake and this in turn is learned by familiarizing oneself with the actual actions and materials involved in flake detachment. In other words, you cannot learn how to select a proper target if you do not already know how percussion works. In this sense, the target selection subassembly fails to be learnable separately from the percussion subassembly even if it possesses a unitary function and is functionally integrated.[8]

6 Expanding the Range of Cultural Modularity

As argued above, when applied to complex behaviors, innovation by recombination and its affiliated notion of cultural modularity can only be properly understood through a closer examination of the generative processes involved in the production of public displays. This view complements cultural evolutionists' more formal treatments while retaining their interest in complex, hierarchically organized behaviors (e.g., see Mesoudi and O'Brien 2008; O'Brien et al. 2010). Other forms of recombinatory processes and cultural modularity exist for sure. In this section, some alternatives are briefly addressed, suggesting that the basic framework elaborated here is readily adaptable to their study. The objective is not to thoroughly argue for these different understandings of cultural modularity. Rather, it is to suggest the framework developed here may prove informative to different kinds of cultural evolutionary research projects.

Linguistic recombination and modularity certainly depend on a different set of processes than those involved in the production of complex behaviors. Nevertheless, the innovative recombination of morphemes and words (e.g., "basketball," "football," "ballpark," etc.) nevertheless depends on the unitary function of the linguistic object (its meaning), the fact that it can serve its semantic function relatively independently of the specific words in which it originally figured (e.g., free morphemes are more

[8] The case of learning the basic flaking unit might not be generalizable to all modular cultural traditions as we might not expect all cultural recipes to depend on practice and trial-and-error learning. However, the case study shows that the material nature of the generative processes can have an important role in such forms of social learning and will thus be relevant when perpetuating a cultural tradition requires each individual in the chain to practice actions and learn about materials.

modular than bound morphemes), and that the linguistic module can be learned independently of a specific set of sentences in which it was first used. Moreover, interfaces are also generally required, such as morpheme allomorphy. Contrary to the cases of technical recipes and tool production examined above, the generative constraints will more likely be situated at the level of the cognitive mechanisms (the first set of factors identified in Section 1.2 above) involved in linguistic production rather than on the specific materials and body parts used.

It is also possible for a group of individuals to exploit the modularity of a cultural recipe and to distribute each sub-task among its members. As was discussed with the case of the Oldowan technique, the basic flaking unit is relatively independent in both function and learning of the material procurement subassembly. This means that, in order to produce an Oldowan flake, one individual could take care of procuring materials and another of detaching flakes from the procured cores. Such socially distributed enactment of a particular cultural recipe is made possible by the very fact that it is a modular recipe. Each individual will serve specific functions. They will be able to specialize in their craft because modules of a complex recipe may be enacted relatively independently from one another and learned independently, here by different individual. However, in these cases, an additional social interface may be required, one that solves the problem of coordinating the actions of two or more agents so that a recipe can be successfully brought to the desired end results by a group of individuals. Cultural evolutionists still need to address cases of socially distributed cultural traits that depend on well-coordinated groups of interactors. A better understanding of cultural modularity as the one developed here offers a promising start to expand the concept of cultural recipe, generally construed as an individual trait, into a more encompassing framework addressing how socially distributed cultural traits evolve.

Finally, the framework developed here insists on the modular structure of the techniques used to produce public displays. Tools are but one kind of such public displays and tools can themselves be understood as being modular (remember the case of the Swiss army knife discussed above). The modularity of tools would be mysterious if the generative processes involved in their production were not themselves modular (Arthur 2009, Wimsatt 2013). Indeed, if one could not produce a miniaturized blade independently from a miniaturized screwdriver, it is hard to understand how the Swiss army knife could be understood as a recombination of blade and screwdriver technology. The inception and further modification of modular tools promise to become clearer once we attend to the specific techniques employed in their production. Tool modules are likely the result of specific techniques that were interfaced together in order to produce something new. Moreover, at least in the case of the Swiss army knife model of tool modularity, each "module" does serve a unitary function (e.g., a blade is meant to cut), a function it can successfully accomplish relatively independently from the rest of the tool (e.g., in order to cut, a blade does not depend on the proper functioning of a screwdriver). Moreover, learning how to produce one module needs not depend on knowing on how to produce another (e.g., you do not need to know how to produce a screwdriver in order to produce a blade, and vice versa). However, as discussed above, an interface must be devised if each tool is to be recombined into a functional army knife, and in this case the interface will likely be one relating to material interactions between the modular tool's parts. Moreover, the interface itself is likely to depend on using a set of techniques, such as one to produce smaller metal tools, so that each module of the tool can be packed into a single, functional item. With some minor adjustments, the framework developed above seems ready to help us better understand modular tools.

7 Conclusion

The primary aim of this paper has been to spell out a conceptual framework in order to better understand the innovation by recombination process and its relation to cultural modularity. The concept of cultural module of recombination (CMR) was grounded in terms of properties of cultural recipes' subassemblies rather than on a circular notion of modules being what is recombined and recombination as a process of joining modules together. A CMR is a subassembly of a cultural recipe that possesses a unitary function, one that can lead to its intended end results relatively independently from the cultural recipe of which it is part, and one that can be learned separately from the recipe of which it is a constituent. Even if we suppose these dispositions of recipe subassemblies are not enough to make them proper cultural modules, the general definition offered here at least offers operational means to start identifying potential modules in actual cultural traditions. The framework developed here opens the door for the study of empirical cases of cultural modules and to link them with the formal treatments of cultural evolution by recombination (e.g., Mesoudi and O'Brien 2008).

The second aim was to show that cultural modularity together with the recombination process and their joint consequences depend on a finer understanding of the generative processes involved in the production phase of social transmission. Importantly, it was shown that the recombination process depends on the inventive production of an interface between modules and the complex recipes in which they figure. The interface itself will depend on the generative processes involved in the enactment of the combined recipe as the interface itself serves mainly to insure the functional cohesiveness of the novel recipe. Again, the point is not to dismiss the informational dimension of cultural transmission. Rather, it is to complement it with a materialistic dimension, emphasizing how the cognitive and material factors of the generative processes involved in the production of public displays can both enable and constrain the production of novel cultural recipes. The informational, cognitive, and material processes are jointly necessary conditions for any episode of social transmission to succeed and thus for patterning cultural evolution.

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References

Arthur, B. (2009). *The nature of technology: what it is and how it evolves*. New York: Free Press.
Basalla, G. (1988). *The evolution of technology*. Cambridge: Cambridge University Press.

Botvinick, M. M. (2008). Hierarchical models of behavior and prefrontal function. *Trends in Cognitive Science, 12*(5), 201–208.
Boyd, R., & Richerson, P. J. (1985). *Culture and the Evolutionary Process*. Chicago: University of Chicago Press.
Boyer, P. (1999). Cognitive tracks of cultural inheritance: how evolved intuitive ontology governs cultural transmission. *American Anthropologist, 100*(4), 876–889.
Brandon, R. N. (2005). Evolutionary modules: conceptual analyses and empirical hypotheses. In W. Callebaut & D. Rasskin-Gutman (Eds.), *Modularity: understanding the development and evolution of natural complex systems* (pp. 51–60). Cambridge, MA: MIT Press.
Braun, D. R., Plummer, T., Ferraro, J. V., Ditchfield, P., & Bishop, L. (2009). Raw material quality and Oldowan hominin toolstone preferences: evidence from Kanjera South, Kenya. *Journal of Archaeological Science, 36*, 1605–1614.
Byrne, R. W. (2003). Imitation as behaviour parsing. *Philosophical Transactions of the Royal Society B, 358*, 529–536.
Byrne, R. W., & Russon, A. E. (1998). Learning by imitation: a hierarchical approach. *Behavioral and Brain Sciences, 21*, 667–721.
Cavalli-Sforza, L. L., & Feldman, M. W. (1981). *Cultural transmission and evolution: a quantitative approach*. Princeton: Princeton University Press.
Charbonneau, M. (2015a). All innovations are equal, but some more than others: (re)integrating modification processes to the origins of cumulative culture. *Biological Theory, 10*(4), 322–335.
Charbonneau, M. (2015b). Mapping complex social transmission: technical constraints on the evolution cultures. *Biology & Philosophy, 30*, 527–546.
Chomsky, N. (1957). *Syntactic structures*. Gravenhage: Mouton & Co.
Claidière, N., & Sperber, D. (2010). Imitation explains the propagation, not the stability of animal culture. *Proceedings of the Royal Society B, 277*, 651–659.
Claidière, N., Scott-Phillips, T. C., & Sperber, D. (2014). How Darwinian is cultural evolution? *Philosophical Transactions of the Royal Society B, 369*(1642), 20130368.
Corbey, R., Jagich, A., Vaesen, K., & Collard, M. (2016). The Acheulean handaxe: more like a bird's song than a Beatles' tune? *Evolutionary Anthropology, 25*, 6–19.
de la Torre, I. (2011). The origins of stone tool technology in Africa: a historical perspective. *Philosophical Transactions of the Royal Society B, 366*, 1028–1037.
Delagnes, A., & Roche, H. (2005). Late Pliocene hominid knapping skills: the case of lokalalei 2C, west Turkana, Kenya. *Journal of Human Evolution, 48*, 435–472.
Durham, W. H. (1991). *Coevolution: genes, culture, and human diversity*. Stanford: Stanford University Press.
Enquist, M., Ghirlanda, S., & Eriksson, K. (2011). Modelling the evolution and diversity of cumulative culture. *Philosophical Transactions of the Royal Society B, 366*, 412–423.
Greenfield, P. M. (1991). Language, tools and brain: the ontogeny and phylogeny of hierarchically organized sequential behavior. *Behavioral and Brain Sciences, 14*, 531–595.
Griffiths, T. L., Kalish, M. L., & Lewandowsky, S. (2008). Theoretical and empirical evidence for the impact of inductive biases on cultural evolution. *Philosophical Transactions of the Royal Society B, 363*, 3503–3514.
Guerra-Filho, G., & Aloimonos, Y. (2012). The syntax of human actions and interactions. *Journal of Neurolinguistics, 25*, 500–514.
Heintz, C., Claidière, N., (2015). Current Darwinism in social science. In Lecointre G, Huneman P, Machery E, Silberstein M (Ed), *Handbook of Evolutionary Thinking in the Sciences* (pp 781–807). Dordrecht: Springer.
Hoppitt, W., & Laland, K. N. (2013). *Social learning: an introduction to mechanisms, methods, and models*. Princeton: Princeton University Press.
Inizan, M.-L., Reduron-Ballinger, M., Roche, H., & Tixier, J. (1999). *Technology and terminology of knapped stone*. Nanterre: CREP.
Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112–136). New York: John Wyley & Sons.
Lewis, H. M., & Laland, K. N. (2012). Transmission fidelity is the key to the build-up of cumulative culture. *Philosophical Transactions of the Royal Society B, 367*, 2171–2180.
Lombard, M., & Haidle, M. N. (2012). Thinking a Bow-and-arrow Set: cognitive implications of middle stone Age Bow and stone-tipped arrow technology. *Cambridge Archaeological Journal, 22*(2), 237–264.
Lyman, R. L., & O'Brien, M. J. (2003). Cultural traits: units of analysis in early twentieth-century anthropology. *Journal of Anthropological Research, 59*, 225–250.

Mesoudi, A. (2011). *Cultural evolution: how Darwinian theory can explain human culture and synthesize the social sciences*. Chicago: University of Chicago Press.
Mesoudi, A., & O'Brien, M. J. (2008). The learning and transmission of hierarchical cultural recipes. *Biological Theory, 3*, 63–72.
Mesoudi, A., & O'Brien, M. J. (2009). Placing archaeology within a unified science of cultural evolution. In S. Shennan (Ed.), *Pattern and process in cultural evolution* (pp. 21–32). Berkeley: University of California Press.
Mesoudi, A., & Whiten, A. (2004). The hierarchical transformation of event knowledge in human cultural transmission. *Journal of Cognition and Culture, 4*, 1–24.
Mesoudi, A., Whiten, A., & Laland, K. N. (2006). Towards a unified science of cultural evolution. *Behavioral and Brain Sciences, 29*, 329–383.
Miller, G. A., Galanter, E., & Pribam, K. H. (1960). *Plans and structure of behavior*. New York: Holt, Rinehart and Winston, Inc.
Moore, M. W. (2007). Lithic design space modelling and cognition in *Homo floresiensis*. In A. C. Schalley & D. Khlentzos (Eds.), *Mental states* (Evolution, function, nature, Vol. I, pp. 11–33). Amsterdam: John Benjamins Publishing Company.
Moore, M. W. (2010). "Grammar of action" and stone flaking design space. In A. Nowell & I. Davidson (Eds.), *Stone tools and the evolution of human cognition* (pp. 13–43). Boulder: University Press of Colorado.
Morin, O. (2016). *How Traditions Live and Die*. Oxford: Oxford University Press.
Neff, H. (1992). Ceramics and evolution. *Archaeological Method and Theory, 4*, 141–193.
O'Brien, M. J., Lyman, R. L., Mesoudi, A., & VanPool, T. L. (2010). Cultural traits as units of analysis. *Philosophical Transactions of the Royal Society B, 365*, 3797–3806.
Pastra, K., & Aloimonos, Y. (2012). The minimalist grammar of action. *Philosophical Transactions of the Royal Society B, 367*, 103–117.
Pelegrin, J. (1990). Prehistoric lithic technology: some aspects of research. *Archaeological Review from Cambridge, 9*(1), 116–125.
Pelegrin, J. (1993). A framework for analyzing prehistoric stone tool manufacture and a tentative application to some early stones industries. In A. Berthelet & J. Chavaillon (Eds.), *The use of tools by human and non-human primates* (pp. 302–317). Oxford: Clarendon.
Pelegrin, J. (2005). Remarks about archaeological techniques and methods of knapping: elements of a cognitive approach to stone knapping. In V. Roux & B. Bril (Eds.), *Stone knapping: the necessary conditions for a uniquely hominin behaviour* (pp. 23–33). Cambridge: McDonald Institute for Archaeological Research.
Perreault, C., Brantingham, P. J., Kuhn, S. L., Wurz, S., & Gao, X. (2013). Measuring the complexity of lithic technology. *Current Anthropology, 54*, S397–S406.
Reader, S. M. (2006). Evo-devo, modularity and evolvability: insights for cultural evolution. *Behavioral and Brain Sciences, 29*, 361–362.
Richerson, P. J., & Boyd, R. (2005). *Not by genes alone: how culture transformed human evolution*. Chicago: University of Chicago Press.
Roux, V., & Bril, B. (Eds.). (2005). *Stone knapping: the necessary conditions for a uniquely hominin behaviour*. Cambridge: McDonald Institute for Archaeological Research.
Schank, R. C., & Abelson, R. P. (1977). *Scripts, plans, goals, and understanding*. Hillsdale, NJ: Lawrence Erlbaum Associates.
Schick, K., & Toth, N. (2006). An overview of the Oldowan industrial complex: the sites and the nature of their evidence. In N. Toth & K. Schick (Eds.), *The Oldowan: case studies into the earliest stone Age* (pp. 3–42). Gosport: Stone Age Institute Press.
Schlanger, N. (2005). The chaîne opératoire. In C. Renfrew & P. Bahn (Eds.), *Archaeology: the Key concepts* (pp. 18–23). London: Routledge.
Simon, H. A. (1962). The architecture of complexity. *Proceedings of the American Philosophical Society, 106*(6), 467–482.
Soressi, M., & Geneste, J.-M. (2011). The history and efficacy of the chaîne opératoire approach to lithic analysis: studying techniques to reveal past societies in an evolutionary perspective. *PaleoAnthropology, 334*, 350.
Sperber, D. (1996). *Explaining culture: a naturalistic approach*. Oxford: Blackwell Publishers.
Sperber, D. (2006). Why a deep understanding of cultural evolution is incompatible with shallow psychology. In N. J. Enfield & S. C. Levinson (Eds.), *Roots of human sociality* (pp. 431–449). Oxford: Berg.
Sperber, D., & Hirschfeld, L. A. (2004). The cognitive foundations of cultural stability and diversity. *Trends in Cognitive Science, 8*, 4046.

Sterelny, K. (2012). *The evolved apprentice*. Cambridge: MIT Press.

Stout, D. (2011). Stone toolmaking and the evolution of human culture and cognition. *Philosophical Transactions of the Royal Society B, 366*, 1050–1059.

Stout, D., & Chaminade, T. (2009). Making tools and making sense: complex, intentional behaviour in human evolution. *Cambridge Archaeological Journal, 19*(1), 85–96.

Stout, D., Toth, N., Schick, K., & Chaminade, T. (2008). Neural correlates of early Stone Age toolmaking: technology, language and cognition in human evolution. *Philosophical Transactions of the Royal Society B, 363*, 1939–1949.

Whiten, A. (2002). Imitation of sequential and hierarchical structure in action: experimental studies with children and chimpanzees. In K. Dautenhahn & C. L. Nehaniv (Eds.), *Imitation in animals and artifacts: complex adaptive systems* (pp. 191–209). Cambridge: Cambridge University Press.

Whittaker, J. C. (1994). *Flintknapping: making and understanding stone tools*. Austin: University of Texas Press.

Wimsatt, W. C. (2006). Generative entrenchment and an evolutionary developmental biology for culture. *Behavioral and Brain Sciences, 29*, 364–366.

Wimsatt, W. C. (2013). Entrenchment and scaffolding: an architecture for a theory of cultural change. In L. Caporael, J. R. Griesemer, & W. C. Wimsatt (Eds.), *Developing scaffolds in evolution, culture, and cognition* (pp. 77–105). Cambridge, MA: MIT Press.