Human Mate Choice is a Complex System

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From a psychological perspective, human mate choice has been viewed as a problem of identifying the individual cognitive preferences and decisions that explain empirical results such as similarity in attractiveness between mates and the right-skewed unimodal marriage hazard curves for marriage rates. Agent-based models provide a powerful theoretical tool for investigating this relationship, but until now have not considered the effects of local neighborhoods or mobility on emergent population dynamics. In failing to do so, they have effectively ruled out the population-level complexity inherent in human mate choice. Real people live in physical space, and their interactions are constrained by their location in and mobility among physical neighborhoods and social networks. We developed a general model of human mate choice in which agents are localized in space, interact with close neighbors, and tend to range either near or far. At the individual level, our model uses two oft-used but incompletely understood decision rules: one based on preferences for similar partners, the other for maximally attractive partners. We show that space and mobility can interact nonlinearly with these individual decision rules and nonspatial aspects of the population structure. In particular, local interactions and limited mobility decrease interpair matching and increase mate search time. We also show that it is too easy to fit various model configurations to the scant available data. More data and more specific predictions are required. Human mate choice is a complex system with properties that emerge from space, mobility, and other factors that structure social dynamics. © 2011 Wiley Periodicals, Inc. Complexity 00:000–000, 2011

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1. INTRODUCTION

U nderstanding the dynamics of human mate choice and its sociocognitive mechanisms is a problem for social psychology, demography, and human behavioral ecology that is typically viewed as discovering the cognitive mechanisms underlying human mate choices. Population-level phenomena, such as correlations in intrapair physical attractiveness [1, 2] or the commonly observed right-skewed unimodal hazard curve for marriage rates [3, 4], are viewed as resulting from the aggregate of many

individual decisions. Researchers have recently recognized the value of agent-based models (ABMs) for shedding light on possible mechanisms of human mate choice [5, 6], allowing us to test hypotheses connecting individual-level decision behavior to population-level data [7]. Previous ABMs have shown, for example, that preferences for maximally attractive partners can produce assortative mating [8], that simple heuristics and bounded rationality can generate robust and realistic demographic patterns [4, 9], and that sex differences in mate search strategies can explain age differences between male and female marriage hazard curves [10].

In previous ABMs, males and females encounter one another by random matching processes, without respect to location in either physical or social space. These models assume a population of marriageable agents constitutes a "dating pool," and that males and females are paired up randomly on consecutive time steps. The dating pool assumption is unrealistic. People live in physical space, and their interactions are constrained by their physical neighborhoods and social networks. People also move in space, and whether they range close or far influences their social encounters. Specifically, location and mobility influence mate choice. Individuals tend to find their marriage partners from within their social groups [11]. Marriage partners also tend to share locations of origin, but this tendency decreases with age as local availability diminishes and mobility increases [12]. Human mate choice, when considered at the population level, is clearly a complex system likely to yield surprising emergent properties. The dating pool assumption in previous models rules these out.

Previous studies using ABMs have masked this complexity—even though they have made the dating pool assumption—by fitting models to empirical data on both assortative matching and marriage hazard rates. This has resulted in specific predictions, such as specifying the rates of divorce and the frequency of unmarried individuals in a population [13]. If, as tacitly assumed, the structure imposed on interactions by space and mobility do not matter, then these predictions may appear robust, but we will show that they are not. In real life, pairings of potential partners are not random. We will show that precise fits to data, under the dating pool assumption, are likely due to unrealistic assumptions or parameter values that effectively eliminate the population-level complexity inherent in human mate choice. Failure to include population-level complexity limits our ability to use these models to make useful predictions and discover emergent properties of human mate choice. It is important, then, to understand the influences of the dynamics of location and mobility on mate search in both physical and social space.

1.1. Modeling Human Mate Choice

Our strategy is to analyze a very general model of human mate choice, so that our results will apply to most if not all past and future mate choice ABMs. Our goal is to include general characteristics of human mate choice that do not rule out emergent social structure and properties. To this end, we believe models of human mate choice should include the following characteristics.

1.1.1. Basic Population

The population consists of a finite number of male and female agents, where each individual has some trait (or set of traits) that influences his or her own behavior and the behavior of potential partners regarding mate choice decisions. For simplicity, we will use a single unidimensional trait to represent attractiveness. In addition, we will also consider the effects of a dynamic population that includes the immigration of new single adults.

1.1.2. Decision Rules

Decision rules are used by agents to accept a potential partner as a mate. These rules may be deterministic (e.g., always accept someone with characteristics above a threshold value) or probabilistic. Decision criteria may include preferences for similarity (homophily), or preferences for a universally agreed on quality (such as physical attractiveness), both of which are supported by empirical studies of human mate preferences (similarity: Refs. [14–17]; attractiveness: Refs. [18–20]. See also Refs. [21] and [22]). Some models may include multidimensional trait spectra [10, 13], and so can model individual differences as well as a mix of homophilic and quality preferences. Nevertheless, they are still versions of two basic types of decision rules: choose the best or choose the most similar. We will examine two probabilistic versions of these rules, and how the inclusion of environmental and social structure interacts with these two types of decision rules. We predict that space and mobility, which reorganize the environment and social structure of individuals, can greatly affect the results from these two decision rules. Any interactions with decision rules should both inform future models with more complex individual preferences and begin to reveal emergent properties of human mate choice systems.

1.1.3. Changing Preferences

Agents' preferences should change as a function of age and/or experience. This may translate to a relaxation of strict preferences as the risks of remaining single begin to outweigh the benefits of holding out for an ideal mate. We assume that agents gradually increase the probability of accepting less-than-ideal partners as they experience more and more failed mating opportunities. Previous and future

models have and will include this assumption in various forms. We investigated a general version of this assumption to assess its impact on mate choice.

1.1.4. Structured Interactions

Non-dating pool mechanisms for how agents are paired up for potential mating choices. As noted, previous models used random pairings, which effectively eliminated environmental complexity and therefore phenomena that emerge from this complexity. Real mate choice systems include interactions limited by physical and/or social space. These limitations may be modeled by locating agents on a lattice, grid, or network. Mobility can be modeled by allowing agents to update their locations in space or by updating edges in a network. In our model, we situated agents on two-dimensional grids, and restricted interactions to include only those agents within a fixed radius. Because it likely matters whether individuals tend to range close or far, we also considered two different random walk strategies that vary in their tendency to facilitate local versus more global searches for mates. These random walk strategies represent generic search strategies with specific characteristics found in a myriad of possible search strategies.

1.1.5. Additional Complexity at the Individual Level

Some models may add complexity to individual-level behavior, such as adolescent learning periods [4, 23], courtship [9, 10, 24], and divorce [13]. We will show that any combination of specific individual-level mechanisms, including learning periods and courtship, can fit any data on right-skewed unimodal marriage hazard curves, and do so by sharing a small set of properties. We will use an extremely simple mechanism with properties similar to previously modeled mechanisms to generate right-skewed unimodal marriage hazard curves with our model. This implies that future models must be better informed by empirical data on individual cognitive and developmental mechanisms to assess their validity.

1.1.6. Additional Complexity at the Population Level

In addition to space and mobility, other population-level features may influence mate choice dynamics. We will consider the example of changes to population density, and examine possible interactions with decision rules and local interactions to illustrate the complexity of human mate choice.

1.2. Expectations About Space and Mobility

Restricting interactions to an individual's local neighborhood should decrease interpair matching and increase the time needed to search for a mate, due to constraints on the number and variety of individuals encountered. For this reason, mobile agents that tend to roam in a local neighborhood will have reduced matching and increased search times relative to more far-ranging agents. We will show that search strategies interact with cognitive decision rules and in some contexts fundamentally alter their implications. Context dependence at lower levels is a signature of a complex system [25].

Once we deviate from reductionistically modeling human mate choice as occurring in a well-mixed population of fixed-size, the inclusion of space and mobility, as we will see, influences population dynamics in less intuitive ways. Different decision rules may respond differently to a variety of changes to the population structure, and these effects may be mediated by limitations to local interactions. Local neighborhoods, after all, are smaller and contain less variety than global populations. We will consider changes to two features of the population that may influence local or global heterogeneity: (1) population density and (2) an influx of new single agents to replace those in mated pairs.

We will also consider the case in which there is variation in the initial age of agents in the population so that there are "immature" agents not yet ready to mate. We will show that including this simple mechanism can produce right-skewed unimodal mating hazard curves like those seen empirically. More generally, we will show that assumptions about the structure of social encounters interact with individual decision rules and population structure. Indeed, if there are no empirical constraints on assumptions, almost any results can be generated from different decision rules by varying assumptions about the environmental structure. This indicates that models of human mate choice must include more rigorous descriptions of the structure of social encounters to make more precise predictions.

2. THE MODEL

Our model assumes a population of N females and N males. To maximize generalizability, each agent i has a single trait A_i, which is a measure of his or her "quality" or attractiveness to a potential partner. A_i is an integer between 1 and k, drawn either from a uniform distribution $U(1, k)$ or a normal distribution $N(\mu, \sigma)$ with mean μ and standard deviation σ, bounded between 1 and k inclusively.

When an agent has reached the age of adulthood, it begins searching for a partner. An agent has x opportunities each time step to find a mate—x simply sets the scale of the time coordinate when examining our data. An agent searches its local neighborhood for an agent of the opposite sex for a "date," from the set of those agents not already on a date. If both agents find their partner acceptable, the two marry and are removed from the dating pool.

FIGURE 1
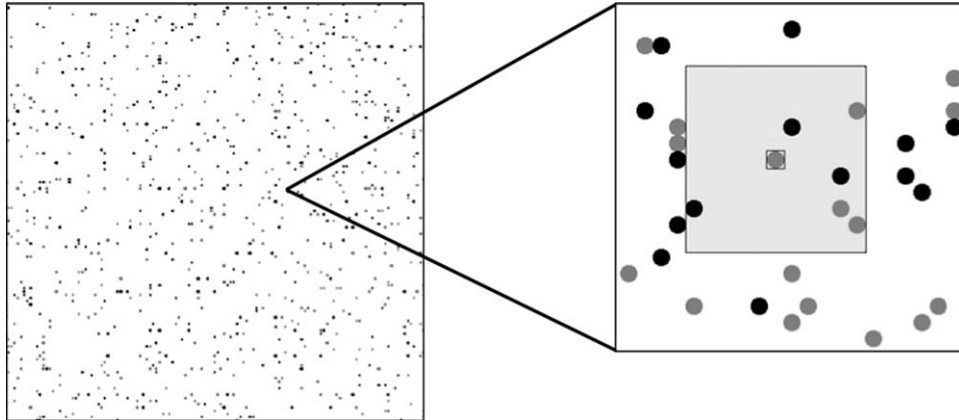
The simulation environment and a local neighborhood. The gray square is the local neighborhood of the gray agent (female) in the inner square, and consists of three potential dates (the black agents, males).

An agent i accepts agent j with probability $p(i, j)$, which we describe below. As an agent experiences an increasing number of unsuccessful dates, its criteria for accepting a date become less rigid, and thus p increases toward unity. This satisficing rule takes the form of an exponent λ, such that

$$\lambda = (D - d)/D, \qquad (1)$$

where d is the number of previous (failed) dates and D is the number of failed dates for which the probability of accepting any partner becomes one.

2.1. Decision Rules

The decision processes that go into selecting a mate are complex, based on multivariate cues that unfold over a prolonged time period [26], and they are not well understood. Our basic aim is to understand the role of socio-environmental constraints on mate choice and how those constraints introduce complexity into human mate choice. Therefore, we will consider two simple rules, recognizing that future models will have to make headway in gathering empirical data that shed light on the multivariate and temporal complexity of human decision making. One of these rules is based on a preference for the most attractive partner (rule 1), and the other is based on a preference for the most similar partner (rule 2). Depending on which rule is used, the probability of agent i accepting agent j is given by

$$p_1 = \left(\frac{A_j}{k}\right)^{\lambda n}$$
$$p_2 = \left(\frac{k - |A_i - A_j|}{k}\right)^{\lambda n}$$

where the exponent n corresponds to the agents' baseline choosiness (i.e., their initial willingness to accept dates that deviate from the ideal given by each rule). In a world where agents use rule 1, maximally attractive dates are always accepted. Likewise, in a world where agents use rule 2, agents that are maximally similar to themselves are always accepted. Kalick and Hamilton's [8] (KH) model used a special case of these two general decision rules.

2.2. Spatial Neighborhoods

In all previous ABMs of human mate choice, agents were assumed to assort randomly. In our model, agents must make their date selection from within their local neighborhoods. The agents' social universe is a two-dimensional square grid of length L. An agent's local neighborhood is defined by a search radius s, consisting of an agent's home cell and extending s cells in each of the four cardinal directions (Figure 1). If no undated agents of the opposite sex are found in the agent's local neighborhood, the agent fails to date on that round.

2.3. Movement Strategies

Agents do not have permanent local neighborhoods; instead they move through their environment using a random walk, taking one step at the beginning of each turn. We used two types of random walks. The first is the standard Brownian (BR) walk in which an agent chooses its destination from among its eight nearest neighboring sites (the Moore neighborhood), with each direction selected with equal probability. In this way, neighborhoods are dynamic, and agents slowly come into contact with new potential partners. The second is the Zigzag (ZZ) walk, in which an agent chooses its destination by moving either to the

TABLE 1

Summary of Decision and Movement Rules

Decision Rules	Interpretation	Movement Rules	Interpretation
Rule 1	Probability of acceptance increases monotonically with j's attractiveness	BR	Move randomly to one of the eight nearest neighboring sites
Rule 2	Probability of acceptance increases monotonically with the similarity between i and j	ZZ	Move randomly forward-left or forward-right
Satisficing Rule	Probability of acceptance (using either rule) increases with the number of unsuccessful dates	NS	No movement and all agents are equally likely paired on any round

Decision rules describe the probability that individual i will accept his or her date j.

forward-left or forward-right (based on its current orientation), each chosen with equal probability. We introduced ZZ because regional, cultural, or individual differences may result in increased contact with strangers. ZZ is a generic random walk strategy for modeling an increased rate at which agents covered previously unexplored areas of the space. For both walk conditions, space was bounded: when agents reached a boundary, they moved away from it in a random direction. The movement and decision rules are summarized in Table 1.

ZZ movement enables an agent to cover ground relatively quickly and therefore change more rapidly the identity of agents in its local neighborhood. BR movement represents a much slower progression with a higher likelihood of remaining near the same agents. To quantify this, we ran 1000 simulations with a single noninteracting agent that moved using either strategy and calculated its Euclidean distance from its starting point after 100 time steps. The ZZ agents moved on average more than twice as far as the BR agents ($\overline{X}_{ZZ} = 25.36$, $\sigma_{ZZ} = 12.57$, $\overline{X}_{BR} = 10.80$, $\sigma_{BR} = 5.56$, $p < 0.0001$).

We also included a nonspatial (NS) condition, for which $s = L$. This is the way the environment has generally been modeled in the past. Encounters are completely random across the population and thus, in contrast with the spatial conditions, uncorrelated in space and time. For all spatial simulations, we used $L = 200$ and $s = 5$.

There are many ways to model differences in mobility, and we readily admit ours is not the only way. Our intention is not that these two movement strategies literally represent the way real individuals move in space, but rather it is to analyze two generic strategies of mobility in mate search dynamics when neighborhoods are localized. These walk strategies represent generic characteristics (e.g., tending to remain in a local area and repeatedly search it or roaming over a larger area and search the same area far less) of how individuals move in space. Thus, our comparison of two random walks is important for examining any effects of the rate at which individuals move through space and encounter new individuals. The two walk strategies are further comparable to the NS case, which represents the upper bound of mobility. For future work, it will be important to have more accurate data on the dynamics of individual mobility through both social and physical space.

Differences between the two movement strategies may be analogous to differences in "social mobility." Although we do not explicitly model social networks as nodes and edges, at any given time in our model an individual has *de facto* network ties to all potential mates in his or her local neighborhood. When agents use the BR walk, these networks change much more slowly than they do when agents use ZZ walk. Thus, we model differences in social mobility in a very similar manner to a more explicit network model.

2.4. Relation to Past and Future Models

Our model is intended to capture essential features of past and future mate choice models. For example, for a single set of parameter values, the KH model [8] is a special case of the NS version of our model. The KH values are presented in Table 2. This model is very well known [5], and represents an important landmark in the use of agent-based modeling to study human mate choice. Moreover, all subsequently published ABMs of human mate choice have been extensions to or modifications of the KH model. Therefore, it is not surprising that these subsequent models shared features or similarities with it (see Refs. [4, 9, 10, 13, 23, 24, 27]). The KH model, however, has never been fully analyzed. That is, we do not know its properties for its parameter space, as only one set of parameters of the KH model were ever simulated and only

for NS and nonmobile agents. This is also true of subsequent mate choice models (i.e., their parameter spaces were not systematically explored). Thus, an analysis of the parameter space of our model, with the inclusion of space and mobility, has implications for all mate choice models. In addition to the results presented below, further analyses are available in the online Supporting Information.

The model was programed in Java using the MASON simulation toolkit [28]. All results are from 100 runs for each set of parameter conditions. Where not noted otherwise, all parameter values were set according to Table 2.

3. RESULTS

As predicted, limited local interactions decreased matching regardless of decision rule, due to restrictions on the local availability of desirable mates [Figure 2(A)]. Importantly, agents with restricted mobility and preferring similar partners (rule 2(BR)) yielded nearly identical matching compared with NS agents preferring maximally attractive partners (rule 1(NS)). The emergence of matching that fits empirical data, then, is not adequate validation for the assumption of particular decision rules if the structure of social interactions is not accounted for. This also demonstrates that the effects of individual decision rules cannot be adequately assessed without including extra-individual properties of space, mobility, and local interactions.

Limited local interactions also increased search times for both decision rules, although the mechanism was different in each case [Figure 2(B)]. When agents preferred maximally attractive partners (rule 1), localization and limited mobility increased search time most dramatically for highly attractive individuals. This was because, in contrast to the dating pool assumption, it was more difficult for those individuals to quickly find a highly attractive partner. The model predicts that less attractive individuals' agents should require more dates to find a partner, and this factor seems to outweigh the effects of localization for less attractive individuals. Search time also increased for very unattractive agents, because the inclusion of space created individual variation in the number of dates, and so agents were no longer guaranteed to be accepted on their

FIGURE 2
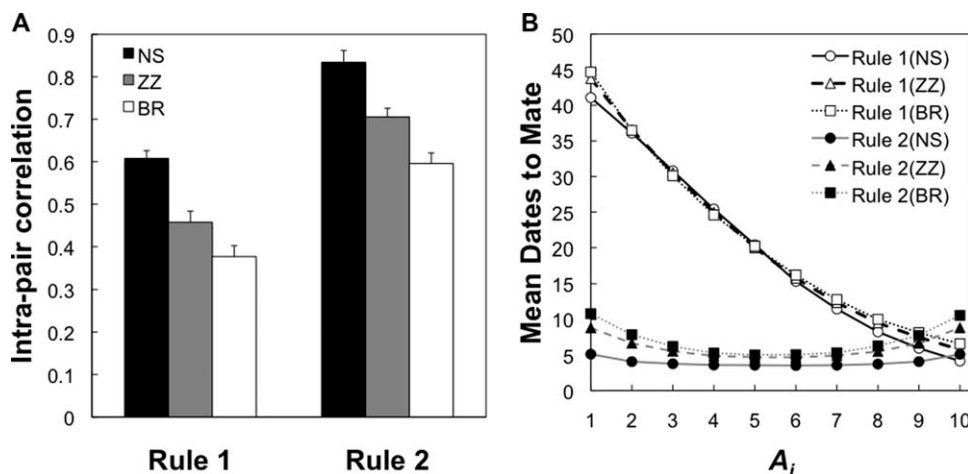
Basic results from the inclusion of space and mobility. (A) Mean intrapair correlations (+SEM) from simulations with default parameter settings for each decision rule and social mobility condition. Limited localization decreases matching for both decision rules. (B) Mean search time in dates to mating for individuals of varying attractiveness. Limited localization increases search time for both decision rules, but the character of the effect is different for each rule.
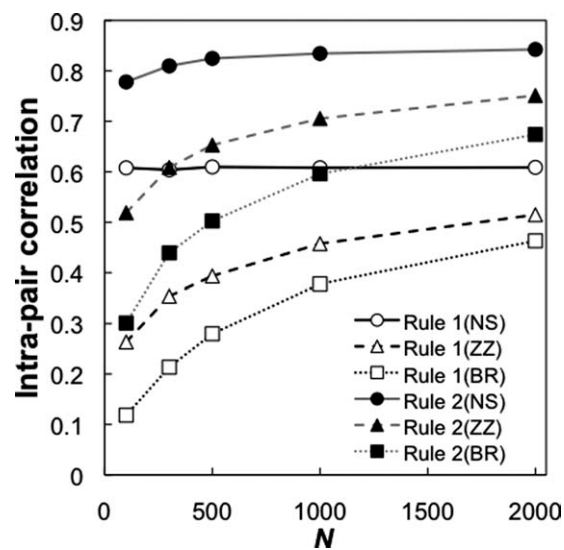
own 50th date. When agents preferred similar partners, localization increased search times across the board. Search times were longest for those agents at the extremes, due to the decrease in number of similar potential partners. This predicts, not unreasonably, that more unique individuals will have longer search times under affiliative (similarity) mating preferences.

We focused on the number of social encounters (dates) required to mate, rather than the absolute search time, although the two can differ in the model's spatial conditions. Limited mobility drastically increased average time required to find a mate, due to increased time between dates (see Figure 4). Thus, restricted mobility increases search time for both the number of dates required to mate and the time between dates.

3.1. Additional Environmental Heterogeneity
Our assumption of local neighborhoods limits the variety of potential partners in a straightforward manner. There are, however, additional heterogeneities that may characterize the spatial or social environment. We examined the influence of two of these factors, and how they may interact with space and mobility.

3.1.1. Dense Versus Sparse Populations
Populations vary in density. In a NS model, this translates to differences in the size of the dating pool from which agents are randomly selected. When agents preferred

maximally attractive partners, there were no effects of population size in the NS case. Agents using decision rule 2, however, showed slightly decreased matching and increased search times for very small populations. Small populations have increased variance among local neighborhoods. Increased search times were most pronounced for agents with very high and very low attractiveness. When agents paired up by similarity, smaller populations yielded longer search times for agents at the extremes of attractiveness. This could, for example, partially explain cultural selection pressures for conformity in smaller communities, which are less prevalent in large cities.

When agents were restricted to search in local neighborhoods, in contrast to the assumptions of NS models, the global population density affected the population dynamics for both decision rules. Sparser populations corresponded to decreased matching (Figure 3) and increased search times (Figure 4). This result was unsurprising: we expected it to take longer to find a partner when populations were sparse, and that pairs would be less well-matched. Still, this result was not predicted by NS models where agents prefer maximally attractive partners. Moreover, because socio-spatial structure and population density each influenced both matching and mate search time, we must be careful before fitting a model that includes these features to existing data.

We also found that increased mobility, in the form of the ZZ walk, increased matching and decreased search time relative to the more restrictive movement of the BR walk. This suggests that in sparse populations, or in the absence of good local mating options, single individuals should adopt strategies to increase their mobility.

Although the number of time steps predictably increased for both movement strategies with decreasing density, there was a curious decrease in the average number of dates for very low densities [Figure 4(A)]. This was because some individuals took a long time to find dates, whereas others had only undesirable potential partners in their local neighborhoods. Consider, for example, a "1" male agent and a "10" female agent that start near each other. They date, but the 10 is unlikely to choose a 1. Population sparseness and limited mobility imply that they repeatedly attempt unsuccessful dates, but, over time, the 10's satisficing criteria begin to lower [see Eq. (1)]. Now, suppose a "5" male agent, which has had few dates due to chance spatial isolation eventually encounters the 10 female, whom he accepts. On a first date, the 10 would be unlikely to accept the 5, but now she has had 20 or 30 dates with the unattractive "1" and is much more willing to compromise.

This is analogous to real-life: two people on a date could have had disparate dating histories, with one person more "experienced" than the other (as courtship periods are not explicitly modeled, however, a failed date could be preferentially interpreted as "rejection" experience rather
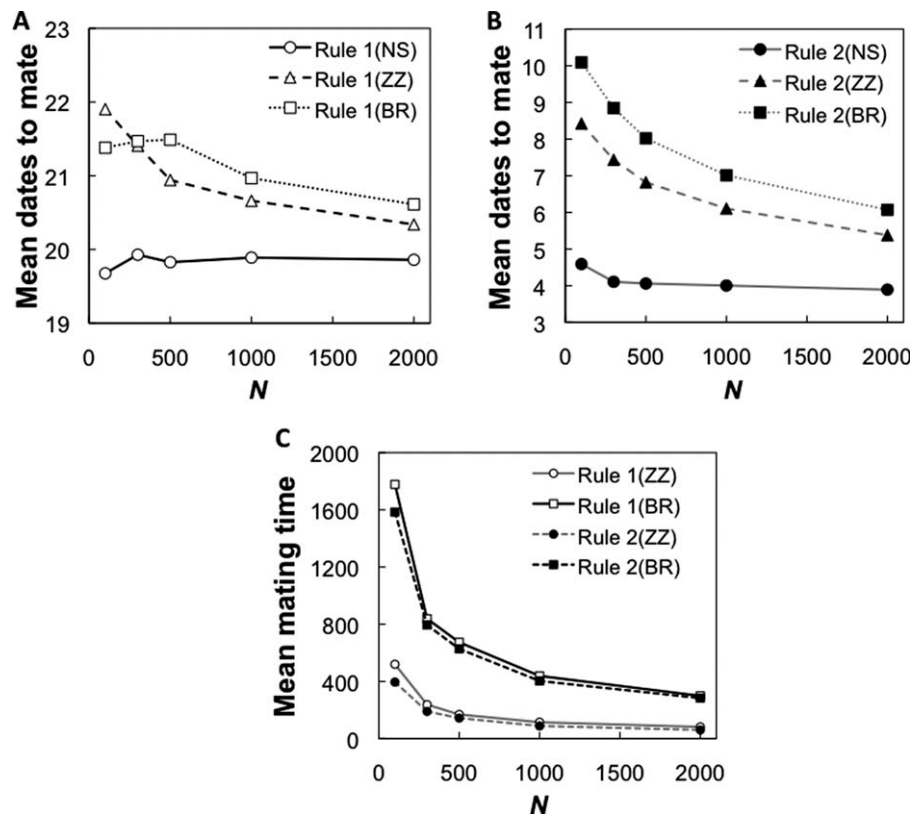
The mean number of dates to mate varies with space, movement strategy, and population size for both rule 1 (A) and rule 2 (B). The absolute search time increases monotonically with declining population density in the spatial conditions (C).

than dating experience). In our model, this effect could be outweighed by absolute search time, which always increased under limited mobility and sparser populations [Figure 4(C)].

3.1.2. Population Replacement

Models of human mate choice have generally assumed that a single, fixed cohort of individuals constitute a dating pool. This is not necessarily problematic; people tend to form couples with those who live close to them [12]. Still, the pool of potential mates may be dynamic as individuals move, change jobs, or make new friends. What if there is a regular influx of new, single individuals?

For these simulation experiments, when two agents formed a couple, they were replaced by two new agents (one of each sex) with randomly chosen attractiveness levels, in random locations. The mechanism we implemented was crude and did not capture potentially important details of migration patterns or facts about the growth and decline of social networks. Simão and Todd [24], however, also used a replacement mechanism similar to our own.

They did not specifically compare their results to the case without replacement other than to note that the percentage of agents mated decreased somewhat [9]. As there was no obvious "end" to a run of the model, simulations were run for 1000 time steps as this provided ample simulated matings to achieve near convergence on the true values for the model.

Population replacement interacted with both limited localization and individual decision rules. In the NS case, replacement decreased matching for rule 1 and increased matching for rule 2 (Figure 5). When agents preferred maximally attractive partners (without replacement), matching was produced in part because agents accepted unattractive partners when only unattractive agents were left in their local neighborhood and their acceptance standards had decreased with unsuccessful dates. A regular influx of more attractive agents disrupted this process, and thus decreased matching. In contrast, when agents preferred similar partners, replacement made it easier to find that "perfect" match.

Without replacement, unattractive agents tended to mate among themselves, as no one would mate with them
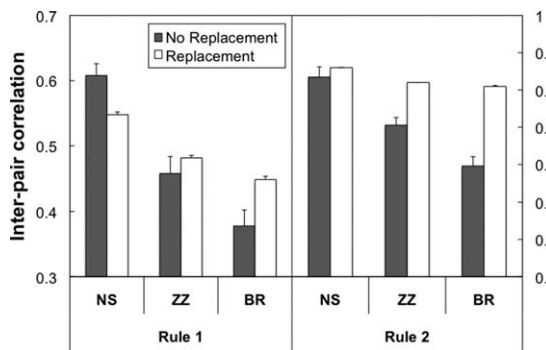
Mean intrapair correlations (+SEM) from simulations with and without population replacement. For the NS conditions, replacement decreased matching for rule 1 and increased matching for rule 2. In all cases, replacement mitigated the influence of local interactions on matching.

early on, and by the time these individuals relaxed their standards, the attractive agents were all gone. However, with the occasional introduction of new highly attractive agents, more disparate pairings sometimes occurred. This was partly because highly attractive agents were rare; they could therefore go on many dates without encountering another highly attractive individual, and thereby lower their standards. This also meant that, as medium attractive agents were marginally more likely to pair with highly attractive ones, very unattractive agents took longer to find mates. Subsequently, search times increased dramatically with replacement for rule 1 (Figure 6). This effect was driven by very attractive agents, who tended to become rare and thus had more difficulty finding acceptable partners, and by very unattractive agents, who were no longer guaranteed to date another "desperate" agent even after many dates. In contrast, replacement decreased search times for rule 2, because variations in the number of available agents of either sex for a given level of attractiveness were reduced.

Replacement also mitigated the effects of limited localization for both decision rules (Figures 5 and 6), largely because local densities did not diminish, and thus the expected spatial distance to a potential mate remained constant. It is therefore important to understand the temporal dynamics of local population densities when modeling human mate choice.

Replacement also provided an opportunity to compare population dynamics under the two decision rules with respect to number of agents mated. With fixed population size, the model was run until most (in many models) or all (in this case) agents were mated. With replacement, new agents were constantly introduced. The model predicted

that many more couples would form under preferences for similarity as compared with preferences for maximal attractiveness. In 1000 time steps, the average number of couples formed under rule 1 was 45,562 (SD = 151), compared with 265,228 (SD = 455) couples formed when agents used rule 2, both under the NS case. The results were qualitatively the same under limited localization, with increased localization decreasing number of mates formed for both rules. This fits with our previous results showing longer search times for rule 1 over rule 2, and indicates that there may be an important fitness trade-off in the sense that time spent searching for an attractive partner may be better spent reproducing with a partner who meets compromised specifications, as has been proposed elsewhere [29].

3.2. The Right-Skewed Marriage Hazard Curve
For all the decision rules and mobility conditions we considered, our model generated monotonically declining hazard curves for mating. Data from many different societies, however, consistently shows a right-skewed, unimodal hazard curve for age of first marriage [3, 4, 10, 13]. This means that the rate of marriages increases early on, peaks quickly, and then declines with age; the average age of marriage is to the "right" of the median age. As our model is a generalization of all previous ABMs of human mate choice, it should also generate right-skewed hazard curves for at least some parameter values.

Previous ABMs have incorporated specific individual mechanisms, including adolescent learning periods [4, 27], courtship periods [4, 9], declining willingness to date versus settle down [10], and strict initial preferences that
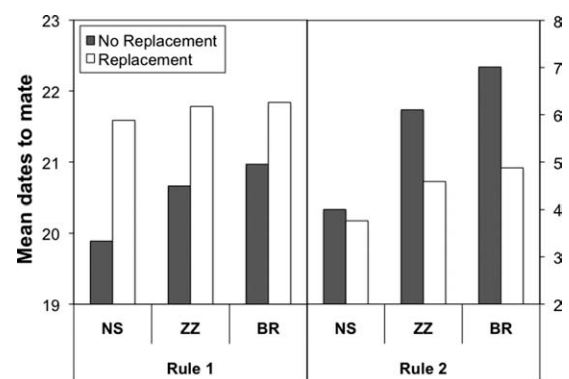
The mean number of dates to find a mate with and without population replacement. Population replacement increased search time in both NS conditions, but eliminated differences in search time between the different movement strategies.
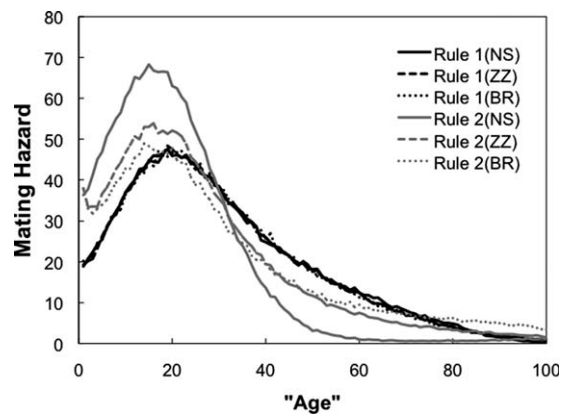
Right-skewed unimodal hazard curves generated under both decision rules and all spatial conditions. For both rules, $\mu_d = 10$, $\sigma_d = 10$, $d_{min} = -10$, $d_{max} = 50$, and $D = 100$. For the rule 1 data, $n = 3$, $k = 10$, $A_i \in N(5.5, 1.8)$, For the rule 2 data, $n = 10$, $k = 100$, $A_i \in U(1, 100)$.

decline at variable rates [13]. In reality, most if not all of these mechanisms may be operating together. Although analogies to real-life psychology and culture vary, each of these mechanisms enable these models to have the following three properties.

1. Very young people are unlikely to accept one another.
2. Individuals gradually increase their willingness to accept a partner.
3. There is variation in the timing of when individuals become increasingly accepting of potential partners.

At first, very few young agents mutually accepted each other, or were available to do so. As agents became more accepting, the hazard rate increased. It then declined as the most desirable agents pair off, and it became more difficult for the remaining agents to find mates.

Any model that exhibits the above three individual-level properties should generate right-skewed unimodal hazard curves. In the simulation experiments described above, all individuals started with their number of dates, d, equal to zero. In the following simulation experiments, d was initially drawn from a normal distribution of mean μ_d, standard deviation σ_d, and bounded between d_{min} and d_{max}. This represents variability in individual age, with older agents more willing to accept less-than-ideal partners. If d was less than zero, the agent was considered immature and thus below the age when they could accept a mate; their dates always failed to yield a mating until $d \geq 0$.

Figure 7 illustrates that both decision rules yielded right-skewed mating hazard curves when initial ages varied and some agents were immature. All of our previous results regarding localization still held: matching decreased and search times increased when search environments were local and mobility was limited. Our aim was not to precisely match empirical data, but rather to show that previous models fit empirical data too easily, because the precise shape of those model-generated hazard curves was calibrated assuming a dating pool model, which can just as easily be fit with models that include space and mobility.

Because thorough analyses of complex models are essential, additional analyses can be found in the online Supporting Information.

4. DISCUSSION

One of our colleagues has been known to warn prospective graduate students: "where you choose to go to grad school determines your children's eye color." The implication is that graduate students often meet their long-term romantic partners in school, so the choice of university largely determines the pool of potential partners. More broadly, marital partners tend to be chosen from within social networks [11] and local environments [12]. Some individuals frequently change the makeup of their dating pool through travel or "social mobility," whereas others maintain a nearly identical social circle for years. At any moment in time, individuals have limited options for social interactions, which are constrained by space and mobility. Understanding the dynamics of human mate choice requires thinking seriously about the factors that structure complex social interactions.

We have provided the first analysis of how space and mobility can influence human mate choice. Our findings should allow researchers to better predict how certain assumptions about space, mobility, decision rules, and additional complexities at the individual and population levels will influence the behavior of their models, as well as which aspects of individual behavior and population structure may or may not be safely ignored. Omitting the influence of localized neighborhoods and mobility constitutes an implicit assumption about the nature of interactions in a population: it assumes they are either actually random, or that the effects of assuming otherwise are negligible. We have seen, however, that local interactions and limited mobility can significantly decrease matching and increase search time. Further, not accounting for local neighborhoods and mobility can distort or ignore the effects of other population or environmental features, including effects of population density, decision rules, and immigration of new marriageable individuals. Human mate choice therefore cannot be reduced to an aggregate of human decisions, but is a complex system in which situated cognition reigns, where socio-environmental constraints influence individual choices and the population-level data observed.

More realistic models should start with fuller analyses of a model's assumptions—especially those that eliminate complexity such as the dating pool assumption. We have seen that, depending on the structure of the interactions and other factors about a population, very different decision rules can generate almost any type of data when physical space, social structure, and mobility are also included. In addition, a variety of mechanisms can each generate the type of right-skewed unimodal marriage hazard curve that is observed empirically, as long as a small set of properties are maintained, and regardless of assumptions of space and mobility. Although demonstrating that a set of conditions can produce the observed population-level data is necessary to explain complex social phenomena [7], it is not sufficient. When a number of differing assumptions all lead to the same result, the empirical adequacy of those assumptions must be carefully assessed. If the addition of a complex mechanism allows a model to generate more realistic output, it is necessary to understand why it does so. This requires us to ask (1) are there other mechanisms that yield the same result and (2) is there a more general principle that underlies the effect? As we have pointed out, any mechanism that introduces initial variation into the time to mate will produce right-skewed unimodal curves. Our results do not eliminate the influence of any specific mechanisms but rather illustrate that models are often underdetermined by the data. Identification of features of models for which this is the case can guide our collection of new types of data that may better determine model features.

This article is not an attempt to provide a detailed model of human mate choice that includes all of the factors affecting choice. No such model has yet been built. Rather, our model is an initial analysis of the types of socio-environmental constraints necessary for building more realistic models and for collecting the data necessary to test them. Thus, this article is a call to both modelers and empiricists that data concerning social structure and mobility are required to make predictive models of human mate choice. Our assumptions about space and mobility are a preliminary take; they represent important generic properties of social dynamics without specifying details. For example, our model creates de facto social networks from the dynamics of local neighborhoods, but we have not included many important features of social networks, such as realistic differences in degree distributions and centrality. Additionally, ours and other models have assumed that individuals make their own mate choice decisions autonomously. Mate choice decisions, however, are often influenced by parents, extended family, and friends [11, 30–32]. The inclusion of these features in future models is essential.

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Human Mate Choice is a Complex System

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SUPPORTING INFORMATION

Table of Contents

1. Overview of Human Mate Choice Models

Human mate choice is a problem of mutual search. One of the first attempts to analyze mate choice was by Gale and Shapley (1962). In their analytical model, equal numbers of men and women were assumed to have perfect information about everyone in the dating pool and had strict preferences among potential mates. This model generated stable matching, but required that individuals possess complete information and perfect rationality, both of which are dubious assumptions (Gigerenzer, Todd, & ABC Research Group, 1999).

Kalick and Hamilton (1986) designed the first ABM of human mate choice to address the matching paradox: individuals express preferences for highly attractive partners, yet partners are correlated in attractiveness. At the time, it was not obvious how preferring the most attractive individuals could produce a moderate correlation in attractiveness. A well-known hypothesis in social psychology (i.e., the "matching hypothesis") explained correlations in attractiveness by postulating that individuals preferred similarly attractive partners (Kalick & Hamilton, 1986). In their model, an initial population of male and female agents were randomly paired for "dates." In addition to sex, the only distinguishing feature was an objective measure of attractiveness, which varied between one and ten. Agents accepted an opposite sex agent using probabilistic decision rules, based on preferences for either maximally attractive or maximally similar partners. If both agents accepted each other, they became a couple, and left the dating pool. To facilitate coupling, the probability of accepting a less-than-ideal partner increased with each unsuccessful date. Kalick and Hamilton demonstrated that a population of agents with strict preferences for attractive partners could generate matching.

A series of ABMs of human mate choice have been developed by Todd and collaborators (Hills & Todd, 2008; Simão & Todd, 2002, 2003; Todd & Miller, 1999; Todd et al., 2005)

following Kalick and Halmilton's (1986) initial ABM. With one notable exception (Hills & Todd, 2008), discussed below, all of these models are similar in that they consist of satisficing agents who base mating decisions on a single one-dimensional attribute, described as mate "quality." In all models, N individuals of each sex were randomly assigned values between 1 and N, so that between any two individuals there would be a strict preference for one over the other. In the first of these models (Todd & Miller, 1999), agents underwent an "adolescent" phase where they could make and receive offers but not accept them, which allowed individuals to estimate of their own worth. The best strategy had each agent adjusting its aspiration level upwards upon receiving an offer from another individual of higher quality than itself, and lowering its aspiration level upon rejection by an agent of lower quality. An issue with this model is that less than half the population found a mate. Subsequent models (Simão & Todd, 2002, 2003) added a courtship phase. These models showed that courtship allowed most of individuals to find mates with strong matching (correlations between .6 and .7), even in the absence of an adolescent period.

Simão and Todd (2003) also examined other demographic data, including the age- at-marriage hazard rates and the effects of skewed sex ratios. Lower quality individuals showed much higher average mating ages, but most individuals mated as soon as possible. The introduction of normal variation in individual courtship time reproduced the data on the left-skewed unimodal marriage hazard curve. In addition, skewed sex ratios lowered the mean time to mating, because of increased opportunities for the rarer sex to find a suitable mate. A subsequent study (Todd et al., 2005) focused on trying to fit features of the previous three models to the well-documented age-at-marriage curves. Paired agents could accept or reject their partner as with the Kalick and Hamilton (1986) model. If agents knew their own attractiveness

and used it as their aspiration level, strong matching was generated, but also an exponentially decreasing marriage age curve. The addition of either an adolescent period with normally varying learning times or a courtship phase with normally varying courtship periods generated left skewed unimodal curves.

Each of these models used a single measure of mate quality. However, both individuals and their decisions can vary along several dimensions. Two recent models have explored this multi-factor aspect of human mate choice. In the first (Hills & Todd, 2008), individual differences were modeled as binary traits (i.e., an individual either did or did not possess a trait). As with previous models, individuals were paired randomly, and if they matched on a certain number of traits (the aspiration level), they coupled. Aspiration levels decreased as agents aged, similar to the "prettier at closing time" rule used by Kalick and Hamilton (1986). The model also assumed individual preferences for similarity rather than objective "quality." Their model was able to generate realistic marriage age curves, and suggested that an increase in cultural heterogeneity in traits might explain the recent trends in both decreasing likelihood of marriage and later age of first marriage.

The KAMA model of French and Kus (2008) also sought to explain marriage age curves, and introduced sex differences in mate search strategies, which allowed for subsequent differences in the marriage age curves. In this model, individuals also had a multidimensional trait profile, but all individuals possessed all traits, each of which had objective minimum and maximum values. Individual differences in preference came from weighting the importance of each trait. Some trait values varied with age, such as those representing wealth and physical attractiveness. Males chose one female to "ask out" from a number of potential partners, while females had to decide immediately whether to accept or reject an offer. Couples underwent a

courtship phase, and met other potential mates with a rate that corresponded to a "computational temperature," which also influenced how choosy an individual was. The model suggested that male preferences for physical attractiveness (which decreased with age), and female preferences for earning capacity (which increased with age) resulted in males marrying at an older age than females. As females placed less weight on earning capacity, the age differential decreased. Of particular interest was that different search strategies for males and females led to higher ages at marriage for males, even with identical trait preferences and profiles.

All of these models assumed that individuals encounter each other randomly. French and Kus (2008) have noted the importance of space and mobility and have proposed a future spatial extension of their model. To our knowledge, however, there have been no studies explicitly incorporating space into human mate choice models. A quasi-exception is an extremely simple cellular automata model by Kenrick et al. (2003), which consisted of connected 2 layers of cellular automata on a 2-D lattice, in which there is a male and a female at each location. Each individual engages in one of two "mating strategies," and individuals switch strategies depending on local members of the opposite sex, using one of several majority rules. This model is an excellent demonstration of the emergence of spatial structure using simple rules, but does not shed much light on mate choice dynamics.

2. Sensitivity Analyses

We feel it is important to understand how a complex model responds to various manipulations of parameters values and environmental assumptions. Here, we present a number of such analyses that were unnecessary for supporting the point made in the main text, but

nevertheless are valuable for understanding the dynamics of our model. Unless otherwise noted, all parameter values were set according to Table 2.

2.1. How Choosy Are Individuals?

The basic form of the decision rules considered in the model is simple: always an accept an ideal partner, and accept any other date with a probability that decreases with their increased deviation from the ideal. Choosier individuals will be less likely to accept partners who don't match their ideals.

We found that either decision rule can generate a very wide range of matching depending on the agents' choosiness. Lower values of n corresponded to a decrease in the intra-pair correlations. Limited mobility further decreased matching, but did not moderate the effects of initial pickiness (Figure S1). Increasing choosiness also increased the average number of dates required to mate (Figure S1), since when agents used a more selective rule, matching was greater but agents took longer to find mates. Choosiness also moderated the effect of localized interactions on the number of dates to mate: decreased mobility yielded larger increases in search times for increased choosiness. In other words, the choosier the agents were at baseline, the longer it took on average to find a mate, and the more this effect was amplified by limits to mobility. It initially appeared that the effect of localized interactions was much weaker for Rule 1, but this was only true for the unattractive individuals, who tended to mate fairly late. When only the most attractive individuals were considered (Figure S1 inset), the effect on search time was very similar to Rule 2.

2.2. How Readily Do Individuals Relax Their Standards?

Regardless of how choosy individuals were at the start, they gradually relaxed their standards as they experienced more and more failed dates. The speed at which those standards

were relaxed after unsuccessful dates was represented in the model by the maximum number of dates, D. Unsurprisingly, the adjusting this number yielded results similar to those obtained from adjusting baseline choosiness (Figures S3 and S4).

The strongest effects on matching were for $D \leq 21$. We generated matching at empirically observed levels for nonspatial Rule 1 with a maximum of only 11 dates. The modal number of dates to mate in this case, however, was also 11, implying that many couples form randomly, hardly a realistic conclusion. Larger values of D had more of an effect on the spatial models than on the nonspatial versions, presumably because an increased hesitance to relax one's standards pays off more when search extends to a wider range of individuals.

Lower values of D also decreased the disparity in the average time to coupling between highly attractive and unattractive agents. We are unaware of any demographic data that correlates physical attractiveness with age of marriage, but such data would certainly help in the construction and analysis of mate choice ABMs.

2.3. What is the Scale of Perceived Attractiveness?

A colloquial American custom denotes a ideal mate as a "ten." Correspondingly, we followed Kalick and Hamilton (1986) in their assumption that individuals vary uniformly along a 10-point scale. There is no evidence, however, that humans or other animals use any particular rating scale. Moreover, use of attractiveness scales has varied between models. For example, other models have used a uniform scale between 1 and 100 (Todd & Miller, 1999; Todd et al., 2005), or a normal distribution centered at 8 with a standard deviation of 2 (Simão & Todd, 2002, 2003). It is therefore important to understand the effects of adjusting this scale. We investigated different uniform distributions of attractiveness levels, where values were uniformly drawn from integers between 1 and k.

Increasing the maximum attractiveness had very little effect for $k > 10$. For small values of k, matching decreased with Rule 1 but increased with Rule 2, with a somewhat stronger effect in the spatial models (Figure S5). For Rule 2, this may be because the probability of encountering a maximally similar agent is very high for each type of agent, while the probability of accepting partner that is slightly more or less attractive decreases exponentially with fewer attractiveness classifications. For Rule 1, when k is small the initial probability of two mid-ranked agents selecting one another grows closer to that of a pairing between a minimally attractive agent and a maximally attractive one, which decreases matching.

Lower values of k also decreased the age of marriage for both rules (Figure S6). This is because the likelihood of finding an ideal mate increased when attractiveness range was small since more individuals *were* ideal. Limited localization had a more dramatic effect on the mean number of dates to mate for Rule 2 than for Rule 1, in all cases increasing the number of dates. Once again the effect of mobility on search time for Rule 1 became more dramatic when only the most attractive individuals were accounted for.

2.4. How Is Attractiveness Distributed?

Our model assumed that attractiveness levels were uniformly distributed, an assumpton also made by several previous models (Kalick & Hamilton, 1986; Todd & Miller, 1999; Todd et al., 2005). However, both physical attractiveness and overall mate quality are likely normally distributed, and most current models incorporate this assumption. Aron (1988) tested the Kalick and Hamilton's (1986) model using normally distributed attractiveness levels, and noted that this lowered intra-pair correlations.

We followed Aron (1988) and ran simulations using a mean attractiveness of 5.5 and standard deviations of 1.8 and 1.1, which are based on empirical studies of human attractiveness.

Distributions more tightly centered around the mean universally decreased matching (Figure S7).
The effect of distribution is less straightforward when it comes to time to coupling. For Rule 2, a
distribution more tightly clustered about the mean lowered the average number of dates to mate,
because agents were more likely to encounter similar partners. For Rule 1, the average number of
dates to mate increased, because there were fewer maximally attractive individuals who would
be selected with certainty. More interestingly, a tighter clustering about the mean changed the
shape of the mating hazard curve from a simple exponentially decreasing one to a sigmoidal
curve (Figure S8A). This highlights the importance of the distribution of values in models of this
type. For example, Todd et al. (2005) found that adding a normal distribution to the lengths of
either adolescent or courtship periods generated a left-skewed unimodal curve characteristic of
empirical demographic data, and we show in the main text that normally distributed starting ages
also generate similar hazard curves.

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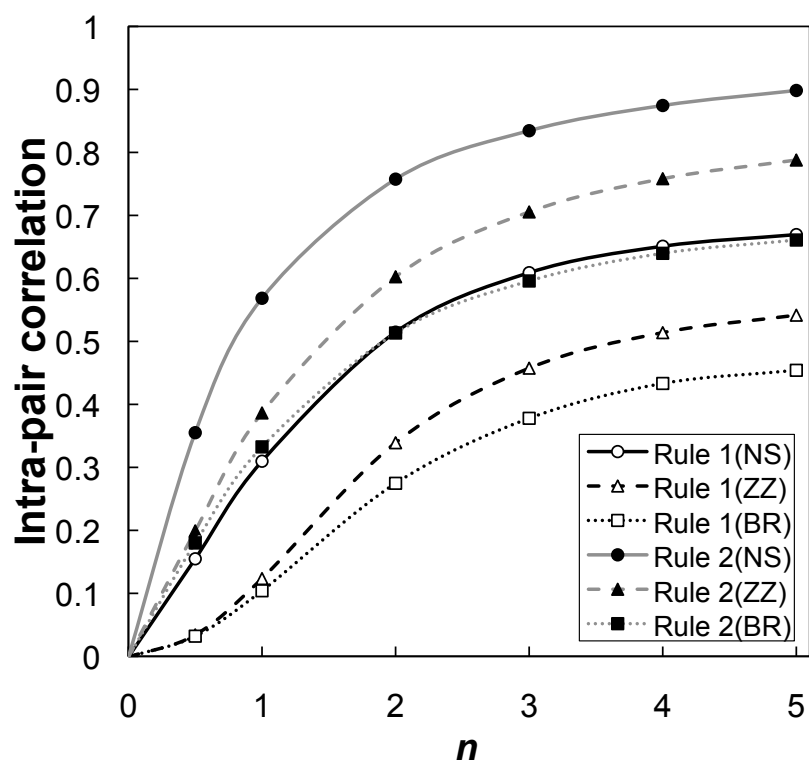
Figure S1. Intra-pair correlations as a function of baseline choosiness, *n*. Notice that Rule 1(NS)

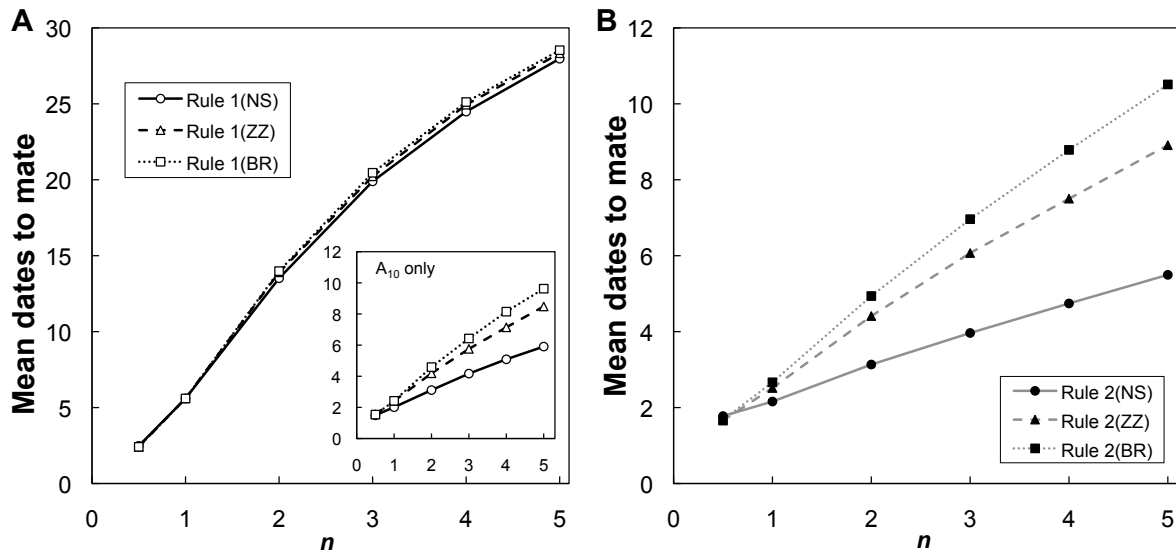and Rule2(BR) are almost identical for all values of *n*.

Figure S2. Mean number of dates to mate as a function of baseline choosiness, *n*. (A) A difference was not observed between movement strategies for Rule 1 when all individuals were included. When only the most attractive individuals were taken into account (inset), the effect of space and movement was similar to that under Rule 2 (B)**.**
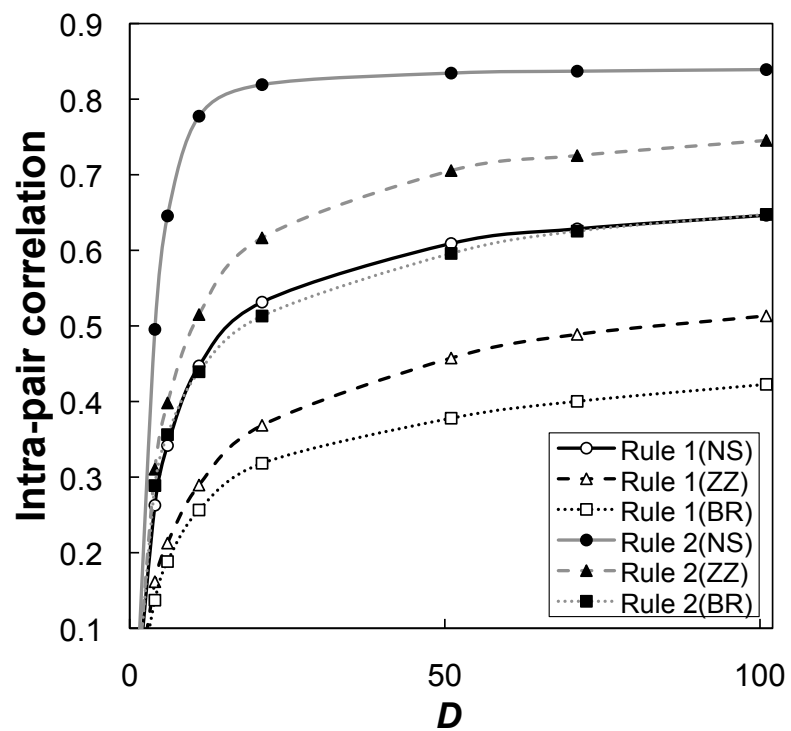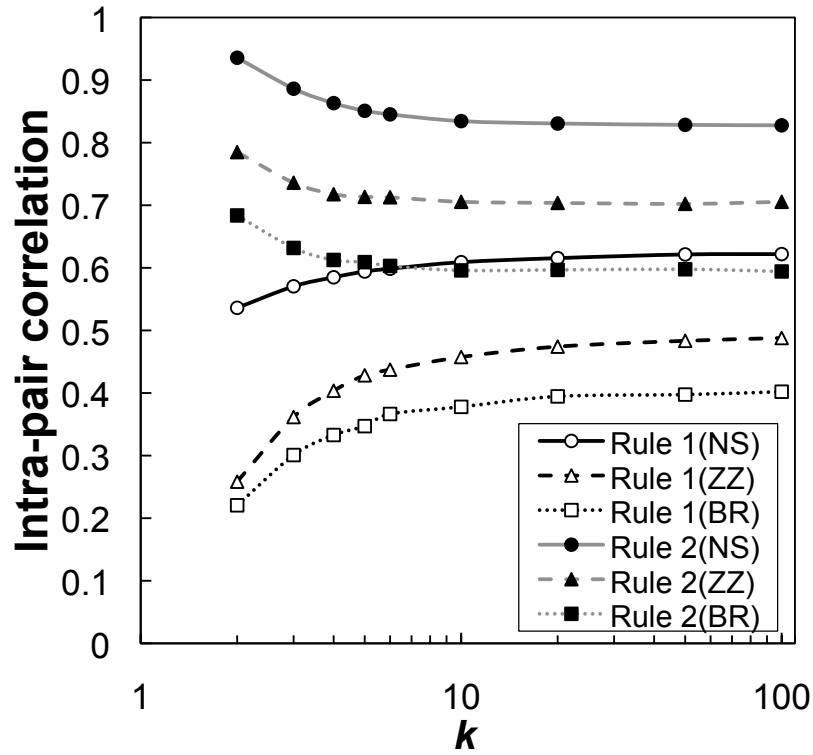
Figure S3. Intra-pair correlations as a function of *D*, resulting from simulations using either decision rule under different spatial conditions. Rule 1(NS) and Rule2(BR) are virtually identical for all values of *D*.
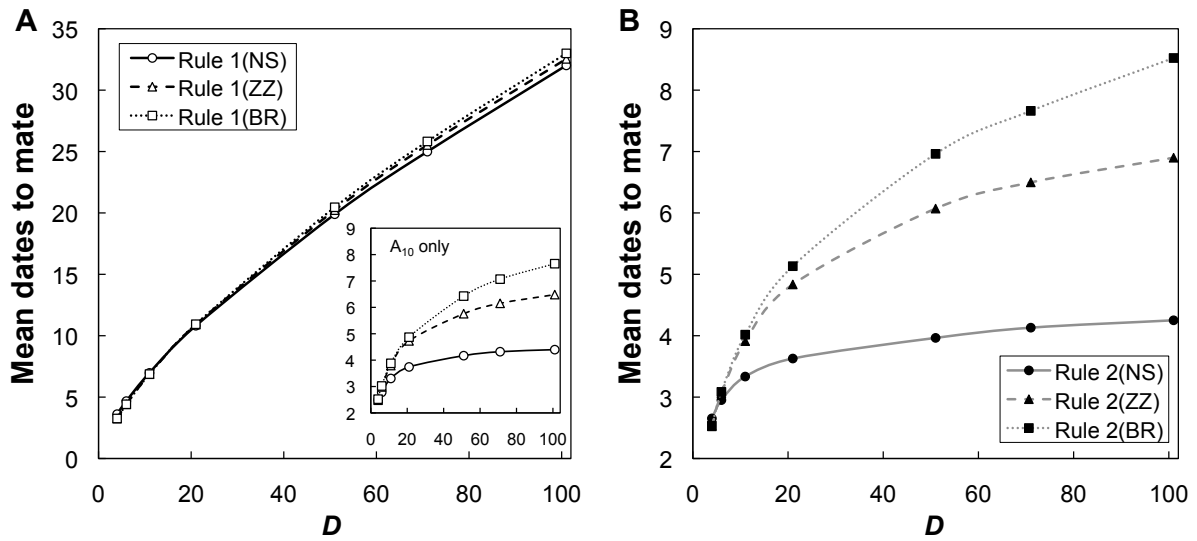
Figure S4. Mean number of dates to mate as a function of the max dates, D. (A) A difference was not observed between movement strategies for Rule 1 when all individuals were included. When only the most attractive individuals were taken into account (inset), the effect of space and movement was similar to that under Rule 2 (B)**.**

Figure S5. Intra-pair correlations as a function of the maximum attractiveness, *k,* on a log scale, under different conditions of social mobility. Rule 1(NS) and Rule 2(BR) closely converge for *k* ≥ 10.
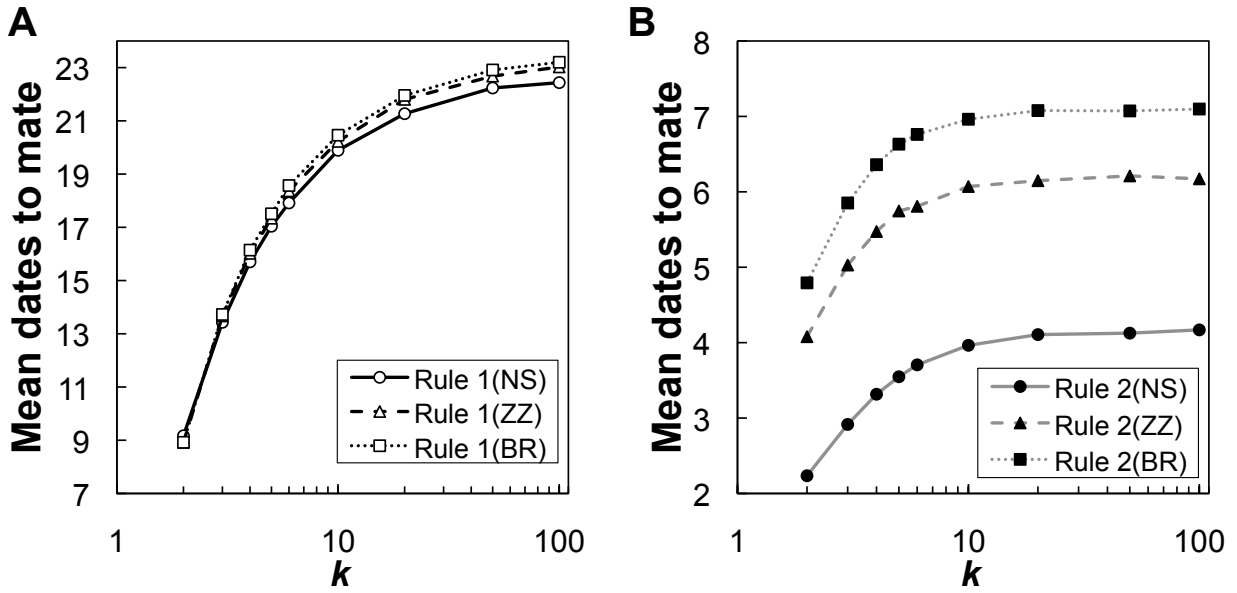
Figure S6. Mean number of dates to mate as a function of the maximum attractiveness, k, on a

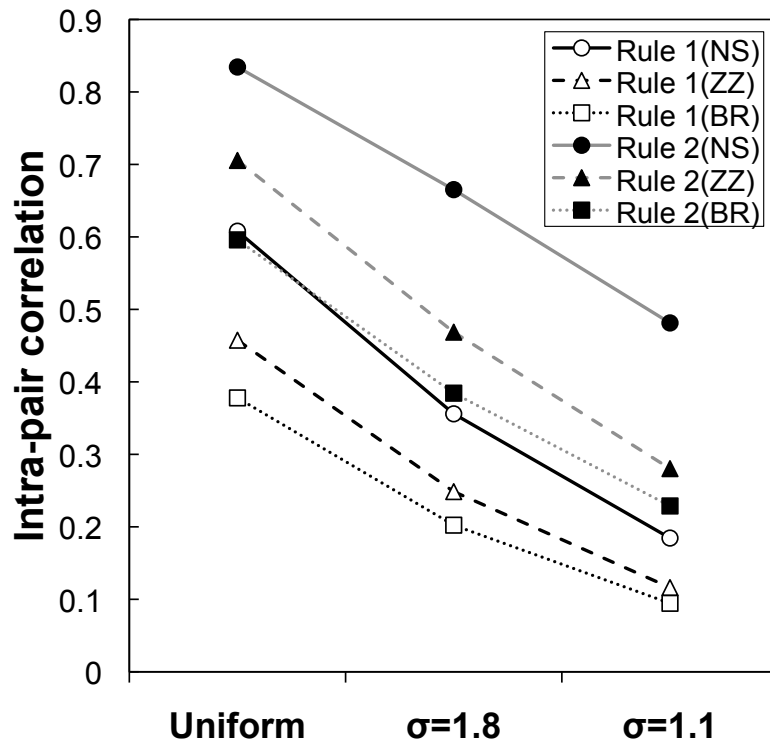log scale for Rule 1 (A) and Rule 2 (B).

Figure S7. Intra-pair correlations under different conditions of social mobility when the distribution of attractiveness levels was either uniform or normal, with two different standard deviations. Distributions more tightly clustered about the mean reduced matching.
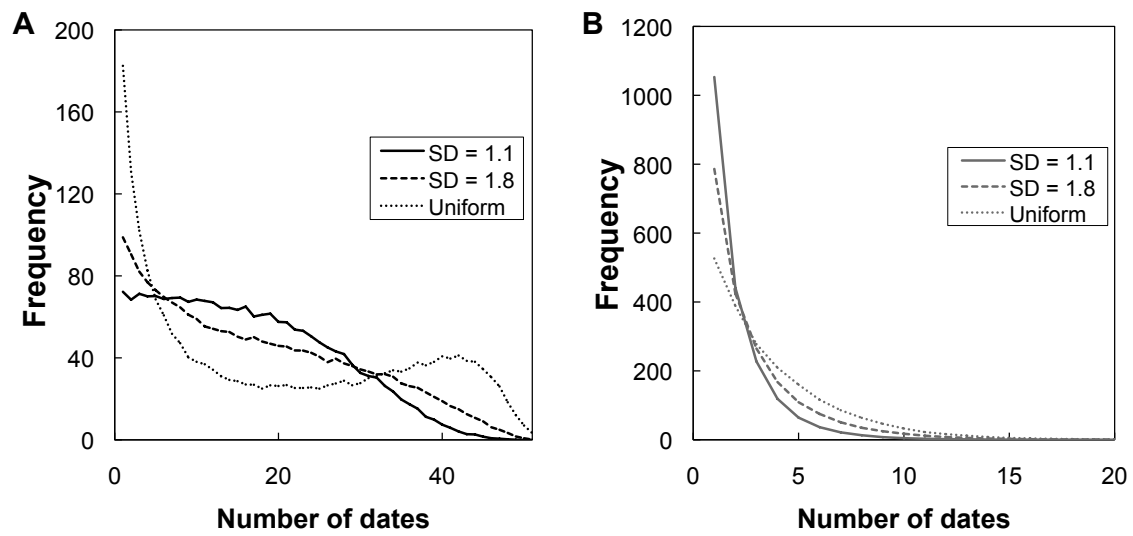
Figure S8. Frequency of mating times with normally distributed attractiveness levels in the nonspatial model for individuals using (A) Rule 1 and (B) Rule 2. Similarly shaped curves were observed in the spatial versions.