



# The dynamics of norm change in the cultural evolution of language

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**What happens when a new social convention replaces an old one? While the possible forces favoring norm change—such as institutions or committed activists—have been identified for a long time, little is known about how a population adopts a new convention, due to the difficulties of finding representative data. Here, we address this issue by looking at changes that occurred to 2,541 orthographic and lexical norms in English and Spanish through the analysis of a large corpora of books published between the years 1800 and 2008. We detect three markedly distinct patterns in the data, depending on whether the behavioral change results from the action of a formal institution, an informal authority, or a spontaneous process of unregulated evolution. We propose a simple evolutionary model able to capture all of the observed behaviors, and we show that it reproduces quantitatively the empirical data. This work identifies general mechanisms of norm change, and we anticipate that it will be of interest to researchers investigating the cultural evolution of language and, more broadly, human collective behavior.**

norm change | collective behavior | modeling | cultural evolution | complex systems

**S**ocial conventions are the basis for social and economic relations (1–4). Examples range from driving on the right side of the street to language, rules of politeness, or moral judgments. Broadly speaking, a convention is a pattern of behavior shared throughout a community and can be defined as the outcome that everyone expects in interactions that allow two or more equivalent actions (e.g., shaking hands or bowing to greet someone) (5, 6). Conventions emerge either thanks to the action of some formal or informal institution or through a self-organized process in which group-level consensus is the unintended consequence of individual efforts to coordinate locally with one another (2, 6). Crucially, since conforming to a convention is in everyone’s best interest when everyone else is conforming, too, social conventions are self-enforcing (5). Yet behaviors change all the time, and old conventions are constantly replaced by new ones: Words acquire new meanings (7), orthography evolves (8), rules of politeness are updated (9), and so on. In isolated groups, shifts in conventions may be driven by the same forces that determine the emergence of a consensus from a disordered state [i.e., institutions or self-organization (6, 7)]. However, a quantitative understanding of the processes of norm change has remained elusive so far, probably hindered by the difficulty of accessing adequate empirical data (10).

Here, we address this issue by focusing on shifts in orthographic and linguistic norms through the lenses of ~5 million written texts covering the period from 1800 to 2008 from the digitized corpus of the Google Ngram (11) dataset. Following the same approach that has allowed quantification of processes such as the regularization of English verbs (12) or the role of random drift in language evolution (13), we analyze the statistics of word occurrences for a set of specific linguistic forms that

have been historically modified either by language authorities or spontaneously by language speakers in English or Spanish. These include words that have changed their spelling in time and competition between variants of the same word or expression. To explore the mechanisms of norm change, we consider three separate cases:

1. Regulation by a formal institution: We analyze the effect of the deliberations of the Royal Spanish Academy, *Real Academia Española* (RAE), the official royal institution responsible for overseeing the Spanish language, on the spelling of 23 Spanish words (complete list is in *SI Appendix, section 3*) (14–20).
2. Intervention of informal institutions: We investigate the effect of dictionary publishing in the United States on the updating of American spelling for 900 words (<https://www.merriam-webster.com>; ref. 21) (complete list is in *SI Appendix, section 10.A*).
3. Unregulated (or “spontaneous”) evolution: We consider the alternation between forms that are either unregulated or described as equivalent by an institution but have nonetheless exhibited a clear evolutionary trajectory in time [i.e., we do not consider the case of random drift as primary evolutionary force (13)]. In particular, we examine (i) the evolution over time of the use of two equivalent forms for the construction of imperfect subjunctive verbal time in Spanish, for 1, 571 verbs (complete list is in *SI Appendix, section 10.C*; verbs and declination for each form are in refs. 22 and 23), (ii) the alternation of two written forms of the Spanish adverb *solo/sólo*

## Significance

**Social conventions, such as shaking hands or dressing formally, allow us to coordinate smoothly and, once established, appear to be natural. But what happens when a new convention replaces an old one? This question has remained largely unanswered so far, due to the lack of suitable data. Here, we investigate the process of norm change by looking at 2,541 linguistic norm shifts occurring over the last two centuries in English and Spanish. We identify different patterns of norm adoption depending on whether the change is spontaneous or driven by a centralized institution, and we propose a simple model that reproduces all of the empirical observations. These results shed light on the cultural evolution of linguistic norms and human collective behavior.**

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(only) (24), and (iii) 46 cases of substitution of British forms (e.g., words) with American ones in the United States (25) (complete list is in *SI Appendix, section 10.B*).

We show that these mechanisms leave robust and markedly distinct stylized signatures in the data, and we propose a simple evolutionary model able to reproduce quantitatively all of the empirical observations. When a formal institution drives the norm change, the old convention is rapidly abandoned in favor of the new one (7, 26–29). This determines a universal process of norm adoption which is independent of both word frequency and corpus size. A qualitatively similar pattern is also observed for norm adoption driven by an informal institution, although in this case the adoption of the new form is smoother and word-dependent. In the case of unregulated norm change, the transition from the old to the new norm is slower, potentially occurring over the course of decades, and is often driven by some asymmetry between the two forms, such as the presence of a small fraction of individuals committed to one of the two alternatives (30–32).

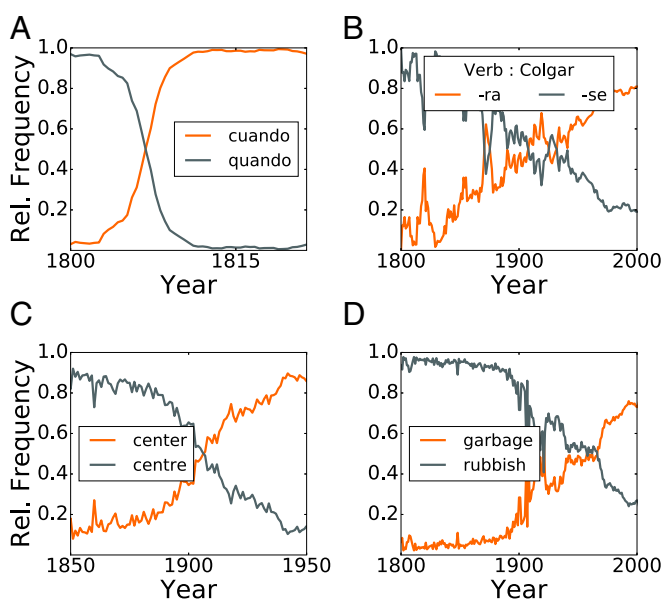
### Data and Historical Background

**Spanish.** Founded in 1713, the RAE (Royal Spanish Academy) is the official institution responsible for overseeing the Spanish language. Its mission is to plan language by applying linguistic prescription to promote linguistic unity within and across Spanish-speaking territories, to ensure a common standard in accordance with article 1 of its founding charter: "... to ensure the changes that the Spanish language undergoes [...] do not break the essential unity it enjoys throughout the Spanish-speaking world." (33–35). Its main publications are the *Dictionary of Spanish Language* (23 editions between 1780 and today) and its *Grammar*, last edited in 2014. Particularly interesting for our study is the standardization process that the RAE carried out during the 19th century, which enforced the official spelling of a number of linguistic forms (15, 36).

Our dataset contains 23 spelling changes that occurred in four different reforms, in 1815, 1884, 1911, and 1954 (additional details are in *SI Appendix, section 3*) (14–20). To illustrate this, Fig. 1A shows the temporal evolution of the spelling change of the word *quando* ("when") into *cuando*—regulated in the 1815 reform—in the Spanish corpus, showing a sharp transition [or "S-shaped" behavior (26–28)]. Different is the case of the adverb *solo* ("only"), whose spelling variant *sólo* was added to the RAE dictionary in 1956 after a long unofficial existence supported by a number of academics (24, 32, 37). We will consider the coexistence of these latter two forms as an example of unregulated evolution [since 2010, the RAE discontinued the *sólo* variant again (24), but our dataset does not include such recent data].

A major example of unregulated norm change is offered by the Spanish past subjunctive, which can be constructed in two—equivalent (38, 39)—ways by modifying the verbal root with the (conjugated) ending *-ra* or *-se* (additional details are in *SI Appendix, section 3*). For example, the first person of the past subjunctive of the verb *colgar* ("to hang") could be indistinctly *colga-ra* or *colga-se*. Fig. 1B shows the growth of the *-ra* variant, for all verbal persons, over two centuries. A similar behavior is found in most Spanish verbs, with the form *-se* being the most used at the beginning of the 19th century (preferred  $\approx 80\%$  of the times) to the less used at the beginning of the 21st century (chosen  $\approx 20\%$  of the times). This peculiar phenomenon has attracted the attention of researchers for the last 150 years and has not been entirely clarified (38).

Recent results suggest that, whereas individuals typically use only one of the two forms, the alternation between the two variants tends to be found only in speakers who prefer the *-se* form (39, 40), as also confirmed by a recent analysis of written texts



**Fig. 1.** Illustrative examples of competing conventions in our dataset [relative (Rel.) frequencies]. (A) Formal institution: the spelling of the Spanish word “quando” (when) was changed into “cuando” by a RAE reform in 1811. (B) Unregulated evolution of two equivalent forms for the past subjunctive, *-ra* and *-se*, for the verb “colgar” (to hang). (C) Informal institution: the American Spelling “center” vs. the British spelling “centre.” (D) Unregulated evolution of “garbage,” the American variant of the British “rubbish.”

(41). Thus, the users of *-ra* appear to be effectively committed to this unique form. As we will show below, the possibility of such asymmetries of behavior have been incorporated into our model.

**British English vs. American English.** The emergence of American English was encouraged by the initiative of academics, newspapers and politicians—e.g., US President Theodore Roosevelt (30)—who over time introduced and supported new reforms (42). The process gained momentum in the 19th century, when a debate on how to simplify English spelling began in the United States (31, 43–45), which was also influenced by the development of phonetics as a science (46). As a result, in 1828, Noah Webster published the first *American Dictionary of the English Language*, beginning the Merriam–Webster series of dictionaries that is still in use nowadays (31, 47). Some changes, such as *color* instead of *colour* or *center* for *centre*, would become the distinctive features of American English. Fig. 1C shows the transition from the British spelling *centre* to the American *center*. The complete list of the 900 words examined is reported in *SI Appendix, section 10.A*.

The phenomenon of “Americanization” of English (25) is not limited to spelling but also includes the introduction of different words or expression which over time replaced the British ones. Recent works (25, 48) report how the globalization of American culture might be favoring the affirmation of their specific form of English. We will consider a list of 46 American-specific expressions in relation to their British counterpart (ref. 25; complete list is in *SI Appendix, section 10.B*), such as *garbage* vs. *rubbish* reported in Fig. 1D or *biscuit* vs. *cookie*. In all cases, we will consider only books listed in the American English Corpus of Google Ngram.

### Model

We introduce a simple model that describes the evolution in time of two alternative forms of a word (i.e., two alternative

conventions). For example, the two norms may represent two spelling alternatives (*-or* vs. *-our* as in *color/colour*), two ways to form a verbal tense (*-ra* vs. *-se*), or two different words to refer to the same concept (*biscuit* vs. *cookie*).

The model describes a system of books where instances of the two conventions are added by authors through the publication of books. Authors select which convention to use (i.e., which form to introduce in the system) either by following the indications of an institution or considering the current state of language. In the first case, authors simply adopt the recommended norm (or “new norm,” for simplicity, as we focus on cases of norm change). In the latter case, the convention to be used is selected with a probability proportional to its current frequency, as in the neutral model for evolution (49). Additionally, some authors can be committed to one specific form, thus being indifferent to any external influence, as suggested by the literature on the study of orthographic norm change in both English (30, 31) and Spanish (32). When an authority is present, the presence of commitment is revealed by the (empirically verified, *SI Appendix*, section 4 and Fig. S1) persistence in time of the old norm and translates into the model such phenomena as, for example, the reeditions of past books whose orthography is not updated (50). In the case of unregulated evolution, committed authors privilege the initially less popular new norm, contributing to its success.

The two different conventions are labeled as “new” and “old,” and their number is  $\mathcal{N}$  and  $\mathcal{O}$ , respectively, so that the total number of conventions at time  $t$  is given by  $\mathcal{W}(t) = \mathcal{N}(t) + \mathcal{O}(t)$ . For a more transparent comparison with the data, aggregated on a yearly basis, we adopt a discrete-time formulation of the model where one time step corresponds to one year. The evolution of the densities  $n(t) = \mathcal{N}(t)/\mathcal{W}(t)$  and  $o(t) = \mathcal{O}(t)/\mathcal{W}(t) = 1 - n(t)$  is described by the following equations

$$\begin{aligned} n(t+1) &= (1-c)(1-\gamma)n(t) + (1-c)\gamma E_{\mathcal{N}} + c, \\ o(t+1) &= (1-c)(1-\gamma)o(t) + (1-c)\gamma E_{\mathcal{O}}. \end{aligned} \quad [1]$$

New words are inserted by writers (authors). A writer is committed to the use of one specific convention, with probability  $c$ , or neutral, with probability  $1-c$ . Neutral writers follow the institutional enforcement, with probability  $\gamma$ , or sample the current distribution of norms, with probability  $1-\gamma$ . For simplicity, we assume that each writer inserts just one convention and that the probabilities  $c$  and  $\gamma$  are constant. When an institution promotes the norm  $\mathcal{N}$ , it makes an effort  $E_{\mathcal{N}} = 1$  and  $E_{\mathcal{O}} = 0$  otherwise. If the institution is impartial, both forms are a priori equivalent, and  $E_{\mathcal{N}} = E_{\mathcal{O}} = \frac{1}{2}$ . Again, for simplicity, in the equations all committed writers privilege the same convention (30–32). This is the new norm in the above equations, while expressions for the symmetric case of committed agents that support the old norm are reported in *SI Appendix*, section 1. The general solution of the system of Eq. 1 is:

$$n(t) = \frac{B}{(1-A)} (1-A^t) + n_0 A^t, \quad [2]$$

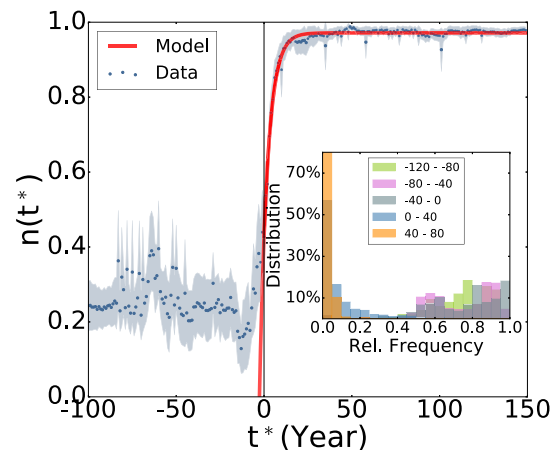
where  $A = (1-c)(1-\gamma)$ ,  $B = (1-c)\gamma E_{\mathcal{N}} + c$ , and  $n_0 = n(t=0)$  (*SI Appendix*, section 2). It is worth noticing that, when  $E_{\mathcal{N}} = 1$ , for  $\gamma = 1$  Eq. 2 describes an instantaneous transition in which the new norm immediately saturates to  $B/(1-A)$  [with  $B/(1-A) = 1$  if the commitment supports the new norm, as here, or  $B/(1-A) = 1-c$  if it supports the old norm; *SI Appendix*]. In this sense, values  $\gamma < 1$  correspond to a situation in which the response of the system to an institutional intervention is not immediate. In the following sections, we show that, by

appropriately varying the parameter values, the analytic solution Eq. 2 reproduces all of the empirical observations.

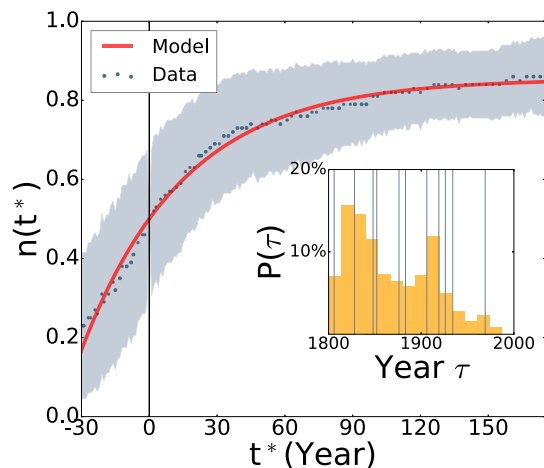
## Results

**Regulation by a Formal Institution.** In Fig. 2, we consider the relative frequency,  $n(t)$ , of appearance of the new spelling for the 23 words in our dataset affected by RAE reforms (14–20) (*SI Appendix*, section 4). By a simple rescaling (translation) of the time axis as  $t^* = t - t_r$  (where  $t_r$  is the regulation year for each specific pair of conventions), we found that all of the experimental curves collapsed. The regulatory intervention ( $t^* = 0$ ) determined an abrupt transition toward the adoption of the new norm. This discontinuity was captured by the distribution of the old spelling among the words before and after the regulation in Fig. 2, *Inset*. Importantly, such rescaling indicates that the transition is size-independent. For example, for the 1815 regulation, our dataset consists of  $B_{1815} = 59$  books and  $S_{1815} = 4, 149, 151$  words, whereas for the regulation enforced in 1954, we have  $B_{1954} = 2774$  books and  $S_{1954} = 244, 138, 299$  words, but transition between the old and new form occurs over approximately the same amount of time in the two cases. Model parameters for the case of formal regulation are  $E_{\mathcal{N}} = 1$  and commitment supporting the old convention for which  $B = (1-c)\gamma$  (*SI Appendix*, section 1, Eq. 1). Fig. 2 shows that the fit of Eq. 2 matches the empirical data ( $\gamma = 0.2$ ,  $c = 0.006$  and  $n_0 = 0.42$  from the data). As we will show below, different values of  $\gamma$  correspond to different roles played by institutions in the process of norm change (*SI Appendix*, section 7, Figs. S3A and S4A for the behavior of individual curves and *SI Appendix*, section 8, Fig. S4B for the corresponding distribution of  $\gamma$ ).

**Intervention of Informal Institutions.** We now focus on the dynamics occurring between American and British spelling through the analysis of 900 words as they appear in our US corpus (complete list is in *SI Appendix*, section 10.A). As in the case of formal institution, we have  $E_{\mathcal{N}} = 1$  and the commitment supporting the old (i.e., the British, here) spelling. For each pair of conventions, we identified the year  $\tau$  in which the British form was surpassed in popularity by the American one [Fig. 3, *Inset*, shows the empirical frequency distribution of these surpassing times  $P(\tau)$ ]. Fig. 3



**Fig. 2.** Regulation by a formal institution (Spanish, RAE). Relative (Rel.) frequency of the new spelling form as a function of the rescaled time  $t^*$  is shown. Blue points represent the average over all of the considered pairs of words, and the gray area shows the SD of the data. The solid line is the prediction of the model outcome (Eq. 2) after parameter fit ( $\chi^2 = 6 \cdot 10^{-5}$ ,  $p = 0.99$ ). The black vertical line denotes the rescaled regulation year  $t^* = 0$ . (*Inset*) Frequency histogram of the old spelling form for all pairs of word forms, for different time periods (negative time refers to periods before the regulation).



**Fig. 3.** Regulation by informal institutions. Relative frequency of the American spelling for 900 English words as a function of the rescaled time  $t^*$  ( $t^* = 0$  denotes the surpassing year, for all pairs of words considered). Blue dots represent the average over all the pairs of words, and the gray area shows the SD of the data. The solid line is the model outcome, Eq. 2, after parameter fit ( $\chi^2 = 8 \cdot 10^{-4}$ ,  $p = 0.97$ ). (Inset) Distribution  $P(\tau)$  of the years  $\tau$  in which the American form overcame the British variant for each word. Vertical lines denote important moments of informal regulations of the US spelling, such as dictionary editions or spelling updates (additional details are in *SI Appendix*, section 5).

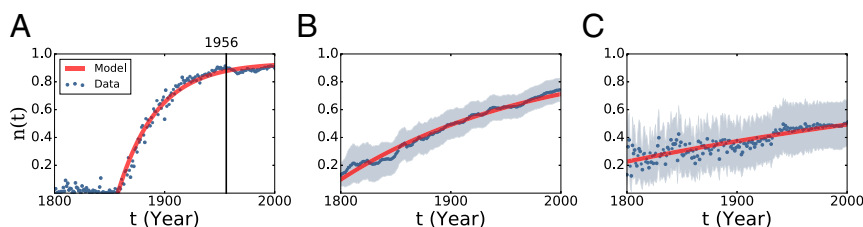
shows that by rescaling time via simple translation  $t^* = t - \tau$  all experimental curves collapse, similarly to the above case of formal institution. The model Eq. 2 reproduces the data. The value of  $\gamma = 0.02$  obtained in this case is much smaller than the one relative to the above case of formal institution ( $\gamma = 0.2$ ), quantifying the weaker role played by informal institutions [other parameters  $c = 0.003$  obtained by the fit and  $n_0 = n(t^* = 0) = 0.5$  by construction]. This result was confirmed by analyzing each pair of competing conventions in isolation (*SI Appendix*, section 7, Fig. S3B, and section 8, Fig. S4).

**Unregulated Evolution.** As a third case, we explored the process of unregulated norm change by considering the relative frequency of appearance of the form *sólo* (vs. *solo*; Spanish for only) (24) in the Spanish corpus, the relative frequency of appearance in the Spanish corpus of the past subjunctive form ending in *-ra* and the one ending in *-se* for 1,571 verbs (*SI Appendix*, section 10.C), and the relative frequency of appearance in the US corpus of 46 cases, among words and expressions, of substitution of British forms for American ones (*SI Appendix*, section

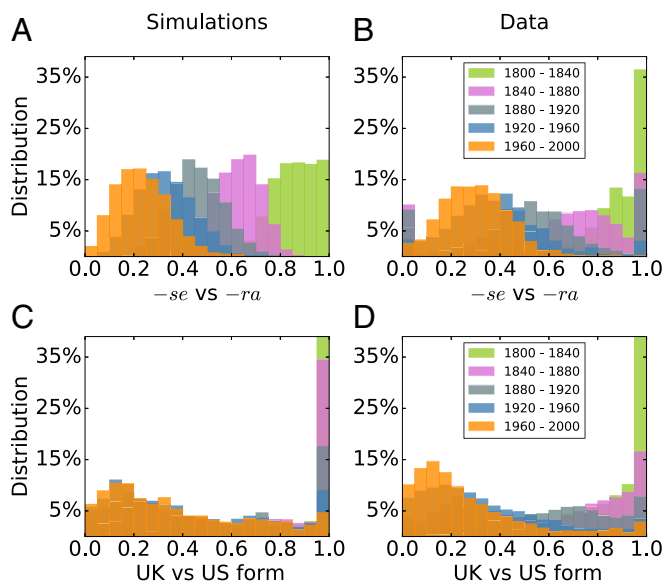
10.B). Since the institution is impartial, we have  $E_N = E_O = \frac{1}{2}$ . Fig. 4 A–C shows that the solution Eq. 2 describes well the data relative to growth of the form *sólo* ( $\gamma = 3 \cdot 10^{-3}$ ,  $c = 0.02$ ), the growing of the *-ra* form for the subjunctive of Spanish verbs ( $\gamma = 10^{-17}$ ,  $c = 0.005$ ), and the growth of American forms ( $\gamma = 10^{-14}$ ,  $c = 0.002$ ), respectively (solid lines correspond to the model predictions after parameter fitting). The values of  $\gamma$  obtained here were significantly smaller than the ones observed for the cases of formal and informal institutions and corroborated the fact that centralized authorities played essentially no role in this case (see also *SI Appendix*, section 8, Fig. S4 for the analysis of individual curves). It is worth noting that *sólo* (without accent) can be also used as adjective and that, while the competition *solo/sólo* concerns only the adverb, the data do not allow us to distinguish between the adverb or adjective use. Our analysis shows that the adverb is dominant, as the adverb-specific *sólo* is nowadays the most used form, but the nonsaturation of the curve in Fig. 4A can be interpreted as a signature of the presence of a percentage of adjectives in our dataset.

**Microscopic Dynamics.** As a further assessment, we ran stochastic simulations of the model to reproduce the microscopic evolution of each pair of conventions for the case of spontaneous transition and for the case of the intervention of informal institution. In each numerical experiment, we imposed the parameters recovered through the fitting procedure described above. We initially considered the case of unregulated (spontaneous) norm adoption. In Fig. 5 A and B, we report the probability distribution of observing a relative frequency  $n(t)$  for the verbal form *-se*, estimated by simulating the evolution of all verbs for which we have empirical record. The simulation results suggested that our model captured well the ensemble evolution over time of the whole empirical distributions. Similarly, Fig. 5 C and D show empirical and numerical results for the class of norm adoption via informal authority, in the case of American spelling change. To account for multiple interventions of informal institutions, numerical experiments were run by “switching on” the parameter  $\gamma$  at different, randomly chosen, times. Moreover, the American case consists of conventions that manifest themselves through specific sets of words—that is, the use of *or* instead of *our* in *behavio(u)r* or *colo(u)r* or *-ize* instead of *-ise* in verbs. Thus, for each simulation, we extracted  $\gamma$  from a Gauss distribution centered in  $\gamma = 0.02$  (as informed by the data, and  $\sigma = 0.005$ ) to reproduce the fact that, in this case, the transition from the old to the new convention is word-dependent.

By visually comparing empirical distributions of conventions over time for each norm adoption class (Figs. 2, Inset, and 5 B and D for formal authority, spontaneous, and informal authority, respectively), it is evident that, microscopically, the transition



**Fig. 4.** Unregulated norm change. (A) Case *sólo* vs. *solo*. Blue dots represent the relative frequency of the Spanish adverb *sólo* (increasing in detriment of the alternative form *solo*). The solid line is the prediction of Eq. 2 for this case, after parameter fit ( $\chi^2 = 4 \cdot 10^{-4}$ ,  $p = 0.98$ ). The vertical line indicates the year 1956, when RAE intervened explicitly on the case (24, 32, 37). The curve saturates to a value  $< 1$  probably due the presence of a percentage of adjectives, indistinguishable from the adverb in the data. (B) Case of *-ra* vs. *-se* in Spanish subjunctive. Blue dots represent the relative frequency of the form *-ra* (increasing in detriment of the alternative but equivalent form *-se*) in Spanish past subjunctive conjugation of verbs, averaged over all verbs considered. Solid line is the specific prediction of Eq. 2 for this case, after parameter fit ( $\chi^2 = 2 \cdot 10^{-3}$ ,  $p = 0.96$ ). (C) Case of Americanization of English in the United States. Blue dots represent the relative frequency of the American variant (with respect to the British variant) in the US corpus, averaged over all of the expressions examined. Solid line is the specific prediction of Eq. 2 for this case, after parameter fit ( $\chi^2 = 6 \cdot 10^{-3}$ ,  $p = 0.93$ ). For all cases, the gray area identifies the SD of the data.



**Fig. 5.** Empirical and simulated distributions for the relative frequencies of a given form. (A and B) Spanish subjunctive case, *-se* vs. *-ra*. Simulation reported in A reproduced the empirical observation of the equivalent distributions (B). (C and D) Intervention of informal institution case, UK vs. US variant. Simulations reported in C can be compared with the actual empirical distribution (D). Simulated distributions from 200 simulation runs with parameters informed by the fitting procedure and  $\mathcal{W} = 2,000$ .

from the old to the new convention is governed by different dynamics. For enforcements by formal authorities (Fig. 2, *Inset*), when the norm is regulated, the system simply switches to the new convention. On the other hand, for unregulated (spontaneous) norm change (Fig. 5B), the distribution essentially remains unaltered, but for a translation of its mean value which gradually shifts from 1 to 0. Finally, the word-dependent transition of the informal institution case yields a broadening of the shape of the distribution over time (Fig. 5D).

## Conclusion

In this work, we have capitalized on a recently digitized corpus to analyze the process of norm change in the context of the cultural evolution of written English and Spanish. Through the analysis of 2,541 cases of convention shifts occurring over the past two centuries, we identified three distinct mechanisms of norm change corresponding to the presence of an authority enforcing the adoption of a new norm, an informal institution recommending the normative update, and a bottom-up process by which language speakers select a new norm. Each of these mechanisms displayed different stylized patterns in the data. We rationalized these findings by proposing a simple evolutionary model that describes the actions of the drivers of norm change previously identified in the literature—namely, institutions and language users committed to the use of one of the two competing conventions. We showed that this single model captures the dynamics of norm change in each of the three cases described above, quantitatively matching the empirical data in all circumstances. In doing so, it differentiates the empirical curves in three classes according to the measured strength of the institutional intervention (fitted values of  $\gamma$  and single curve evaluation; *SI Appendix, section 8*), thus confirming a posteriori the validity of our approach. Finally, through numerical simulations, we were also able to reproduce the observed microscopic dynamics of norm adoption.

When a formal institution is present, the transition is sharp and does not depend either on the properties of the considered

system (e.g., year or number of published books) or the relative importance of the linguistic convention subject to the norm change. The effect of informal institutions is weaker, resulting in a slower reaction of the system and a smoother transition. Finally, in the bottom-up process of spontaneous change, the mechanisms of imitation and reproduction are key in bringing about the relatively slower onset of the new norm, catalyzed by the presence of “committed activists” (30–32).

It is important to delimit the scope of our findings. First, we only considered cases for which historical records show that a norm change did occur, and we did not attempt to predict whether a specific form is at risk for being substituted or not (12). Second, we considered that the new convention had an advantage over the old one, represented either by the intervention of an institution or by the presence of committed users (30–32), and we did not consider examples where random drift is the dominant evolutionary force (13). In this respect, it is worth mentioning that the role of a committed minority has been investigated in the context of various multiagent models, where it has been shown to play an important role on the final consensus, provided its size exceeds a certain threshold (6, 51–53), as also observed in recent laboratory experiments (54). Third, we focused on the case where the competition takes place between two alternative norms, but more complex cases where more conventions concur to the process of norm change could exist (25). Fourth, the model we introduced describes the process of norm change for an isolated linguistic group and does not address the important case of language change resulting from the contact between two linguistically independent populations or conflict between different languages (7). Finally, our analysis did not consider regional differences or any geographical factors. All these points represent directions for future work.

Taking a broader perspective, our results shed light on the dynamics leading to the adoption of new linguistic conventions and have implications on the more general process of norm change. Today’s technology, and in particular online social networks, are reportedly speeding up the process of collective behavioral change (55, 56) through the adoption of new norms (54, 57–59). Understanding the microscopic mechanisms driving this process and the signature that it may leave in the data will lead to a better understanding of our society as well as to possible interventions aimed at contrasting undesired effects. In this perspective, we anticipate that our work will also be of interest to researchers investigating the emergence of new political, social, and economic behaviors (10, 60).

## Materials and Methods

The Google Ngram dataset provides  $\sim 4\%$  of the total number of books ever printed (11). We analyzed the following data. Regulation by a formal institution: 23 Spanish words that changed their spelling recovered in refs. 14–20 (*SI Appendix, section 3*). Intervention of informal institutions: 900 words with the double American and British spelling as reported in *SI Appendix, section 10.A*. The list was extracted from ref. 21, and the double spelling was verified with the Merriam–Webster dictionary (<https://www.merriam-webster.com>). Unregulated evolution: (i) case of Spanish past subjunctive, 1,571 Spanish verbs, 325 of which were irregular. All of the verbs, together with their declination, are listed in refs. 22 and 23. (ii) Case of Americanization of English, 46 among words and expressions (the complete list is provided in *SI Appendix, section 10.B*).

For the microscopic dynamics, we performed numerical simulations of the model. At the beginning, we set  $\mathcal{W}_0$  conventions in the state  $\mathcal{O}$ . At each time, the authors extracted and replaced the conventions of the previous time with the following rules. With probability  $c$ , the author was committed. If the commitments supported the new conventions, a convention in the state  $\mathcal{N}$  was added; otherwise, a convention in the state  $\mathcal{O}$  was added; with probability  $(1 - c)(1 - \gamma)$ , the author reproduced the convention extracted; and with probability  $(1 - c)\gamma$ , the author followed the institution effort: With probability  $(1 - c)\gamma E_{\mathcal{N}}$ , a convention in the state  $\mathcal{N}$  was added, while with probability  $(1 - c)\gamma E_{\mathcal{O}}$ , a convention in the state  $\mathcal{O}$  was added. We

imposed the values recovered by the fitting procedure to set the parameters  $c$  and  $\gamma$  in the simulations.

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