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Mapping complex social transmission: technical constraints on the evolution of cultures

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Abstract Social transmission is at the core of cultural evolutionary theory. It occurs when a demonstrator uses mental representations to produce some public displays (utterances, behaviors, artifacts, etc.) which in turn allow a learner to acquire similar mental representations. Although cultural evolutionists do not dispute this view of social transmission, they typically abstract away from the multistep nature of the process when they speak of cultural variants at large, thereby referring both to variation and evolutionary change in mental representations as well as in their corresponding public displays. This conflation suggests that differentiating each step of the transmission process is redundant. In this paper, I examine different forms of interplay between the multistep nature of social transmission and the metric spaces used by cultural evolutionists to measure cultural variation and to model cultural change. I offer a conceptual analysis of what assumptions seem to be at work when cultural evolutionists conflate the complex causal sequence of social transmission as a single space of variation in which populations evolve. To this aim, I use the framework of variation spaces, a formal framework commonly used in evolutionary biology, and I develop two theoretical concepts, 'technique' and 'technical space', for addressing cases where the complexity of social transmission defies the handy assumption of a single variation space for cultural change.

Keywords Social transmission · Cultural evolution · Evolutionary constraints · Techniques · Palaeoarchaeology

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Introduction

It is now common knowledge among evolutionary biologists that the mapping between genetic and phenotypic variation is not a simple one-to-one relation (Hallgrímsson and Hall 2011; Pigliucci and Kaplan 2006). Genetic variants participate in the production of multiple phenotypic traits, and phenotypic traits have many genetic influences, and the very nature and structure of the developmental processes that express genetic variation play a non-negligible role in constraining and enabling phenotypic evolution (Hall 1999; Maynard Smith et al. 1985). A strict focus on variation at the genetic level alone will miss important patterns of phenotypic evolution brought about by the very structure of the developmental mechanisms. The transmission of phenotypic variation is a complex process, and evolutionary biologists are now seriously attending to the project of elucidating just how developmental complexity can enable and at the same time constrain the mapping between genetic and phenotypic variational change.

Social transmission is at the core of cultural evolutionary theory (Boyd and Richerson 1985; Richerson and Boyd 2005; Cavalli-Sforza and Feldman 1981; Claidière et al. 2014; Claidière and Sperber 2010; Durham 1991; Heintz and Claidière (in press); Laland and Brown 2010; Lyman and O'Brien 1998; Mesoudi 2011; Mesoudi et al. 2006; O'Brien and Lyman 2000; Sperber 1996, 2000, 2006; Richerson and Boyd 2005) and it is also a complex process (Hoppitt and Laland 2013; Sperber 2006). Individuals possessing mental representations produce public displays, such as utterances, behaviors, and artifacts, all observable by others. In turn, these public displays serve as the basis for transmission as they are used by learners to acquire mental representations of their own, thereby propagating cultural traditions. Whereas this view of social transmission as a multistep process is not a subject of contention among cultural evolutionists, the complexity of the process is typically abstracted away through talk of cultural variants at large, referring without distinction to variation and evolutionary change both in mental representations as well as in public displays. This conflation suggests a one-to-one mapping of variational change at each step, supporting the assumption that it would be redundant to differentiate each step in model-building and empirical work. Although I believe that most if not all cultural evolutionists would *not* subscribe to such a simplistic mapping as a matter of principle, it nevertheless seems to be widespread in practice, as cultural evolutionists typically conflate each step into a single varying and evolving entity, the 'cultural variant'.

The objective of this paper is not to criticize this aspect of current practice. Rather, it is to identify a possible avenue for extending current cultural evolutionary theory by taking account of cases where the complexity of the cultural transmission process has important evolutionary implications. Since the production of public displays is a necessary step in the social transmission process, the latter intrinsically depends on how mental representations can be expressed. Hence if it turned out that there was no simple one-to-one mapping between variation and evolutionary change at each step of the social transmission process, then the assumption that variational change in mental representations and in public displays can be conflated would lead to incorrect expectations about cultural evolutionary patterns. Cultural evolutionists have not offered much discussion of such a possibility. My contribution will be a first step in that direction.

In this paper, I examine different forms of interplay between the multistep nature of social transmission and the metric spaces used by cultural evolutionists to measure cultural variation and model cultural change. I first discuss modeling approaches based on what I will refer to as the *conflation assumption*: the complex causal sequence of social transmission is modeled as a single space of variation in which populations evolve. I offer a conceptual analysis of reasons why cultural evolutionists use this simplifying assumption. To this aim, I use the framework of variation spaces, a formal framework commonly used in evolutionary biology (McGhee 1999, 2007; Stadler et al. 2001) and to some extent in cultural evolutionary theory (e.g., Acerbi et al. 2011, 2012; Enquist et al. 2011). However, my analysis will be verbal, as I will use the concepts of metric spaces, neighborhood, distance, and multi-space mapping as they have often been used by cultural evolutionists, albeit sometimes implicitly. I show that the conflation of variation spaces of mental representations and those of public displays relies on the assumption that they are topologically structured in the same way and that change on one level will produce equivalent evolutionary change on the other.

I further argue that the conflation assumption rests not on principles or idealizations ostensibly necessary for building evolutionary models, but instead on empirical claims. This means that other approaches can be useful for studying cultural change, especially for cases where the complexity of the social transmission process introduces important constraints on the accessibility of cultural variation. I believe that the transmission of technologies is especially prone to such complex forms of transmission, and I illustrate this claim by comparing the morphological evolution of PaleoIndian projectile-points with that of lithic blades. Conflating variational change in mental representations and in public displays appears to be justified in the former case, but not in the latter. This comparison leads me to propose the notions of 'technique' and 'technical space' as theoretical concepts for cultural evolutionary theory. These concepts refer to the demonstration phase of social transmission, namely the production of public displays by mental representations. I aim to offer a conceptual analysis of the factors that may disrupt the one-to-one mapping of variation spaces and also to suggest avenues for expanding the set of formal cultural evolution approaches in order to deal with more complex social transmission processes. I examine how technical space can be used as a conceptual and theoretical tool for studying the evolution of complex behaviors and artifacts.

The conflation of mental representations with public displays

Social transmission as a multistep process

Suppose I attempt to teach you my personal technique for tying a neck tie. First, I must possess some mental representation of the technique. Based on this mental representation, or recipe for action, I demonstrate my knowledge of how to tie neck ties so that you can observe it and learn how to do it by yourself. The displays I produce for communicating the relevant information concerning my technique can take many forms. I might explain it to you through verbal instructions. I could also demonstrate it to you by taking a neck tie and tying it around my neck. I could tell you a nursery rhyme about foxes chasing rabbits and I might coordinate the rhyme with a demonstration of my tying a neck tie around a mannequin's neck. From these public displays—they are public because you can observe them, whereas you cannot directly access my mental representations—you will learn how to tie neck ties on your own. Acquiring my technique could be immediate in that you might be able to tie neck ties like I do after a single demonstration. But it is more probable that you would need me to repeat my instructions or my demonstrations, and that you would require some practice to finally master the skill I wish to share with you. In the end, if the technique gets transmitted, you will have formed your own mental representation of my tying technique. A good assessment of your having learned my technique rather than someone else's is that you will be able to enact a necktie tying technique close to mine and maybe even teach it to somebody else.

From this simple example, we can see that social transmission minimally consists of an alternating sequence of a demonstrator's mental representations participating in the production of some public displays, such as behaviors (including utterances) and artifacts, which in turn participate in the production of mental representations in a learner. I will refer to these processes of production as *demonstration* and *acquisition*, respectively (see Fig. 1). Successful social transmission leads to the retention of some relevant information, meaning that socially transmitted mental representations will be similar to one another in relevant respects (Sperber 2000; Sperber and Wilson 1995). The same applies for socially acquired behaviors and artifacts. A learner need not replicate the demonstrator's behavior or the artifact perfectly, however she must reproduce the relevant features of the public displays (Sperber 2006). Two public displays are similar enough (in the relevant respect) to count as two behaviors or artifacts of the same kind if they lead individuals to acquire similar mental representations. Complementarily, two mental representations are similar if they lead to the production of relevantly similar public displays.[1] Traditions, then, are causal chains of mental representations and public displays that ensure the persistence of some relevant information by being similar to one another through time.

Cultural evolutionists and scientists studying social learning processes typically abide by this minimal description of social transmission (e.g., Heyes 1993), although there are divergences regarding the theoretical language used to describe the transmission process as well as controversies as to what a richer account of social transmission should consist in.[2] However, once precise theoretical, empirical,

[1] Similarity of mental content might appear at first sight to be a better measure of similarity of mental representations, but mental content can only be assessed through the proxy of the behaviors expressing that content. This is because we do not have any direct access to someone else's (and possibly even our own) mental contents.

[2] Cultural epidemiologists (Claidière et al. 2014; Claidière and Sperber 2007, 2010; Sperber 1996, 2000, 2006; Sperber and Hirschfeld 2004) agree with the minimal characterization I have offered above. Sperber (2006) explicitly describes social transmission as a social cognitive causal chain (SCCC), a sequential interlocking of private mental representations and public representations. Another theoretically-loaded approach to characterizing the multistep nature of social transmission is adopted by the proponents of an analogy between genetic and cultural inheritance (Boyd and Richerson 1985; Cavalli-Sforza and Feldman 1981; Mesoudi 2011). Mental representations serve as cultural analogs of the genotype and public displays as cultural analogs of the phenotype (e.g., Boyd and Richerson 1985, pp. 33–36; Mesoudi 2011, p. 44). Others refer to mental representations as ideational units, and public displays as empirical units (e.g., O'Brien et al. 2010). It goes beyond the scope of this paper to critically examine and compare these different theoretical approaches as they are based on the minimal view I am examining here.

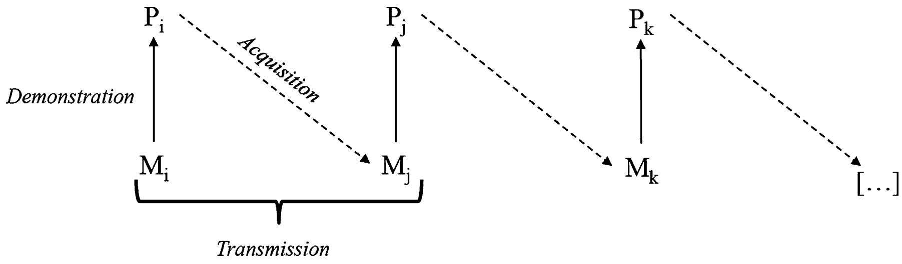

Fig. 1 Social transmission as a multistep process. A demonstrator's mental representation M_x is used to produce (demonstrate) some public display P_x (utterances, behaviors, artifacts, etc.). A learner acquires a similar mental representation M_{x+1} by observing the demonstrator's public display, and so on. Compare with Durham (1991, Fig. 4.3), Heyes (1993, p. 1003), and Sperber (2006, Fig. 1), among others

and simulation work is undertaken, the minimal distinction between mental representations and public displays typically fades away.

The conflation of variation and change in mental representations and public displays

Cultural evolutionists usually talk of cultural variants or cultural traits, referring indiscriminately to variant mental representations (e.g., beliefs, preferences, etc.), to variant public displays (e.g., practices, shape of artifacts, etc.), or to both at the same time. This, in fact, is a ubiquitous practice among cultural evolutionists. For instance, Claidière and Sperber (2007) discuss an attractor model in which the habit of smoking a certain number of cigarettes per day evolves. At first, it seems they are modelling the change in a behavior—how many cigarettes are actually smoked—but in their model, attractors for smoking a certain number of cigarettes per day are actually discussed in terms of what individuals want and decide that they should smoke, i.e., mental representations. Here, referring to mental representations is used interchangeably with referring to behavioral traits. This case is not an exception. Most models and empirical studies on cultural evolution do not track evolutionary change in mental representations separately from evolutionary change in variant public displays.[3]

The conflation between variational changes at the level of mental representations with that at the level of public displays should not be understood as a denial by cultural evolutionists that social transmission is a process based on causal chains of alternating

[3] Examples of the use of the conflation assumption are not restricted to idealized mathematical models. In the laboratory experiments conducted by Mesoudi and O'Brien (2008a), the authors track only the shape of 'virtual arrow-heads' produced in their experimental set up, which points out that they are assuming that what is visually represented on the Ipads they use for the experiment corresponds to what their subjects intend to transmit. The assumption becomes clearer once it is pointed out that the intricacies of the actual knapping techniques used to produce the real arrow-heads (the evolution of which they are modelling) are replaced by pinches on an iPad, an extremely unsophisticated behavior. What this replacement shows is that, whatever the technique used for producing public displays, no differences in variation is expected between what individuals want to transmit (mental representations) and what these individuals actually use to do so (public displays, here a visual picture on an Ipad). This sort of operationalization of the conflation assumption will be made clearer in the discussion that follows (see, especially, "Technical constraints on social transmission" section).

mental representations and public displays. If that were so, one would have to offer an alternative understanding of social transmission that does not rely on a distinction between the two.[4] On the contrary, I believe it makes much more sense to assume that cultural evolutionists conflate both steps of social transmission in their models and explanations on the assumption that it would be redundant to differentiate variation at one step from variation at the other. As long as changes in transmitted information will produce equivalent changes in mental representations and in the public displays (behaviors and/or artifacts) of those who acquired this information, there is no need to differentiate these steps in evolutionary models and explanations. In the cigarette smoking case of Claidière and Sperber, there is little reason to believe that the number of cigarettes individuals want to smoke will differ from the amount they actually do smoke. In cases like this one, one is right to abstract away from a strict distinction between mental representations and public displays as there is no reason to assume that changes will not be largely equivalent. The trait is very simple and the processes of demonstration and acquisition are straightforward. Moreover, the cigarette model is just that, a model, and the simplifying assumption of abstracting away from the complexity of the transmission process is not problematic in this case.

However, when it comes to more complex cultural traits that rely on complex techniques and elaborate recipes for action, the processes of demonstration and acquisition may be more susceptible to interfering factors that make the conflation problematic, if not untenable. These more complex traits might not be amenable to the handy conflation typically used by cultural evolutionists because the mapping of variation and change at each step might not be straightforward.

Before turning to one of these more complex cases ("Technical constraints on social transmission" section), I will first give an explication of the conflation assumption through the framework of variation spaces and examine an empirical case study that successfully uses such models. This will allow a better contrast with the new approach I propose for dealing with complex cases of social transmission such as those that characterize technological traditions, among others.

An explication of the conflation assumption with a case study

Variation spaces

Here I address the question of the conflation of variation and evolutionary change in mental representations with variation and evolutionary change in public displays through the framework of variation spaces. The representation of evolutionary change as a population walking through a space of variation is common in both evolutionary biology and cultural evolutionary theory. Spatial models are well-defined, formal tools (McGhee 1999, 2007; Stadler et al. 2001). From a

[4] Even memeticists (Blackmore 1999; Dennett 1995) agree on this minimal characterization, even though they characterize mental representations and public displays as cultural replicators in their own right. The mere fact that imitation is involved in memetic transmission means that, at some step, mental representations and public displays are involved in the process of cultural replication, whichever one if any is the preferred cultural replicator.

mathematical point of view, a variation space is a set of elements with accessibility relations. Variants are structured through their accessibility relations. There are many different possible relations that can structure such sets. I will focus here on two such relations that play a major role in the use of spatial models in cultural evolutionary theory: neighborhood and distance. I will however restrict my discussion to a non-formal use of these spaces and their core relevant concepts (for an in depth mathematical treatment, see Gaal (1964)).

A variant is a *neighbor* of another if there is an operational rule that can transform the first variant into the other in a single step. In the context of spatial models of evolution, the permitted types of operations are those that map the effects of variation-generating mechanisms. For instance, taking the mechanism of point mutations to define a space of variant DNA strands, a DNA sequence of length N has as its neighbors all its one-nucleotide mutants (3 N neighbors), since any nucleotide can take only four forms (ATGC). In the context of cultural evolution, mechanisms that introduce cultural variation will define which variant is a neighbor of which other ones. I will discuss the copying-error mechanism of variation in quantitative traits in more detail below.

The *distance* between two variants is the probability that a variant will transform into another in a specific number of generations.[5] Distances between two variants are thus dependent on the transformation rules (neighborhood), on the probability that a certain number of transformation occur per generation, and on the number of generations required for a population to reach a variant from another, starting variant. The distance between the two nucleotide sequences GT and TA, assuming a one point mutation per generation with a mutation event every generation is, at closest, a two generations, or 1/18.

How can we employ these concepts to express the conflation assumption typically held by cultural evolutionists? Let us assume, for simplicity's sake, that each variant in mental representations can produce only one specific variant in public display, meaning that having some specific mental representation X always leads you to exactly produce a specific public display X′. Now, suppose that a learner can only acquire the mental representation X through the public display X′. This creates a strict one-to-one mapping between variants at each level. Variant X′ in public display leads someone to acquire the mental representation X that in turn will serve to produce public display X′ again, whereas variant Y′ in public display leads someone to acquire the mental representation Y that in turn will serve to produce public display Y′ again, where X is different from Y and X′ different from Y′. In other words, throughout a cultural lineage, social transmission is perfectly faithful (or reconstructs very stably) so that mental representations will always produce public displays that in turn reproduce the very same mental representation. This gives us a mapping between the sets of variants at each level.

Now let's introduce an evolutionary component by assuming a variation-generating mechanism that transforms or 'mutates' the cultural variants, at any one

[5] I talk of probability and not of the number of transformations in order to stay coherent with current practice in cultural evolutionary theory. In many models, neighbor variants can be accessed with different probabilities, and often accessing some more probable variant increases the chance that other variants can be accessed in the next generation.

specific level, into another variant at that same level (so that an X mutates into a Y, and a X′ mutates into a Y′). This mechanism will allow us to determine the transformation rule required to define the neighbors of each variant and their relative distances. The variation mechanism generates new variants that are similar, according to some metric, to the original one. What we have now is an emerging mapping network of neighborhoods and distances for each level of variation. Applying the mapping logic of the previous paragraph, we obtain an isomorphic projection between the two variation spaces. This implies that in addition to any variant at one level corresponding to one and only one variant at the other, neighborhoods and distances are structured the same way in both spaces. Evolutionary change at either level is commensurable, i.e., change at each level is proportionally equivalent. We thus can use the very same metric to measure evolutionary change at each level.

In terms of spatial analysis, the *conflation assumption* thus consists in saying that the variation space of public displays maps onto the variation space of mental representations and back again in such a way that evolutionary change in one space produces an equivalent evolutionary change in the other. More precisely, it means that (1) for any public display P corresponding to mental representation M, P has for neighbors the public displays Q′, R′, S′, etc., public displays that correspond in turn to M's neighbors Q, R, S, etc., respectively, and that (2) the metrics of both spaces are commensurable. In other words, the conflation assumes that the mapping between mental representations and public displays is an isomorphism. If this isomorphic mapping holds between the two spaces, we can assume that any change in mental representation will be reflected by an equivalent change in public display, and vice versa. As such, there is no harm in regarding one space as representative of the other since any distinction between variation and change at either level would be redundant.

Although the conflation assumption may be benign in theoretical models, it needs to be grounded in empirical cases, as it is not obvious whether such a complex scheme holds in all cases of social transmission and cultural evolution. I now turn to the copying-error mechanism of variation generation and examine how it can be used to justify the conflation assumption in the case of the morphological evolution of the Rosegate series of PaleoIndian projectile points.

The accumulated copying-error model

Copying-error is a process that introduces new variation in an undirected, gradual, and unconscious manner (Eerkens 2000; Eerkens and Bettinger 2001; Eerkens and Lipo 2005, 2007; but see Gandon et al. (2014); Schillinger et al. (2014)). Evolutionary archaeologists have used this source of cultural variation to develop null-models (or drift models) of trans-generational change in the variation of artifactual form (e.g., Neiman 1995; Kempe et al. 2012; Hamilton and Buchanan 2009). These errors, which are too subtle for individuals to detect, are consequences of the diverse ways in which cultural transmission can get distorted. Eerkens and Lipo (2005) identify three sources: misinterpretation of the information to be acquired by the learner, errors in the production of the public display that will serve to transmit information, and inaccuracies/biases introduced by heterogeneity in the materials the public display is made of (e.g., Schillinger et al. 2014). To this we may add deterioration of the information held in the transmitter's memory (Boyd and Richerson 1985, pp. 67–68) and systematic cognitive biases in acquiring some mental representation from a specific kind of public display (e.g., Griffiths et al. 2008; Sperber and Hirschfeld 2004), in which case the error is not completely random.

Copying-error as a mechanism that generates new variation specifies both a neighborhood relationship and a distance metric for quantitative character states. Minor alterations in artifactual form that are accessible in one generation through copying-error are neighbors, and the larger the difference in form, the more distant two variants are, so that multiple episodes of copying-error will gradually lead from one form to another, more distant one. The assumption here is that, given a quantitative measurement of the character state of interest (e.g., projectile-point size), two variants, A and B, are closer to one another than either is to a third variant, C, if the quantitative difference between the states of A and B is smaller than the quantitative difference between either A and C or B and C. This assumption gives us a metric space of continuous quantitative change for the character, and such spaces have often been used by cultural evolutionists (evolutionary archaeologists and others) to claim that cultural change is a process of gradual cumulative evolution, in theoretical (e.g., Boyd and Richerson 1996), empirical (e.g., Bettinger and Eerkens 1997, 1999), and experimental work (e.g., Mesoudi and O'Brien 2008a).

Eerkens (2000; see also Eerkens and Bettinger 2001; Eerkens and Lipo 2005, 2008) examined how the (in)accuracy of human perception of length can systematically induce copying errors that go unnoticed by individual stone knappers. Cognitive scientists have shown that two objects must differ by about 3 % in some morphological property for an observer to detect the objects as different in length, irrespective of the objects' absolute size; Eerkens 2000; Eerkens and Bettinger 2001).[6] Moreover, in the context of cultural transmission, we can expect other factors to introduce imprecisions. The limited accuracy of memory, of the ability to convert a mental template into a physical object, and of motor execution (e.g., variance in skill) could also produce variation in artifacts, even if there is some standard form to be reproduced.

Note that the copying-error mechanism has a special structure. The perceptual and memory processes that are responsible of the transmission of the cultural variants are the *very same* as those at the origin of the new variations in the form of the artifacts. In other words, with regard to the learning and reproduction of artifactual properties, the same cognitive processes of perception, modal memorization, and recall are used (1) to produce the artifact from memory (mental template comparison with artifact), (2) to recognize the relevant information to be learned from the public display, and (3) to introduce new variations through imperfect modal-specific similarity judgments.

Given the mechanism of error copying, perceptually similar behavioral or artifactual variants are prone to being confused. This means that two mental representations that produce perceptually similar public displays will thus tend to be confused by a learner. Generalizing this reasoning to the mapping of all mental

[6] Perceptual discriminations of object properties such as length or weight each has its own ratio, which varies with the discriminating modality, and is commonly referred to as the "Weber fraction" of the measurement or as the "Weber-Fechner law".

representations to their public displays, we can assume that any change in mental representations will produce equivalent change at the level of the public displays, and vice versa. This mechanism apparently justifies the conflation of variation in mental representations with variation in public displays. This is because the very same set of processes (copying error through imperfect modal discrimination) defines the topology of each space of variation in the exact same way (closeness through perceptually similar morphologies).

Eerkens and Lipo (2005) apply the accumulated copying-error model to the evolution of the basal width and thickness of Rosegate projectile-points. This series of projectile points is especially interesting because it is thought to represent the transition from atlatl-projected-darts to bow-and-arrow technology (Bettinger and Eerkens 1997, 1999). Eerkens and Lipo (2005) data show that there is a gradual decrease through time in the variance of basal width, which they suggest is due to the winnowing effect of a learning bias tracking performance of the projectile points. It also shows a gradual increase in variance for thickness, a property of projectile-points which had less impact on performance and was thus left to vary relatively freely. Eerkens and Lipo convincingly argue that a copying-error fraction of 5.8 % could explain this increase in thickness variation over 20 generations (Eerkens and Lipo 2005, pp. 326–327), which is close to the 5 % obtained experimentally by Eerkens (2000).

Eerkens and Lipo thus present what appears to be a good case of gradual evolutionary change where a distinction between mental representations and public displays would be redundant, as the copying-error mechanism ensures a one-to-one mapping between the two. However, as will be argued below, the case for conflating variational change of mental representations with that of public displays can only be justified if the techniques used to produce the different projectile point variants allow such one-to-one mapping. In the next section, I examine the implications of apparent gradual quantitative change in lithic blades using the accumulated copying-error model and argue that the conflation assumption does not hold in that case since different techniques constrain the mapping between variation and change at each step of the social transmission process.

Technical constraints on social transmission

Techniques and technical spaces

The notion of technique is meant to refer to the demonstration phase of social transmission.[7] Techniques encompass the environmental properties and processes that

[7] Here I emphasize the evolutionary constraints imposed by the demonstration process of social transmission. Of course, social transmission also depends on the acquisition process (see Fig. 1). Others have studied the acquisition phase in more detail, which in turn can also impose its lot of constraints, enabling spaces, and difficulties in measuring the topological structure of cultural variation. For instance, cultural epidemiologists have been studying the inference processes that extract the relevant information to be learned from public displays (Griffiths et al. 2008; Kirby et al. 2007, 2008; Scott-Phillips and Kirby 2010; Sperber and Hirschfeld 2004). I see no reason why the acquisition phase should not also benefit from an informed use of the spatial framework presented in the previous section.

play an active role in the production of some complex public display, such as complex behaviors and artifacts, and in the interactions between the actions of the individual and these environmental processes. I propose to borrow the notion of 'technique' as it is used in palaeoarchaeology (e.g., Inizan et al. 1995) and adapt it to an evolutionary framework by giving it the following definition: a technique is a socially transmissible set of procedures used to produce a specific kind of public display. A technique is thus an arrangement of the following elements: (1) the cognitive processes used to produce some public display from mental representations (decisions, tacit knowledge, motor control, etc.), (2) the external actions recruited in the production of the public displays (locomotion, prehension, manipulation, pronunciation, etc.), (3) the specific tools used to produce the public displays, and (4) the ecological processes engaged in the production of the public displays (specific materials, phase transitions, chemical reactions, percussion effects, fluid dynamics, etc.). An example of a technique would be using soft-hammer percussion to produce conchoidal fractures on a brittle material such as chert in order to shape a handaxe.[8]

To be meaningful, the concept of technique must allow some fluidity in the organization of a particular technique's constitutive operations (cognitive, external, and ecological) given that specific environmental circumstances may never allow the repetition of the exact same procedural pattern (e.g., every knapped stone has its very own particularity (Whittaker 1994)). Moreover, one can produce different forms of public displays with the very same technique (e.g., two different sequences of dance steps may nevertheless belong to the same dancing technique). I will refer to the precise spatiotemporal sequence of operations employed in a particular environment in which the technique was processed as the 'method' used to produce a specific public display together with its specific character states, e.g., the 4.5 cm long flint Folsom point I knapped this morning (Inizan et al. 1995).

Specific character states such as the length of an arrowhead or the specific percussion incidence used to produce a Levallois flake are produced by means of a technique, but the states themselves give little indication as to which technique was used to obtain them. Recipes for action are mental representations that consist in a set of instructions for producing a range of public displays with varying character states, whether or not these character states have corresponding mental representations (Mesoudi and O'Brien 2008a, b; O'Brien et al. 2010). One can enact the same recipe—i.e., use a specific technique—while varying the mental representations used to specify the public displays' character states. Of course, variation in the shape of the artifact will imply variation at the level of the gestures (e.g., incidence of percussion), cognitive decisions (e.g., comparison with a mental template), and interactions with the knapped material (e.g., shaping sequence of the flake). While the *method* will change accordingly, the overall structure of the *technique* will remain the same since we can expect the same recipe to be transmitted for multiple morphological variants. However, variation in some character states may imply a

[8] This definition does not preclude non-artifactual public displays, such as behaviors, from being products of techniques. For instance, dancing depends on a set of cognitive processes and decisions, often the manipulation of some object (e.g., a hat and a cane, another dancer), implies a series of physical processes (e.g., moon-walking and friction), etc., but produces no artifacts (aside from sweat and scuffed floors).

more dramatic change in the means of production (e.g., the fluting of an arrowhead, adding notches, etc.), but these variants will also imply a change at the level of the recipe. Therefore, I consider that different sequences of actions employed to produce different public displays belong to the same technique if they are the expression of the same specific set of recipes or instructions for action, independently of the local idiosyncrasies and environmental contingencies' affecting their specific expression and also independently of the final character states that are produced by these sequences of action.

Following the tools offered by spatial analysis, discussed in "An explication of the conflation assumption with a case study" section, a specific technique's space of variation can be seen as the set of all the methods employing the technique leading to the production of some class of public displays. Such a technical space is delimited by being the enactment of a specific set of recipes. Technical space in general consist of the total sum of specific technical spaces. The topology of such spaces—how a population proceeds through some variation-producing mechanism to the evolutionary exploration of these technical spaces, specifically and at large—is an empirical question that requires deeper analysis of the relationship between techniques, mental representations, public displays, and variation-generating mechanisms, an investigation that goes beyond the scope of this paper.

I will talk of technical space as an intermediary space that relates the variation spaces of mental representations with the variation spaces of their corresponding public displays. This is to allow us to better see how the enactment of specific techniques can shape the mapping between variation and change in mental representations and public displays. As different recipes are expressed, different techniques will be enacted. As different techniques are enacted, different behaviors and artifacts will be produced. The same goes for mental representations relating to specific character states of public displays. Keeping the recipes the same, variation in mental representations will fuel the corresponding technique into producing variation in the public displays' specific character states.

Technical space has topological properties of its own that we can identify without the aid of a variation-generating mechanism. For instance, since techniques concern the *demonstration* process of social transmission, technical spaces are shaped and bounded by the set of methods that are *enactable*. In other words, sequences of operations that human individuals cannot produce are excluded from technical space. For instance, while prehension and manual rotation of a chert rock with a diameter of 10 cm at its widest is possible, the analogous process is impossible to enact with a 10-meter-wide piece of chert. This means that the evolutionary exploration of technical spaces consists in a population traveling from one enactable method to another, in the case of specific technical spaces, and from one enactable technique to another in technical space at large. We do not need to empirically study techniques to know that some of them are not enactable. However, in order to produce more refined technical spaces by identifying the constraints and the structure they impose on social transmission and cultural evolution, extensive empirical studies must identify and study how cognitive, behavioral, environmental, and material processes and objects shape the social transmission process.

Technical undermining of the conflation assumption

Consider a case analogous to the Rosegate projectile points: the evolution of lithic blade morphology.[9] Blades are detached flakes that are at least twice as long as they are wide (Inizan et al. 1995). Observed variation in blade morphology ranges from more than 40 cm in length to around 1 cm, with a range of 3–4 cm to 2 mm in width (Pelegrin 2012). Blades are usually obtained through different pressure-flaking techniques, although they can be produced by direct and indirect percussion techniques (Pelegrin et al. 1988). Given that direct and indirect percussion hardly produce any standardized blade forms as a consequence of the lack of control on the outcome offered by these techniques (a technical constraint), I will only consider blades produced by pressure-flaking techniques.

By pressure-flaking techniques, blades are separated from a preformed core through the application of pressure on an edge (platform) of the core by means of a pressure tool, such as a deer antler or a copper-tipped handle (Whittaker 1994). Following the logic of the accumulated copying-error model, the (shortest) distance in numbers of generation between a blade of 8 mm and one of 18 mm in width, assuming a 5 % Weber fraction, is about 16 generations. However, the actual distance between these two variants is indefinite. Indeed, there is no single pressure-flaking technique that can produce this range of blades.

In an experimental assessment of the pressure-flaking techniques plausibly used to produce lithic blades, Pelegrin (2012) shows that no single technique is able to produce all the diversity in length and width of blades observed in the archaeological record.[10] Pelegrin differentiates between five modes that vary by the kind of pressure flaker used (hand-held flaker, shoulder crutch, short crutch, long crutch, and lever), which in fact, through combinatorics, represent 40 different techniques[11] (Fig. 2 illustrates these modes). The results of these experiments show that the range of blades that can be produced is different for each technique, with some overlap in the space of artifact variants that each technique can access. However, there is not a single technique that can produce all artifact variants. Pelegrin's results are summarized in Fig. 3.

Pelegrin's explanation for this distribution points to the maximal and minimal quantity of pressure that each technique can effect. The more pressure there is, the wider the blade, assuming the core allows it (Crabtree 1968). While the use of a shoulder crutch (mode 2) slightly increases the maximal size of blades in comparison to the hand-held pressure tool (mode 1), the use of a short crutch (mode 3) or of a long crutch (mode 4) adds to the pressure exerted by the knapper its own

[9] Cavalli-Sforza and Feldman (1981 pp. 308–314) take blade variation and evolution as a candidate example of mutation (copying-error) in continuous traits.

[10] See the papers in Desrosiers (2012) for reviews of the ethnoarchaeological distribution of blade variation.

[11] For each mode, Pelegrin tested the differences induced in the range of producible blades when using pressure tools with different tip materials (ivory vs. copper), when using different core materials (flint and obsidian), and when using heat-treatment of the core. More techniques are possible given that crutches may themselves vary in design and manner of use (Clark 1982; Crabtree 1968). The same goes for the different core stabilizers (Pelegrin 2012).

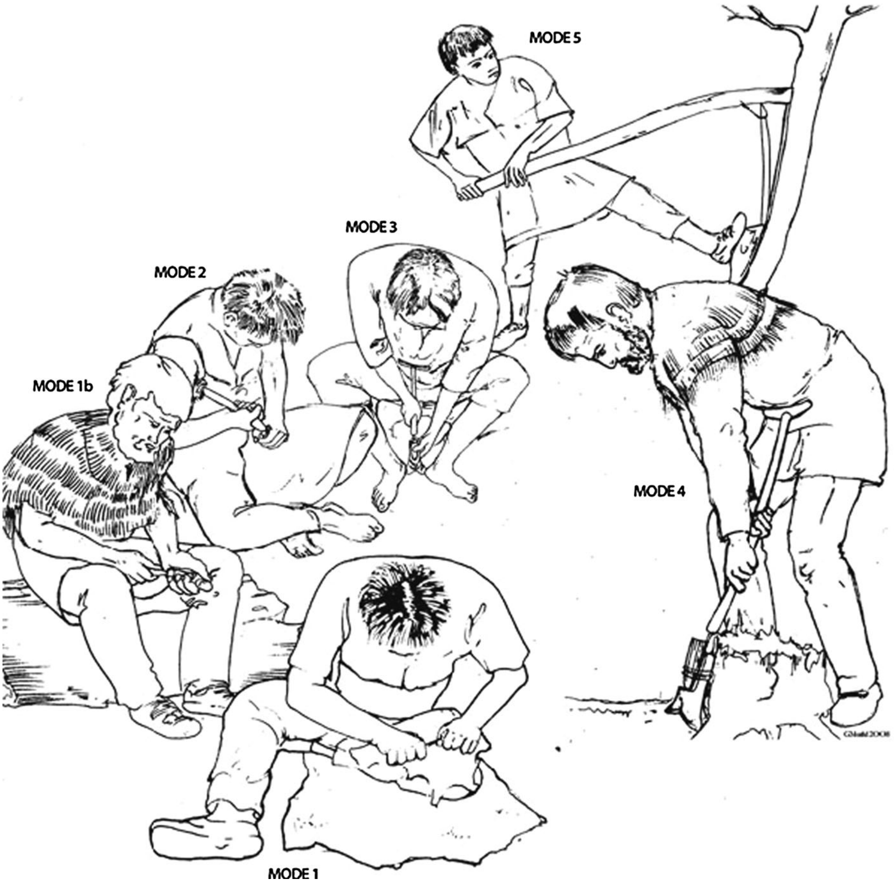

Fig. 2 Illustration of the five modes experimentally examined by Pelegrin. *Mode 1* hand-held pressure flaking without and with (mode 1b) a core stabilizer. *Mode 2* short (shoulder) crutch pressure flaking with hand-held core stabilizer. *Mode 3* short crutch with fixed core stabilizer. *Mode 4* long crutch with fixed stabilizer. *Mode 5* lever pressure with fixed stabilizer. From Pelegrin (2012, p. 491), used with permission

weight. However, only the use of a lever (mode 5) can increase the pressure to the 300 kg required to produce the longest blades found in the archaeological record (Pelegrin 2012). Moreover, more powerful levers can be devised, thus allowing the production of longer blades, with the size and homogeneity of the raw material determining the range's boundaries (Pelegrin's experiments were limited to producing 6 cm wide, 40 cm long blades).

These pressure techniques also depend on the use of different stabilizing devices as the flaking proceeds. While modes 1 and 2 depend on applying pressure through a flaker in one hand and holding the core in a hand-held stabilizer (or holding the core directly in one's hand as in mode 1a), modes 3 and 4 require that the core be stabilized on the ground for the knapper's weight to be properly applied. This change in stabilization technique also adds up to precision in flaking, as "the force is

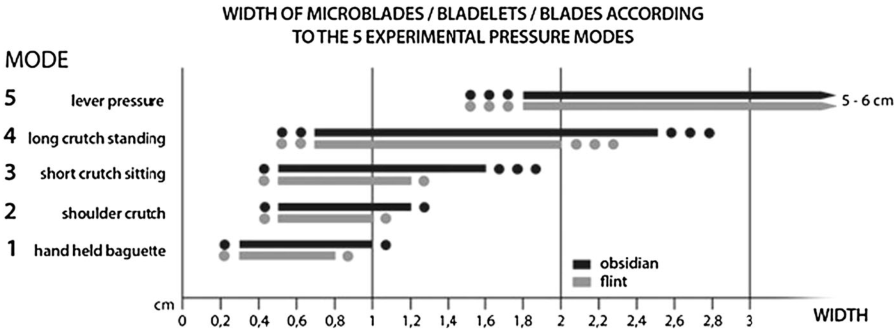

Fig. 3 Blade production techniques. No single technique is able to access the same regions of blade morphology. *Points* represent the extended range of each technique if they incorporate copper heads instead of ivory or antler heads, and the effects of heat treatment on the core. From Pelegrin (2012, p. 479), used with permission

delivered in a straight axis that can be better controlled by the eye and exerted exactly in line with the blade to be removed […]. This explains a '*jump*' in the regularity of blades produced due to excellent control of the flaking direction, whereas many of the microblades detached by modes 1–2 are somewhat twisted or skewed." (Pelegrin 2012, pp. 471–473; emphasis added) Finally, heat-treatment on the core increases the maximal width of the accessible flake products for each mode by about 20–30 %, with a copper tip for the flaker increasing the amount of pressure that can be applied on the core (ivory- or antler-made tips tend to crush more easily).

While the different techniques rely on different recipes for action, it is not the structure of these recipes that constrains the space of variation in the artifacts. As much as a knapper may desire to produce a 20 mm width blade through a hand-held baguette, the amount of force required will simply be out of reach, even though one could teach a recipe to produce these blades by suggesting that "one must press very, very hard on the core." What these results show is that different techniques of lithic production effectively constrain the upper and lower limits of the accessible blade morphologies. The factors that constrain artifactual variation are not the desired outcomes of the knapper, but rather the technical factors that come into play in the production of the blades. The amount of pressure applied is critical to determine the length of a blade, and human musculature alone can only do so much. This is why enhanced human capabilities through crutches and levers allow the production of longer blades, in parallel constraining the size of the shortest blades that can be produced through the same techniques. The materials used and heat treatment also result in important changes in the range of artifacts that can be produced with these techniques. All these factors—pressure and the means to obtain it, the structure of the material and its reaction to pressure, etc.—are physical constraints on the production of the blades.

Eerkens and Lipo approach projectile-point evolution through the implicit assumption that the mapping of the variation spaces of mental representations and public displays is an isomorphic one (Fig. 4a). This is because they conflate

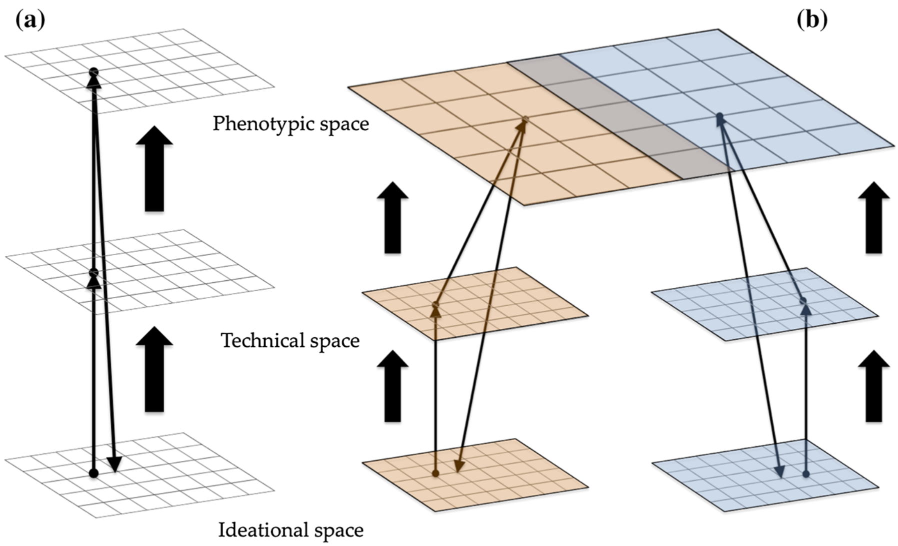

Fig. 4 Technical space as an intermediary space shaping the mapping of variation and change in mental representations and in public displays. *Large arrows* represent the causal direction of demonstration. *Upward slim arrows* represent the demonstration of a specific public display from a specific mental representation; *downward slim arrows* represent acquisition of a specific mental representation from a specific display. **a** A mapping where the conflation assumption holds, such as in the Rosegate series case: technical space allows an isomorphic mapping between the two other spaces. A small copying-error will produce an equivalently small change at each level. **b** A mapping where the conflation does not hold, such as in the lithic blade case. A small change in public displays through the region where the two techniques overlap may not produce an equivalently small change in mental representations. A change in technique will be required

variational change in mental representations and public displays. However, missing from their account is a justification that the whole range of forms they studied is accessible through the very same technique. They give no indication of the techniques used other than the fact that the projectile points were made of obsidian. I believe it is safe to assume that Eerkens and his colleagues do not expect changes in the recipe or the technique used for the production of projectile points of different width and thickness, i.e., only the information concerning the shape of the artifact is subject to variation. In this sense, I agree with them that the conflation of variation and change at each level of the transmission process is warranted.

However, a similar assumption in the case of lithic blades would lead to incorrect evolutionary expectations. To have a correct understanding of the evolution of lithic blades, we need to take into consideration how technical space shapes the mapping between each step of the transmission process. Indeed, because the variational change of the mental representations of blade morphologies does not map in a one-to-one manner to variational change in actual blade morphologies, the conflation assumption fails to hold across the range of blade variants. Detours through technical space are required, with each technique delimiting its own range of accessible public displays (Fig. 4b). Of course, the mapping inside the range of accessible forms allowed by a technique can be isomorphic, i.e., the conflation assumption can hold inside specific boundaries as with the Rosegate series case. However, it remains necessary to empirically validate the mapping and thus to consider the techniques in order to know the boundaries inside which an isomorphic mapping can be assumed.

Tools for more research

As change in the techniques a given population employs can redefine which public displays are accessible for that population and which ones are out of reach, an examination of the complexities introduced by techniques will thus be crucial for determining the boundaries of accessible cultural variation and for assessing the pattern and pace of cultural evolution. The present framework promises to be useful for expanding cultural evolutionary theory by offering tools to address issues in which the topology of variation spaces is likely to have evolutionary effects. To conclude, I briefly point to two issues that could benefit by furthering the present framework, namely cultural gradualism and cultural convergence. Obviously, a deeper understanding of cultural gradualism and convergence requires much more work than I can offer here. I merely indicate that a focus on multiple spaces of variation, their boundaries, and their mapping, promises to be relevant in addressing the interface between multiple metrics of cultural change and issues related to convergence. Substantiating these claims can only proceed through the refinement of this preliminary framework, that is, by putting it to use with specific case studies.

Any claim of gradualism in cultural evolution is based on the idea that cultural change proceeds by small incremental steps. However, what can appear as small changes in public display can be the result of important technical changes (e.g., as with the case of lithic blades and the invention of the lever for producing larger lithic blades). Conversely, large changes in public displays could in fact be the result of small technical changes. What will count as gradual cultural change, and how we measure it, will thus depend on the specifics of the level at which change occurred and how the production of public displays and the learning of mental representations relate to one another through the transmission process. Metrics to assess what counts as small or large change in the structure of a technique is generally lacking in the literature, and should be systematically studied. Nevertheless, the use of variation spaces and the framework of technical space offer natural tools for studying those cases where the mapping between each step of the transmission process is not an isomorphism.

Assessing the boundaries and the topological structure of the variation space of some particular class of mental representations and public displays can also help the cultural evolutionist to examine issues of cultural convergence. Convergence is the evolutionary phenomenon in which independent lineages evolve similar forms as a result of developmental and/or functional constraints (McGhee 2011). Differentiating convergence with synapomorphy (i.e., related lineages sharing a same trait that is present in their common ancestor) allows us to test for the historical relatedness of similar cultural traits. Studying the technical constraints on the production of public displays such as complex behaviors and artifacts can help with the task of determining what forms are possible given the presence of specific techniques. Should we find that a technique allows only highly constrained spaces of public display such that different populations possessing the technique are likely to produce similar cultural products, the analysis would support claims of independent invention (Lycett 2011).

Technological evolution is likely to be a domain of investigation where the evolutionary dynamics of complex behaviors and artifacts—and thus of the mental representations involved in their reproduction—promises to be such a complex affair, with boundaries of variation and complex multi-space mapping having important roles in shaping the evolutionary process. Nevertheless, I see no principled reason why these considerations could not be extended to other cultural domains. The absence of constraints on cultural variation is as much an important phenomenon as their presence, and models built on the conflation of variational change at both steps of the transmission process are not designed to address the localization of boundaries on cultural variation. This is not to say they are wrong. Rather, it means that the adoption of a one-to-one mapping strategy needs to be empirically grounded, and that the question about the mapping of variational space needs to be addressed. The framework developed here aims to serve this very purpose.

Conclusion

Modeling techniques conflating variational change in mental representations and in public displays will be well suited for cultural traits for which there are few or simple constraints on the transmission process. In other cases, the mapping of variational change through the different constitutive processes of social transmission (demonstration and acquisition) will not be as straightforward. The preliminary framework developed here offers new research avenues for integrating the results of empirical studies concerning the cognitive, material, and embodiment constraints on the enactment of techniques into the evolutionary framework of cultural evolutionary theory.

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