Rapid Communications

Fading of collective attention shapes the evolution of linguistic variants

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Language change involves the competition between alternative linguistic forms. The spontaneous evolution of these forms typically results in monotonic growths or decays, such as in winner-take-all attractor behaviors. In the case of the Spanish past subjunctive, the spontaneous evolution of its two competing forms (ending in −ra and −se) was perturbed by the appearance of the Royal Spanish Academy in 1713, which enforced the spelling of both forms as perfectly interchangeable variants, at a moment in which the −ra form was predominant. Time series extracted from a massive corpus of books reveal that this regulation in fact produced a transient renewed interest for the old form −se which, once faded, left the −ra again as the dominant form up to the present day. We show that time series are successfully explained by a two-dimensional linear model that integrates an imitative and a novelty component. The model reveals that the temporal scale over which collective attention fades is in inverse proportion to the verb frequency. The integration of the two basic mechanisms of imitation and attention to novelty allows us to understand diverse competing objects, with lifetimes that range from hours for memes and news to decades for verbs, suggesting the existence of a general mechanism underlying cultural evolution.

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Alternative linguistic forms such as synonyms (garbage-rubbish), spelling differences (behavior-behaviour), or past-tense regularization (spilt-spilled) are in constant tension and present a unique case to study the dynamics of cultural transitions [1,2]. This rivalry between competing cultural expressions occurs in a timescale of centuries or decades, but similar phenomena can be observed also in the timescale of hours for memes [3] and days in news [4].

Cultural transitions have been modeled with a variety of approaches going from formal and normative approaches [3,5] to some that explicitly incorporate the cognitive mechanisms that may produce them [2,4,6,7]. Distinct versions of the cognitive approach have proposed three mechanisms that account for the fading of certain cultural forms, being replaced by alternative versions which dominate the scene: (1) limited attention, (2) imitation, and (3) preference for novelty or adaptation [4].

Recently, a specific mathematical model [2] was proposed to explore transitions in language which included the Spanish subjunctive. This presents a quite privileged window to investigate cultural rivalry because it comes in two virtually perfectly exchangeable variants [8–11] (ending in −ra or −se, as in *cantara* and *cantase*, from the verb cantar, to sing), which allows to isolate and model specifically the selection forces that bias speakers towards either alternative. Starting approximately in 1800, written word usage reveals a monotonic decay of the form −se, which is replaced by the form −ra that dominates the Spanish subjunctive to this day. The model by Amato and collaborators [2] can explain these dynamics, since it predicts monotonic trajectories of competing populations. However, as one goes back in the history of the subjunctive, as we detail below, one finds a nonmonotonic dependence with a transition in which the form −se increases its popularity, which is then followed indeed by a slow and progressive decay in which the form −ra takes over again. This more interesting behavior resembles the dynamics of a damped oscillator in a critical regime, suggesting that the dynamics of this transition is governed by a two-dimensional linear process.

The aim of the work described in this Rapid Communication is twofold: (1) to understand how nonmonotonic cultural transitions can be accounted for by models which include imitation and novelty as used in different domains and temporal scales of culture, and (2) to understand, from a normative perspective, how novelty, which can be modeled as a dynamic forcing of one of the competing forms, leads to a minimal form of competing model equivalent to critically damped oscillators.

We begin with a brief history of the Spanish subjunctive, which presents several outstanding aspects that shaped its evolution over the last six centuries. The subjunctive is a grammatical mood that expresses states of unreality such as wish, possibility, or action that have not yet occurred (e.g., "Wish you were here"); this mood is often contrasted with the indicative, used mainly to point out that something is a statement of fact (e.g., "You are here") [8]. Notably, −ra is the only verbal form in the history of Spanish that changed its mood from its Latin indicative value (which was preserved in Old Spanish) to its modern subjunctive value. Ralph Penny says that from the fourteenth century on, −ra "began to be used as an imperfect subjunctive, coming into competition with −se and eventually ousting this form in many varieties of Spanish" [12]. A long process mediated the ascription of these forms to the subjunctive, and it was not until the 17th century that they began

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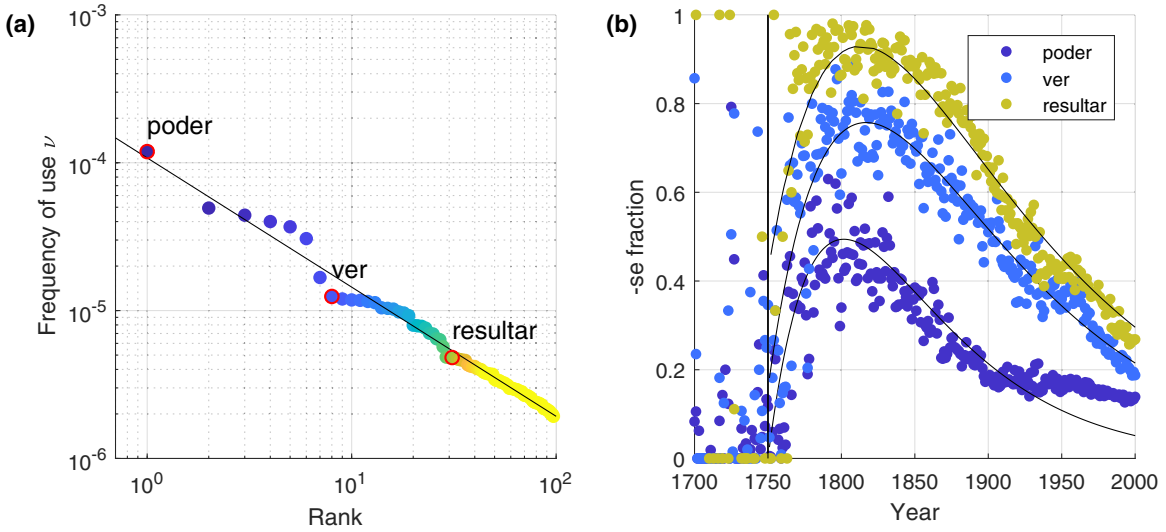

FIG. 1. Evolution of the fraction −se in the period 1750–2000. (a) We computed the frequency of subjunctive tokens (normalized to the size of the corpus) for the 100 most used Spanish verbs, which follow the Zipf's law. (b) Time traces of the −se fraction of poder (to be able), ver (to see), and resultar (to result), representatives of high-, medium-, and low-frequency of use (Spanish corpus of Google Books). Time traces show an overshoot circa yr. 1800. The vertical line at yr. 1750 indicates the cutoff point after which the density of forms −ra and −se is enough for data analysis.

to occupy contexts reserved to the −se form, first in final subordinate sentences and then in the rest of the contexts [13].

One century later, in 1713, the Royal Spanish Academy (RAE) was conceived as the official institution responsible for overseeing the Spanish language and promote linguistic unity within and across Spanish-speaking territories [2,14]. The Academy produced a global standardization process that enforced the official spelling of a number of linguistic forms, including −ra and −se as completely interchangeable variants of the past subjunctive in any context, without change of meaning [12,13,15].

Our conjecture is that in a context where the form −se was declining [12], this would produce a percolating effect of novelty which should lead, as in a critically damped oscillator, to a sharp transition of the −se form followed by a reestablishment to the preferred −ra form once the novelty effect lost its traction.

To explore the dynamics of the equivalent forms after the institutional regulation, we collected tokens of Spanish verbs from the two main Spanish corpora, the Spanish Google books [16] and the New Historical Spanish Dictionary (CDH) from the Royal Spanish Academy [17] (see Methods). Figure 1(a) shows the frequency of the first 100 verbs in subjunctive mood, computed in the period 1700–2000. As expected, verbs follow Zipf´s law [18].

From all collected tokens, we computed the number of each subjunctive variant N_{ra} and N_{se} on a yearly basis. In Fig. 1(b) we show traces of the relative frequency for −se, $s = \frac{N_{se}}{N_{ra}+N_{se}}$, for verbs of different frequency in the list. The traces show that the −se form systematically increased its popularity during the 18th century, which is also supported by analyses on small private corpora [11]. Then, after attaining a maximum value around 1800, the trend reversed and the form −se decreased monotonically, making −ra the dominant form observed at the present time across the Spanish-speaking countries [11].

As we go back in time, the number of books per year diminishes and the collected tokens become increasingly sparse. We therefore bounded our analyses to the period beginning at year 1750 (vertical line) for which subjunctive instances for all verbs are greater than 1000 tokens per year in the Google Books corpus [19]. The amount of tokens per year depends in turn on each specific verb. We required the existence of subjunctive instances in each 5-year window within the period 1750–2000, which holds for the top 40 most frequent verbs (see Methods).

Recently, a discrete model for the competition of linguistic variants under different enforcements was presented [2]. Notably, control on a few parameters allows fitting the model to experimental data of spontaneous competitive processes or under the action of formal or informal authorities. In particular, the model was used to fit the evolution of the fractions s and r in the period 1800–2000. According to the model, at each year t writers contribute to the corpus of books in this way: a fraction c of them use the −ra convention; the rest of them (fraction $1-c$) either follow the institutional enforcement E (fraction γ) or sample the current distribution (fraction $1-\gamma$). With these ingredients, the model reads

$$r_{t+1} = (1-c)[\gamma E_r + (1-\gamma)r_t] + c,$$
$$s_{t+1} = (1-c)[\gamma E_s + (1-\gamma)s_t].$$

The dominance of −ra is guaranteed by the asymmetry introduced by the parameter c in the first equation. The fractions E_r and E_s represent the institutional enforcements that bias writers towards either convention. Setting $E_r = E_s = 1/2$ to account for the equivalence of both forms, the authors of the work successfully fitted the time series of the variants in the period 1800–2000, when −se decreases monotonically [2].

We capitalized on this to model the evolution of the fractions throughout all the temporal window for which there is sufficient data (from the early 18th century to these days) which displays a nonmonotonic progression. We first assumed

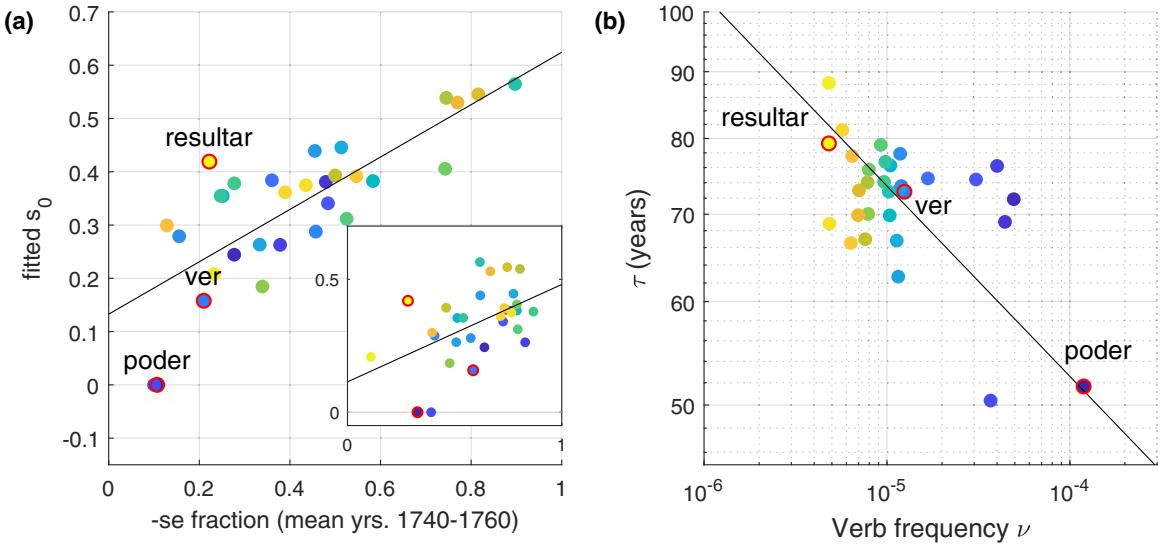

FIG. 2. Relaxation times decrease with verb popularity. (a) The values of s_0 in Eq. (2) represent the fraction $-$se at year 1750, fitted with our model using data from the Spanish corpus of Google Books in the period 1750–2000. These values are positively correlated with the mean value of $-$se in the period 1740–1760 ($r = 0.78$, $p < 0.001$). (Inset) The same analysis is shown for data from the independent CDH corpus ($r = 0.52$, $p < 0.002$). The color map covers the range of verb frequencies, from high (blue) to low (yellow) values. (b) The most used verbs are less sensitive to novelty effects, evidenced by the inverse relationship between the relaxation timescale τ and frequency of use ν (Deming-corrected linear regression, $r = 0.55$, $p < 0.002$).

no intrinsic assymmetry between conventions ($c = 0$). Taking the continuum limit ($x_{t+1} - x_t \to \dot{x}$) and defining $\tau = 1/\gamma$, the equation for $-$se reads

$$\tau \dot{s} = -s + E_s(t), \tag{1}$$

with an equivalent equation for the fraction $-$ra (r). Here we deal with the effect produced by the large-scale promotion of both linguistic variants in the early 18th century, when people were allowed to choose between an infrequent "novel" form ($-$se) and the traditional one ($-$ra). Based on the consumption of cultural products at multiple domains (such as papers, movies, patents, and music) that show universal decay functions [20], we propose the ansatz

$$E_s(t) = a\tau\, e^{-t/\tau} \tag{2}$$

to model the way in which the novel form $-$se is consumed, fading exponentially among the population. With this ansatz, the resulting equation (1) is solved by the functions

$$s(t) = (at + s_0)\, e^{-t/\tau}, \tag{3}$$

which overshoot the stimulus $E_s(t)$ and then follow the exponential decay, a picture that qualitatively describes the behavior of the time series shown in Fig. 1(b), where $-$se gains popularity before decaying [19].

To quantify this, we associated a different set of parameters s_0, τ, and a to each verb in Eq. (3). The parameter s_0 represents the $-$se fraction at the beginning of the period (we set $t = 0$ at yr. 1750), which depends on the past history of each verb. The association of a specific decay τ to each verb is based on the concept of preferential attachment, which refers to a process in which a certain quantity is distributed among individuals according to how much they already have. Preferential attachment is present across cultural domains; for instance, the decay in the citing rate of an academic paper depends on the cumulative citations received by that paper along its history [20]. We therefore let the verbs react to novelty with their own decay constant τ. In principle, the parameter a in Eq. (3) can also be informative of the dynamics of each verb. However, the complete set of verbs can be successfully fitted using a single value of $a = 0.027 \pm 0.004$, which we kept for simplicity (see Fig. 1(b) and [19]). In this framework, a represents the global strength of the perturbation produced on the writers.

In Fig. 2(a) we show that the fitted s_0 are positively correlated with the experimental values of the $-$se fraction at year 1750 both for the Google Books and the CDH corpus (inset). More interestingly, Fig. 2(b) shows that relaxation times τ are inversely related to the frequency of use ν of the verbs, following the power law $\tau = \nu^{-\beta}$ ($\beta \sim 0.14$).

In this description, $E_s(t)$ is the fraction of writers driven by attention to the variant $-$se, and consequently, $E_s(t) = a\tau\, e^{-t/\tau} \leqslant a\tau \leqslant 1$. As expected by the statistical interpretation of the model, this holds for low relaxation times [$\tau \leqslant 1/a \sim 43$ years, see Fig. 2(b)] that correspond to highly popular verbs. However, the model successfully fits experimental traces for all verbs, even those of much lower frequencies than required by the statistical interpretation. This invites to consider the system of equations (1) and (2) as a more abstract model for the variants, which can be rewritten as the autonomous two-dimensional linear system

$$\begin{pmatrix} \dot{s} \\ \dot{e}_s \end{pmatrix} = \begin{pmatrix} -1/\tau & 1 \\ 0 & -1/\tau \end{pmatrix} \begin{pmatrix} s \\ e_s \end{pmatrix},$$

where $e_s = E_s/\tau$. For this system, trajectories in phase space (s, e_s) approach the origin without oscillations and faster than any other linear system. From this abstract perspective, the

onset of the regulation acts as a perturbation $e_s(0) = a$ that kicks the system away from the equilibrium $(0, 0)$, to which it then relaxes with a timescale τ inversely proportional to the frequency ν of each verb.

The competition of subjunctive forms seems to be dominated by a general preference for the form −ra across the Spanish-speaking countries [21], which is indeed manifested in the fact that the institutional enforcement produced just a local perturbation in the trend of increasing dominance of −ra. Forces that drive selection to one of the alternatives in competition have been explored and include social and cognitive factors as well as phonological and biophysical factors [22,23]. Although the forces underlying the preference for −ra rest unknown, the dynamics that drive speakers towards the preferred form are modulated by collective behaviors such as those analyzed in the present work. Here we capitalized on the access to massive digital corpora [16,17] and previous models [2,4,5,20,24] to advance a simple dynamical system that fits experimental traces of imperfect subjunctive variants collected from written texts. The model integrates two basic forms of collective behavior: an imitative component (writers contribute to the corpus by sampling the current distributions of the variants) and a novelty component (writers temporarily pay attention to the declining form).

Our main findings are as follows: (1) The simple functional form of Eq. (3) fits well to experimental time traces for the corpus of Spanish verbs starting at year 1750, close to the external regulation that promoted the equivalence of the variants. (2) This functional form arises naturally from a model of collective imitation [2], when an exponential decay is introduced to account for a fading in novelty. In dynamical terms, the regulation acts as a perturbation that unfolds the underlying dynamics of the problem, compatible with a linear system in a critical regime. (3) Adjusting the dynamics for each verb revealed that the relaxation timescales decrease with the verb frequency, which means that novelty fades faster for popular verbs.

Beyond language, imitation and decay of novelty have been also suggested as necessary components for modeling the consumption of objects from different cultural domains such as movies, music, papers, and patents [20] and the dynamics of collective attention in Twitter [24]. The integration of these basic behaviors allows us to understand diverse competing objects, with lifetimes that range from some hours or days for news [4] and memes [3] to decades for verbs. This suggests a general mechanism underlying cultural evolution and provides us with a general framework to study cultural phenomena.

We extracted the list of 889 Spanish verbs with more than one instance of imperfect subjunctive from the LexEsp corpus [25]. For each verb, we built the list of all conjugations in both imperfect subjunctive forms: −ra (cantara, cantaras, cantáramos, cantárais, cantaran) and −se (cantase, cantases, cantásemos, cantáseis, cantasen). These tokens were then collected from the Google Books [16] and CDH [17] corpora. From all collected tokens, we selected those corresponding to verbs that occurred at least once in each 5-year window from 1750 on [19]. This condition was met for the top 40 most used Spanish verbs in the Google Books corpus. The frequency of use of each verb was computed as the ratio between all the conjugations for the simple past subjunctive collected in the corpus and the size of the corpus (8.4×10^{10} tokens).

In the absense of regulation, many orthographic forms coexisted in Old Spanish. For instance, the verb haber (to have) included the following −se orthographic variants for the imperfect subjunctive: oviese, oviesse, hobiese, and hubiese. We verified that the archaic forms were absent after 1700 [19], and therefore only the modern past subjunctive forms were collected and analyzed.

Four verbs were explicitly excluded from our analyses. The verbs ser (to be) and haber (to have) serve a different function, as auxiliars for the compound tenses in Spanish. Also, the verb ir (to go) shares the same imperfect past subjunctive with the verb ser (to be), i.e., fuera/fuese. For these reasons, those cases were a priori excluded from our analyses. The time trace of the verb deber (should) was not fitted by the model and was also excluded from the analysis.

Parameters a, τ, and s_0 of Eq. (3) were fitted to the experimental time traces using a standard least-squares method. The pairs (s_0, τ) for each verb in the set were calculated as a function of a, whose value was then set as the value that minimizes the sum of errors for all verbs. The range of $a = 0.027 \pm 0.004$ was determined by bootstrapping (100 repetitions of two randomly chosen verbs).

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