Modeling the spatial dynamics of culture spreading in the presence of cultural strongholds

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Cultural competition has throughout our history shaped and reshaped the geography of boundaries between humans. Language and culture are intimately connected and linguists often use distinctive keywords to quantify the dynamics of information spreading in societies harboring strong culture centers. One prominent example, which is addressed here, is Kyoto's historical impact on Japanese culture. We construct a minimal model, based on shared properties of linguistic maps, to address the interplay between information flow and geography. We show that spreading of information over Japan in the premodern time can be described by an Eden growth process with noise levels corresponding to coherent spatial patches of sizes given by a single day's walk (∼15 km), and that new words appear in Kyoto at times comparable to the time between human generations (∼30 yr).

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I. INTRODUCTION

It is generally understood in historical linguistics that geolinguistic diffusion, the process by which linguistic features spread geographically from one dialect or language to another, plays a central role in the evolution of languages [1–3]. Origins of linguistic changes are plentiful where societal changes and movements are of pivotal importance. The dynamics and causes of linguistic change provide, therefore, important clues to the historical developments of, as well as the interplay between, societies and civilizations [4,5]. It has long been observed that linguistic features, just like innovations, spread outward from an originating center [6]. Spatial patterns are, however, rather ambiguous. Some cases [7] bear evidence of a hierarchal diffusion process where, e.g., dialect changes propagate in a cascadelike manner from larger to smaller cities. Other cases [1] show an isotropic geographic distribution where linguistic features spread as a wave front among adjacent speech communities. A unifying theme is, however, that recent changes are found close to the source.

In this paper, we study the dynamics of culture spreading around strong culture centers. As a proxy for the spreading of cultural traits, we use the spreading of words and put forward a model concerning the spatial dynamics of competing wave fronts where the key feature is that new words are more prone to be adopted than old. This view contrasts with most models dealing with information spreading, whether it concerns innovations [8], opinions [9], or linguistic traits [7], where two different pieces of information are treated on an equal footing. Our take on the problem is different. It is based on the fundamental property that *the value of information decays with time*. Previous studies [10,11] have established that an ongoing replacement of old information by new has major consequences for its spatiotemporal dynamics.

II. SPATIAL DISTRIBUTION OF LINGUISTIC TRAITS IN JAPAN

As a case study, we consider the geographic distribution of words over Japan. Careful analysis of linguistic maps [12] has unveiled that words in many cases are arranged in concentric ringlike patterns with Kyoto, Japan's ancient capital, as the focal point. This was first realized by Kunio Yanagita, a famous Japanese folklorist, who studied the distribution of the word for snail (*kagyu*) [13]. He found that the same old variants were used in the southern and northern parts of the country but not in the middle. This lead him to formulate the "periphery propagation theory of dialects" (*Hougen Shuken-ron*) in which he visualized waves of new words emerging in Kyoto which spread radially outwards.

The most beautiful example of Yanagita's theory is the distribution of swear words. The Japanese are not known for their frequent use of swear words, but if you nevertheless are cursed at by someone with *baka* (∼stupid person), the one you are having trouble with is probably from Tokyo. If you instead hear *aho* (∼dumb), he or she is most likely from the Kyoto-Osaka area. The confrontation between these two swear words is so clear that it is considered by the people as a part of the competition between the two major cultural centers. The results of a comprehensive survey [1] of the different variants of *aho-baka* [14] are displayed to the left in Fig. 1; the concentric patterns centered around Kyoto are unmistakable. *Aho* and *baka* are indicated by dashed lines, and Tokyo is a part of the circular area where *baka*, not *aho*, is being used. *Baka* used to exist in Kyoto in the past but has been overrun by the newer *aho*. Other noticeable features are that the area of the word patches grows with increasing distance from Kyoto (Fig. 1, right), and that only a fraction of the words are found both to the north and south of Kyoto (e.g., *goja* is only found to the north). These observations are well described by our model.

[1]The survey was done in 1991, by sending questionnaires to the local education committees all over Japan, asking for the traditional expressions of swearing that correspond to *baka* in the Tokyo area and *aho* in the Osaka area. Over 1370 questionnaires were collected out of 3245 sent out and the results are published as a word map in [14], from which the data in Fig. 1 were taken.

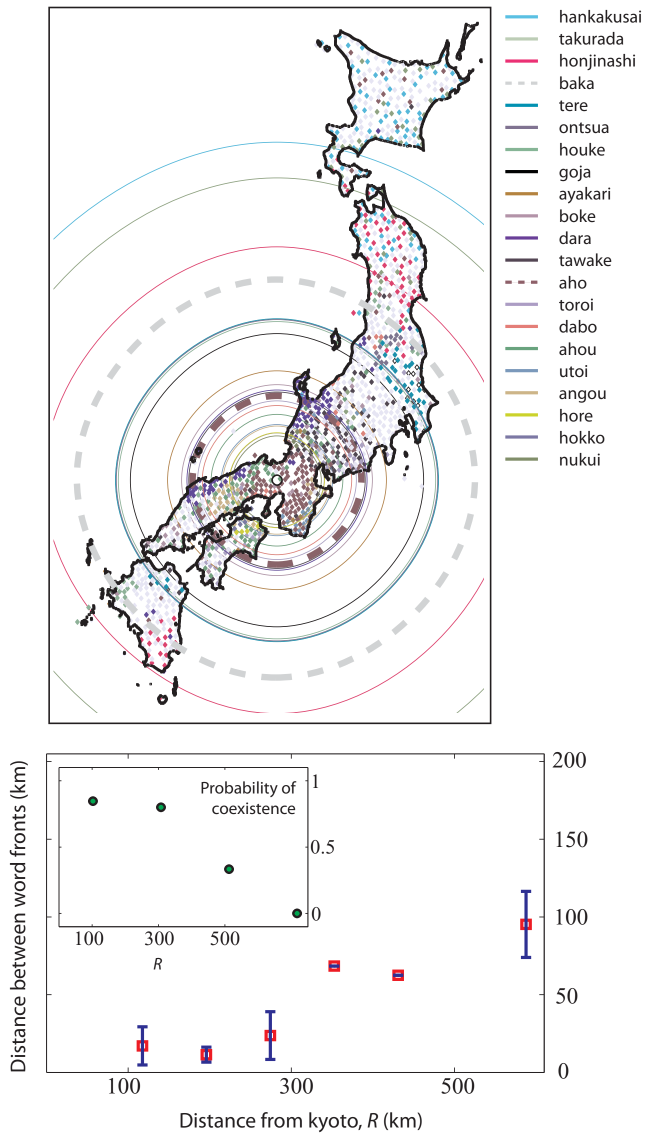

FIG. 1. (Color online) (Left panel) Distribution of swear words (*aho-baka*) over the Japanese mainland [14]. Each word (see list to the right) is given its own color, and the concentric circles represent the mean distance for each word from Kyoto. Dashed lines indicate *aho* and *baka* where the newer one, *aho*, is in general found closer to Kyoto. (Right panel) Distance between consecutive word fronts grows as one moves away from Kyoto. The inset shows the fraction of surviving words that coexist both to the north and south of Kyoto. The data in the right panel was binned and averaged with a bin size of about 100 km in order to reduce noise.

III. MODEL DESCRIPTION

Our model is defined on a two-dimensional lattice on which words, after being coined in the culture center, spread. In order to capture the ongoing adoption and subsequent communication of new words originating with a given frequency f_{word}, at each time step, a word is replicated and passed on to a neighboring randomly chosen lattice site. If it is sent to a location inhabited by an older version, the new one is adopted. But, if it is transmitted to a place where an even newer variant exists, the older word is ignored; new concepts always overrules old. We point out that our model captures the way in which new words invade new territories and not how they coexist. Additional model details are given in Appendix A. We have implemented our model in an interactive online Java applet [15] which can be used by anyone who wishes to explore the properties of our model.

IV. RESULTS

Figure 2 shows three snapshots of our Java applet. In the left panel, each new word is given its own random color and Kyoto (middle of the map) is marked in black. Our model gives rise to patterns of concentric coherent patches penetrating the landscape moving outward from the source. In particular, notice how the same color is found on either side of Kyoto without being present in the middle, just like in the real data (Fig. 1). The blue (small) and red (large) circles highlight two examples. If we calculate the corresponding radii for all colors in the landscape and average over many landscapes, the mean distance between two consecutive words increases as a function of distance from Kyoto as is shown in the left panel. This result obviously hangs on the value of f_{word} as well as the coarsening of space. The graph, therefore, depicts two cases where we used lattice spacings of $\Delta = 15$ km (35×35 lattice sites) and $\Delta = 30$ km (20×20 lattice sites) where the word frequency was adjusted in each case such that about 20 words could be distinguished simultaneously on Honshu Island (the main and largest Island of Japan), just as in Fig. 1. Based on the estimate of the average spreading velocity of a new word $v_{\text{word}} = 1$ km/yr [16], we find from our model that new words are being coined in Kyoto on average every 30th yr for $\Delta = 15$ km and every 60th yr for $\Delta = 30$ km. Further details are given in Sec. V. Other features are that some words are only found on one side of Kyoto and that this correlates with distance. One example is indicated by the orange (light gray) arc. We, thus, measured the fraction of surviving words that existed on both sides as a function of distance, and the result is shown in the inset of the graph. For the crude coarsening ($\Delta = 30$ km), the probability decays quite rapidly and at $R = 300$ km (southern tip of Honshu), as little as 14% of the surviving words coexist on both the north and south side of Kyoto, while the corresponding number is 54% for the finer lattice ($\Delta = 15$ km). These results, combined with that the increase in the width of the color patches for the $\Delta = 15$ km case match the real data better, lead us to conclude that this constitutes a reasonable level of spatial coarsening for our system. The middle panel in Fig. 2 shows the word age distribution at the same time point as portrayed in the left panel; There is a clear age gradient (light to dark) from Kyoto toward the north and south parts of the country.

In addition to the geographical distribution of words, our model predicts along which routes the words traveled. To do this, we at each lattice point remember not only the age of the latest word, but also where it came from. This means that starting from any point in the plane, we can follow

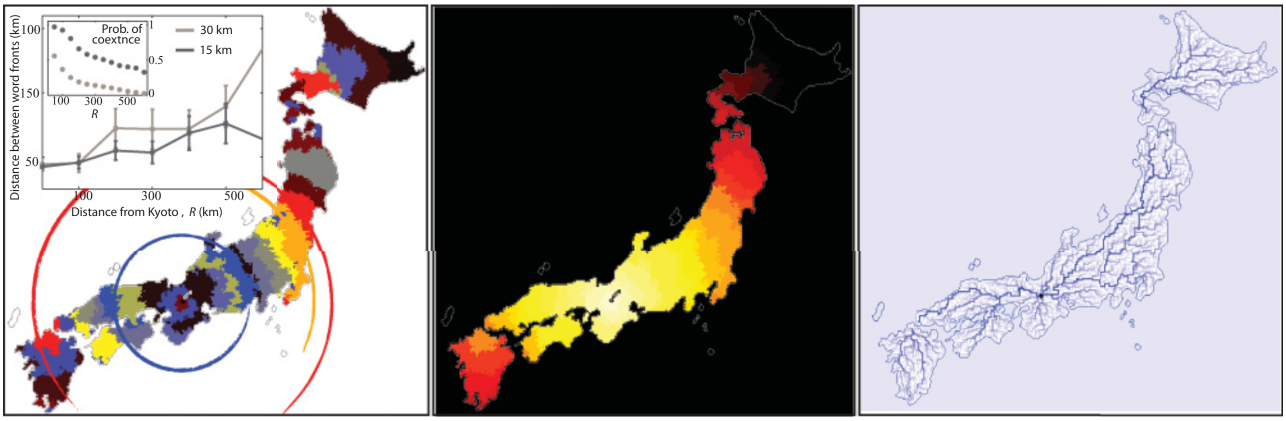

FIG. 2. (Color online) Snapshots of a simulation showing the spatial dynamics of word spreading over the Japanese mainland. (Left panel) Ongoing spreading where each color represents a different word. Blue (small) and red (big) circles show two examples where the same word form is found symmetrically on either side of Kyoto. The orange (light gray) broken circle belongs to a word which only is present at Kyoto's north east side. The graph in the upper left corner shows the mean distance between two adjacent fronts (averaged over many runs) as a function of distance from Kyoto. The probability that a surviving word coexists on both sides decays with distance away from Kyoto in a way shown in the inset. We investigated the behavior when the spatial resolution (width of lattice site) was set to 15 and 30 km, respectively. (Middle panel) Age landscape illustrating how older and older words (yellow to dark red coloring) are encountered as one moves further away from Kyoto. (Right panel) River landscape showing the paths the new words took as they left Kyoto. In order to improve figure quality, a lattice spacing of $\Delta = 5$ km (100×100 lattice sites) was used.

information pointers downstream and eventually reach all the way back to the source. If the landscape is frozen at some time point and the paths from all points in the plane are mapped out, we obtain an "information river network" that is shown to the right in Fig. 2. River depth, symbolized by light to dark blue (gray) coloring, is proportional to the number of reachable upstream lattice points. The predicted river network is self-similar and obeys similar scaling relations as river networks of flowing water (but with different exponents). The real "information rivers" will in addition be influenced by other factors, such as mountain ranges and variations in population density.

Our model of replicating information is based on the idea that new information always replaces old. This is a simple principle which, of course, is not always true. With this in mind, it is interesting to see the consequences if old information sometimes can win over new, say with a probability p. Running the model with this modification effectively reduces the spreading speed of words, and leads to the fragmentation and an increased roughness of the word patches (see Fig. 3 in Appendix B for the $p = 0.8$ case). In the limit $p \to 1$, where old information wins over new just as often as the other way around (i.e., unbiased diffusion of words), new words have major difficulties leaving Kyoto and the ringlike structure of the word landscape is lost.

The density of word fronts, as well as the probability of two words being present on either side of Kyoto, is connected to the annihilation of old words by new ones catching up from behind. In order to increase our understanding of the dynamics of the problem, we ran our model on a simpler system than the Japanese mainland, namely, on an elongated rectangular lattice with width L. Placing a line source at the base, our simulations demonstrate (see Appendix C) that the spacing between two word fronts increases as $z^{0.5}$ for large distances z away from the source. In one dimension, our model maps exactly onto the limiting behavior of the reaction-diffusion problem $A + B \to A$ [17], for which the density $\rho(t)$ decays with time t as $\rho(t) \sim t^{-0.5}$: relating z to the constant average speed of the surface, $v_{\rm surface}$, via $z = v_{\rm surface} t$, gives $\rho(z) \sim z^{-0.5}$. The mapping is admissible also in two dimensions when the motion of one interface can be represented by a single coordinate (when correlations extends over the whole boundary).

V. DISCUSSION AND CONCLUDING REMARKS

Our model of information spreading is based on the idea that new information (words) continually replaces old. With this simple principle, we could reproduce measured swear-word distributions on the Japanese mainland. The model has a time scale (one Monte Carlo step $T_{\rm MC}$), a spatial scale (lattice constant Δ), and a free parameter $f_{\rm word}$ designating the frequency at which new words are being coined. The simulated propagation speed of the boundary between new and old words was found to be about $0.6\,\Delta$ per Monte Carlo step. The corresponding measured value $v_{\rm word}$ from the field research [16] is 0.1–4 km/yr. As an estimate for our case, we, therefore, set $v_{\rm word} = 1$ km/yr from which we fix the relation between the time scale and the spatial scale: $\Delta/T_{\rm MC} = 1$ km/yr. Furthermore, the *aho-baka* map allowed us to quantify typical distances between word fronts as well as the fraction of words that existed simultaneously on the north and south side of Kyoto. We tuned Δ and $f_{\rm word}$ to fit the data and found the best choice to be $\Delta = 15$ km and $f_{\text{word}} = 1/30\ \text{yr}^{-1}$. [2] We find these numbers intriguingly correspond to the size of coherent geographic regions accessible in a single day's walk and to the time between human generations, respectively.

Concentric wave patterns of linguistic traits surrounding cultural strongholds is by no means unique for Japan. Already in 1872, the German linguist Johannes Schmidt discussed a wave theory (Wellentheorie) for how changes propagate in a speech area [18]. Similar ideas have also emerged in spatial economics [19]. Our model of information spreading also bears resemblance to other growth models in biology and physics. The average propagation of a new word into the background of an old is similar to a discrete version of the wavelike front described by Fishers's equation for bacterial growth [20]. Our model also incorporates stochastic properties of growing interfaces of new information that mimic Eden surface growth [21] in which unoccupied perimeter sites of a growing cluster are filled randomly with probabilities proportional to the number of occupied nearest neighbors.

The view of an ongoing replacement of "new" with "old" differentiates our work from other growth models where focus has been on one single front [21], or on the mutual exclusion of bacterial strains growing into the same free territory [22–24]. By opening for an ongoing replacement of one culture with another, our model could be generalized to more complicated spatial battles in living systems. Already when considering the spreading of simple words, it is in fact not all words which show regular circular wave patterns. Some patterns are fragmented which presumably reflects a competitive dynamics where the difference between new and old is close to neutral. The main feature of our model is the interplay between coherence within the culture and the ability to transmit information. If we deformed the space on which the information spreads by adding shortcuts, such as roads, our model predicts enhanced cultural coherence. When Romans conquered Europe, they instantly build roads which served as communications lines that kept the provinces culturally coherent with Rome [25]. Likewise to our scheme, the battle for cultural dominance will be ruled by information flow.

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APPENDIX A: MODEL DETAILS

Our model of competing information is simulated on a two dimensional lattice where new words nucleate at a constant frequency f_{word} in Kyoto. At each lattice i, two pieces of information are stored: the time t_i of the most recent word that has reached i, and from which neighboring lattice site the word came from (the latter is used to construct the information river network). At every time step in the simulation, the following events occur:

(1) Choose a lattice site i at random and any one of its perimeter sites j.

(2) If the word at site j is older than i, set $t_j = t_i$ and the information pointer toward i. But, if the word at site j is newer, no update takes place.

Simulation time is then updated after items (1) and (2) have been repeated for all sites. In order to test the effect if old information can beat new, we introduced a parameter p in step (2) which denotes the probability of accepting old information (see Appendix B).

APPENDIX B: DYNAMICS WHEN OLD INFORMATION SOMETIMES BEATS NEW

Our model is based on the simple principle that new information is considered more valuable than old. This is, indeed, a simplification, and it is interesting to see how the model behaves when this condition is relaxed. We, thus, introduce a parameter p which is the probability that old information can overrule new (new words still, however, always win over old). For $p = 0$, we recover the original model, while $p = 1$ is the case when new and old information are considered equal. Figure 3 shows the case when $p = 0.8$ and is analogous to the left panel in Fig. 2. The concentric word distribution is still visible, but the interfaces between the word patches are rougher compared to the $p = 0$ case,

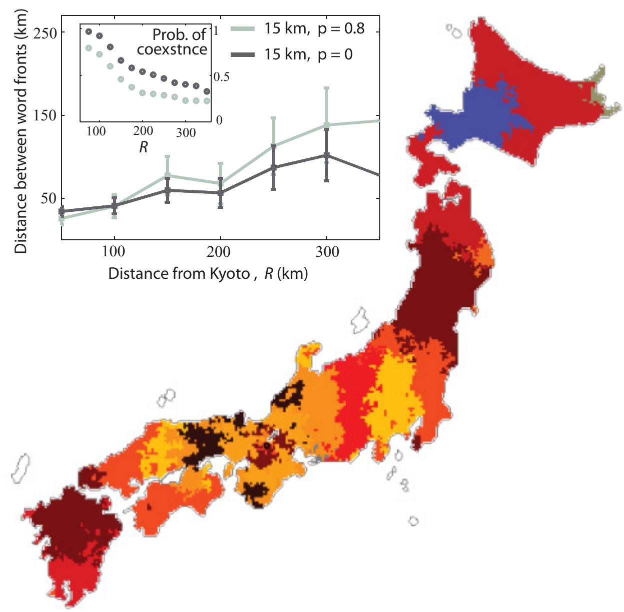

FIG. 3. (Color online) Spatial dynamics of words where old words overtake new in 80% of the cases. Each color represents a different word. The graph to the upper left shows how the distance between two adjacent word fronts grows with distance from Kyoto compared to the original model of $p = 0$ for the coarsening $\Delta = 15$ km. The probability that the same word variant exists on both sides of Kyoto is depicted in the inset. In order to improve the quality of the word landscape, we used a lattice spacing of $\Delta = 5$ km (100×100 lattice sites).

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[2] For $f_{\text{word}}^{-1} = 30$ yr, new words are invented at every time step, while for $f_{\text{word}}^{-1} = 60$ yr, this occurs at every fourth time step.

especially close to the center. Finite values of p thus increase the noise level in the system which also can be seen in the graph in the upper left corner. The speed of the growing interfaces, of course, decreases with increasing p.

APPENDIX C: DYNAMICS OF THE MODEL ON A RECTANGULAR LATTICE

In order to improve our understanding of the model, we performed simulations on a rectangular lattice with width L (which was chosen to be smaller than its height). New words are introduced along a line source at the base of the lattice at the frequency f_{word} and an invasion attempt to a neighboring lattice site occurs with rate k_R. The results are depicted in Fig. 4. The lower panel shows that the interface density $\rho(z)$ at large distances z from the source is well described by $\rho(z) \simeq A(L)z^{-0.5}$, i.e., the distance between two consecutive word fronts grows as $z^{0.5}$. This holds in one dimension ($L = 1$) as well as in two ($L = 10$ and $L = 100$) dimensions. The dependence of system size on the prefactor $A(L)$ in log-log scale is shown in the inset.

The probability that two words exist on both sides of the source can also be quantified in this simple setting if we place the line source in the middle of the system. The likelihood of coexistence decays with z as is shown in the top panel (for $L = 5$) for $f_{\text{word}}/k_R = 0.01$. The linear fit indicates that the probability decays as $z^{-0.4}$.

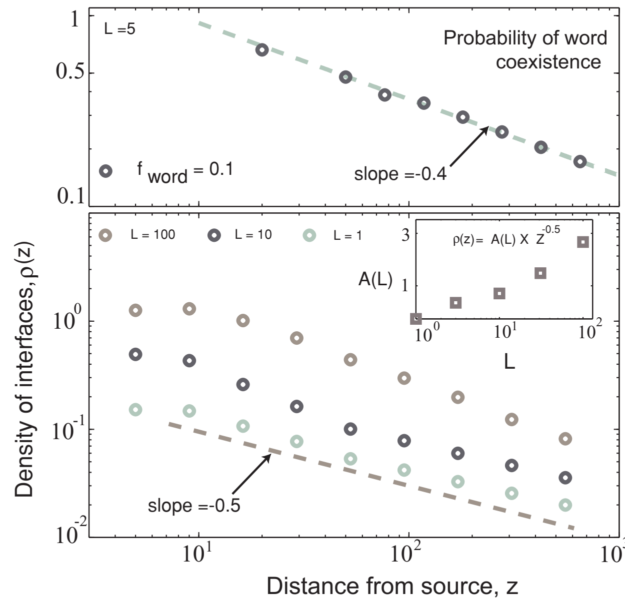

FIG. 4. (Color online) Simulation results from a rectangular lattice with width L, replication rate k_R, and frequency of new words f_{word}. (Bottom panel) Decay in surface density $\rho(z)$ as a function of distance z away from the source for three different system sizes. An average is taken over 1000 runs and $f_{\text{word}}/k_R = 1$. System size dependence on the prefactor $A(L)$ is shown in the inset. (Top panel) Probability that a word is present on both sides of the source as a function of distance z.

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