This description of the model presented in Miller-Atkins and Premo (2018) follows the ODD protocol (Grimm et al. 2010).

Purpose

We employ this spatially explicit agent-based model to begin to examine how time-averaging can affect the spatial scale of cultural similarity in archaeological assemblage data. The model was built to address this question: to what extent does time-averaging affect the scale of local spatial association in the relative frequency of the most prevalent cultural variant in an archaeological landscape?

Entities, State Variables, and Scale

In the context of our research question, the agents in our model represent hominins, but here we refer to them more generally as individuals. Each individual displays two variables: age (either a 0 or a 1) and a neutral cultural variant, denoted cultvariant. If born on the current time step, the individual has an age of 0. If born the previous time step, the individual has an age of 1. Each individual displays a cultural variant, represented by an integer. In this model, cultural variants are selectively neutral in the sense that they do not confer fitness benefits upon the individual. Individuals have three actions: learn, deposit a cultural variant, and die. Naïve individuals (age=0) learn a variant from the experienced generation (age=1). Naive individuals learn socially through one of three cultural transmission mechanisms: unbiased, vertical, or conformist. Experienced individuals can engage in horizontal intergroup cultural transmission.

There are 10 global variables: *N*, initPopulation, extinctionProb, errorProb, copyErrorModel, cultTrans, intergroupCTRate, intergroupCTExtent, *d*, and seed. *N* is the maximum number of individuals per group. When initPopulation = heterogeneous, are initialized with unique cultvariant values. By contrast, when initPopulation = homogeneous, then every individual is initialized with a cultvariant of 0. extinctionProb represents the probability per group per time step of local extinction. Each extinction event is followed by a recolonization event. errorProb is the probability per intragroup transmission event that the naïve agent makes an error when copying the target value of its cultural variant. copyErrorModel designates which of three copy error models are employed through the simulation run. According to a bidirectional single-stepwise model of copy error, the naïve individual mistakenly adopts an integer that is one greater or one less than the target value with equal probability. For example, a naïve individual who makes an error while attempting to copy the variant "5" will ultimately adopt either "4" or "6" with equal probability. Note that the bidirectional single-stepwise model of copy error allows for "back-innovations," such that an error results in the same variant displayed prior to the previous copy error. In fact, under the bidirectional single-stepwise model, an error results in a "back-innovation" with probability .5. We also investigate the effects of time-averaging under a finite variants model of copy error in which the number of possible variants is arbitrarily capped at 100. In this case, each copy error results in the naive individual being randomly assigned one of the 99 variants that is not its intended target value. The probability of a "back-innovation" (per copy error) in the finite variants model is 1/99. The infinite variants model of copy error eliminates the possibility of back-innovation altogether. With infinite variants, each copying error results in the introduction of a novel cultural variant never before seen during the course of the simulation run. cultTrans designates the mechanism of intragroup cultural transmission employed throughout the simulation run. Under unbiased transmission, each naïve individual randomly selects (with replacement) an experienced member of its group to serve as its teacher.

Vertical cultural transmission is modeled in the same way as the genetic transmission of haploid genes during asexual reproduction—each naïve individual inherits its parent's cultural variant. Under conformist biased cultural transmission, naïve individuals attempt to copy the modal cultural variant of the experienced members of their group. If the majority of a group's experienced members display "5," then every member of the naïve generation in that group will attempt to copy "5." In the event that a group's experienced generation exhibits more than one mode, each naïve individual in that group chooses from among the modal variants with equal probability. For instance, assuming "5" and "8" are both modes of a group's experienced generation, some naïve members of that group may try to copy "5" while others in the same group try to copy "8." intergroupCTRate represents the proportion of the population that engages in intergroup cultural transmission. intergroupCTExtent defines the spatial extent over which horizontal intergroup cultural transmission takes place. When intergroupCTExtent=local, each agent chosen to form a pair randomly chooses its intergroup transmission "partner" from among the members of one of the eight groups immediately adjacent to its group. When intergroupCTExtent=global, each agent chosen to form a pair randomly chooses its partner from a group other than its own without respect to the other group's location on the lattice. *d* represents the duration of assemblage formation. Increasing *d* increases the degree to which an assemblage is time-averaged. seed is the integer value used to seed random number generator at the start of the simulation.

Time is represented with discrete steps, or "ticks" in the parlance of NetLogo. In this model, each tick encompasses the time required for both intergroup cultural transmission among members of the experienced generation and intragroup transmission of cultural variants from the experienced generation to the naive generation. The model is spatially explicit. The "world" consists of a 20 x 20 grid, wrapped around a torus to avoid edge effects. Each square grid cell, called a patch in NetLogo, can be occupied by up to *N* individuals. Each patch also contains an archaeological assemblage that forms as inhabitants deposit cultural variants through simulated time. Following terminology used in distributional archaeology (Ebert 1992), we refer to the entire set of 400 assemblages collectively as the archaeological landscape.

Process Overview and Scheduling

Seven processes take place every time step in the following order: intergroup cultural transmission, local extinction, recolonization, agents age, a new generation is born, intragroup cultural transmission, and then the experienced generation is culled. Once the simulation has reached 10,001 ticks an eighth process, cultural variant deposition, occurs after the experienced generation is culled.

1. Intergroup Cultural Transmission

A proportion (intergroupCTRate/2) of agents are randomly chosen and asked to find a partner outside of their own group. When intergroup transmission is "local," the partner must come from a neighboring group. When intergroup transmission is "global," the partner can be a member of group other than ego's. Once a partner is chosen, the pair of individuals simply swap their cultural variants with each other across group boundaries.

2. Local Extinction

Each patch draws a number from a uniform distribution between 0 and 1. If that number is less than or equal to extinctionProb, then all agents occupying that patch die.

3. Local Recolonization
Each patch with zero members randomly selects a patch from among those in its Moore neighborhood that have at least 2 members. The randomly chosen neighbor then sends half of its members (rounded up to the nearest whole number) to the empty cell to serve as the recolonizers.

4. Aging
All agents set their age to 1, establishing the "experienced" generation that will teach members of the naive generation. Only "experienced" agents may serve as teachers.

5. Create Naive Generation
Each group creates N naive individuals that have age = 0. In the presence of conformist biased cultural transmission or unbiased cultural transmission, N naïve individuals are created in each patch without reference to any biological parents in the experienced generation. Because cultural transmission is oblique in both cases, there is no need to track biological lineages. By contrast, in the presence of vertical cultural transmission each member of the experienced, or "parental," generation in each patch reproduces (asexually) iteratively until N naive individuals have been created.

6. Intragroup Cultural Transmission
Cultural transmission occurs via one of three mechanisms: conformist, unbiased, or vertical cultural transmission. Note that naïve agents cannot learn from members of neighboring groups under any condition. Intragroup cultural transmission is imperfect and naive individuals can make mistakes during transmission. Thus, each naive agent commits a copying error with probability errorProb per transmission event.

7. Cull Experienced Generation
All individuals in the "experienced" generation (i.e., age=1) die.

8. Deposit Cultural Variant
Starting with time step 10,001, at the end of each time step every agent contributes its cultvariant to the archaeological assemblage of its cell.

Design Concepts

Learning

Individuals are social learners. Naïve agents learn from the experienced generation. Naive individuals adopt cultural variants through one of three cultural transmission mechanisms: conformist, unbiased, or vertical cultural transmission. Experienced individuals can also learn horizontally via intergroup cultural transmission.

Sensing

Naïve individuals have access to the age and cultvariant of the experienced individuals that occupy their patch.

Interaction

Agents interact with each other only during cultural transmission. Interactions between agents of different ages are restricted to members of the same group. Naïve individuals do not interact with each other. Experienced individuals interact with each other only during intergroup cultural transmission.

Stochasticity

Stochasticity figures heavily in this model--here are just a few examples: Copying error and local extinctions are both probabilistic. In unbiased cultural transmission, teachers are chosen randomly (and with replacement) from among the experienced group members. In conformist biased transmission, ties between multiple modes of cultural variants are broken randomly. During recolonization, the colonizing group is chosen randomly from among the empty cell's Moore neighbors that contain at least 2 members and recolonizers are chosen randomly from the selected group. Please see the source code for the many other examples of stochasticity in this model.

Collectives

There are two kinds of collectives in this model: groups and generations. The population is spatially structured by groups. Each unique cell on the 20x20 grid can host one group of *N* individuals. Cultural transmission takes place within groups. Only the members of the group that currently occupies a cell can contribute cultural variants to that cell's assemblage during the current time step. A local extinction event eliminates all individuals within the affected group. Individuals are also classified by age into two distinct generations. Naive individuals are marked by an age of 0. Members of the experienced generation are marked by an age of 1.

Details

Initialization

Each simulation starts with 400 groups of *N* individuals. Population size is held constant throughout the simulation. The parameter values used in our experimental design are shown in Table 1. Twenty unique simulations were run for each parameter combination reported. Please see BehaviorSpace to run the same experiments reported in Miller-Atkins and Premo (2018).

Table 1. Parameter values used to initialize the simulations reported in Miller-Atkins and Premo (2018).

Parameter	Value(s)
N	25
initPopulation	Heterogeneous
extinctionProb, *e*	0.01
errorProb, μ	0.0001, .001, .01
copyErrorModel	bidirectSingleStepwise, finiteVariants, infiniteVariants
cultTrans	unbiased, vertical, conformist
intergroupCTRate, *m*	0, 0.05
intergroupCTExtent	local, global
d	1, 1000, 10,000
seed	1-20

Data Collection

The relative frequency of the most prevalent cultural variant was collected for the assemblage in each patch in order to calculate Local Moran's I_i with the "spdep" package in R (Bivand and Piras 2015, Bivand et al. 2013). These data were collected at 10,001 (*d*=1), 10,010 (*d*=10), 10,100 (*d*=100), 11,000 (*d*=1000), and 20,000 (*d*=10,000) ticks.

Submodels

Intergroup Cultural Transmission ("intergroup-cultural-transmission"):

At the start of each time step, a proportion (intergroupCTRate/2) of individuals from the experienced generation are asked to pair with a member of a different group and then the pair swaps cultural variants across group boundaries. When intergroupCTExtent=local, the group from which the partner is chosen must be in the Moore neighborhood of ego (excluding ego's group). When intergroupCTExtent=global, the group from which the partner is chosen can be any group other than ego's. Note that intergroup cultural transmission is horizontal and it is not susceptible to copy error in this model.

Local Extinction ("local-extinction"):

After intergrooup cultural transmission, each cell draws a random number from a uniform distribution between 0 and 1. If the number is less than extinctionProb all agents located on that cell die.

Recolonization ("recolonize"):

The recoloniztion of empty cells occurs only after all groups have been exposed to local extinction. Each empty cell randomly selects one of its Moore neighbors (the 8 adjacent cells) that contains at least 2 members. The chosen patch sends half (rounded up) of its members (chosen randomly) to the empty cell. These recolonizers serve as the "experienced" generation of the vacant cell to which they move. The same group may be involved in multiple fission events during the course of a single time step.

Intragroup Cultural Transmission ("intragroup-cultural-transmission"):

Cultural transmission from the experienced generation to the naive generation occurs via one of three mechanisms: conformist, unbiased, or vertical cultural transmission. In each case, naïve individuals learn from members of the experienced generation within their groups. Under conformist learning, each naive agent learns the modal variant displayed by the experienced generation within its group. If there are multiple modal variants, then each naive agent randomly selects one of the modal variants. Under unbiased cultural transmission, each naive agent randomly selects a teacher (with replacement) from the experienced members of its group. Unbiased cultural transmission allows for multiple naive agents to select the same teacher. Vertical transmission can be viewed as single parent-to-child transmission. Under vertical transmission, every member of the "experienced" generation in a group teaches an equal number of students whenever *N* is a multiple of the size of the group's experienced generation. For example, if there are 5 experienced individuals in a group, then each one will teach 5 naive individuals. However, if *N* is not a multiple of the size of the group's experienced generation, then some experienced individuals (chosen randomly) will teach one more student than the other experienced individuals. For example, if there are 8 experienced individuals in a group, then 7 of them will teach 3 naive individuals and 1 of them (chosen randomly) will teach 4 naive individuals.

Cultural Variant Deposition (“create-total-assemblage” and “create-patch-assemblage”):

There are two global lists in the model. The total diversity list includes every unique cultural variant deposited in the archaeological landscape though time. The total frequency list records the frequency (at the same position) of each unique cultural variant in the archaeological landscape. Near the end of each time step, each individual compares its cultural variant to the total diversity list. If its integer is not already represented on the total diversity list, the agent adds its integer to the end of the total diversity list and adds a 1 to the end of the total frequency list, ensuring that information regarding that variant holds the same position in both lists. If the individual’s variant is already represented on the total diversity list, its previous frequency on the total frequency list is simply increased by 1 (say, from 22 to 23), but there is nothing new to add to the total diversity list.

Each patch contains two patch-specific lists similar to the global lists. The patch diversity list includes an entry for every unique cultural variant deposited in the patch through time. The patch frequency list records (at the same position) the number of times that each of the unique cultural variants in the patch occurs in the patch’s assemblage. As in the global case, each individual in the patch first checks whether its cultural variant is present in the patch diversity list. If it is not present, the individual adds the integer value of its cultural variant to the end of the patch’s diversity list and inserts a "1" to the end of the patch frequency list using "lput". If the variant is present on the diversity list, then the individual increments by 1 the value on the frequency list that holds the same position as the cultural variant on the diversity list, but there is nothing new to add to the patch's diversity list.

Calculate Relative Frequency of Most Prevalent Variant ("calculate-relative-freq")

This submodel is a patches method. It calculates the relative frequency of the "most prevalent variant" in each patch's assemblage. If the patch's assemblage does not contain at least one instance of the most prevalent variant (i.e., most prevalent at the scale of the entire archaeological landscape over duration *d*), then relativeFreqMostPrevalentVariant is set to 0. If the patch's assemblage does have at least one instance of the most prevalent variant, then relativeFreqMostPrevalentVariant is set equal to the frequency of the most prevalent variant in that patch's assemblage divided by the number of artifacts in the patch's assemblage. Note that the denominator increases as a function of *d*.

Important Model Assumptions/Caveats

The model was developed to investigate the effects of local group extinction and time-averaging on the scale of spatial association in the relative frequency of the most prevalent cultural variant in an archaeological landscape. The cultural variants in our model are selectively equivalent; variants do not differentially affect an agent’s ability to reproduce. This was a pragmatic decision. Archaeologists tend to address culture in the archaeological record by focusing on “stylistic” traits, traits that are assumed to have provided no fitness benefit to those who displayed them. The model could be modified to investigate traits that affect the fitness of those who display them. We chose not to do that here to better isolate the effects of local extinction and time-averaging.

It is also important to note that our model considers just one kind of recolonization—-namely, local recolonization. There are multiple ways to model recolonization, most of which would likely affect our results. For example, if colonizers were randomly drawn from the entire population, regardless of distance to the empty cell, rather than from just one neighboring cell, it is unlikely that new group would closely resemble its neighbors culturally. That is to say, without local recolonization, one would not expect clusters of culturally similar groups to emerge. Under such conditions, it may be impossible for the assemblages of spatially proximate cells to accumulate similar frequencies of the most prevalent cultural variant. In that case, one should expect spatial lag to have no effect on mean I_i values, holding extinctionProb and d constant.

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