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How social learning adds up to a culture

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1 **How social learning adds up to a culture: from**
2 **birdsong to human public opinion**

3
4 **Running title: How social learning adds up to a culture**

5
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16 **keywords: social learning, culture, birdsong, vocal learning, public opinion**

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19 **Summary statement:** We review recent converging studies, across birdsongs and human cultures,
20 about how social learning adds up to a stable but rich culture.

21

1 **Abstract**

2

3 **Distributed social learning may occur at many temporal and spatial scales, but it rarely**
4 **adds up to a stable culture. Cultures may vary in stability and diversity (polymorphism),**
5 **ranging from chaotic or drifting cultures, through cumulative polymorphic cultures, to**
6 **stable monolithic cultures with high conformity levels. What features can sustain**
7 **polymorphism, preventing cultures from collapsing into either chaotic or highly**
8 **conforming states? We investigate this question by integrating studies across two**
9 **disjoint disciplines: the emergence of song cultures in birds, and the spread of public**
10 **opinion and social conventions in humans. In songbirds, the learning process has been**
11 **studied in great detail, while in human studies the structure of social networks has been**
12 **experimentally manipulated in large scales. In both cases, the manner in which**
13 **communication signals are compressed and filtered – either during learning, or while**
14 **traveling through the social network – can affect culture polymorphism and stability.**
15 **We suggest a simple mechanism of a shifting balance between converging and diverging**
16 **social forces to explain those effects. Understanding social forces that shape cultural**
17 **evolution might be useful for designing agile communication systems, which are stable**
18 **and polymorphic enough to promote gradual changes in institutional behavior.**

19

1 Introduction

2
3 Social learning and diverse (polymorphic) cultures are two cornerstones of human civilization.
4 Culture is not unique to humans though (Social Learning In Animals: The Roots of Culture,
5 1996). Distributed social learning can give rise to the accumulation of shared behaviors in
6 groups of dolphins (Hassler and Hogarth, 1977; Reiss, 2011), monkeys (van de Waal et al.,
7 2013) and songbirds (Fehér et al., 2009). Cultures evolve in three stages: innovation (often by
8 a single animal), transmission through a social network, and modifications (at the population
9 level) (Henrich, 2001). Cultures vary in their stability and richness: At one extreme, culture can
10 quickly evolve into a stable monolithic state, with high conformity across individuals (**Fig. 1A**).
11 An experimental demonstration of this was done in wild vervet monkeys: when a group was
12 presented with two food sources, edible red corn and bitter-tasting pink corn, the group
13 quickly developed a ‘culture’ of avoiding the pink corn, and sustained it for several months
14 after the bitter taste had been removed from the pink corn. Young individuals that migrated
15 into that group, from a group of monkeys that had received the opposite treatment (and
16 avoided red corn), quickly switched to consuming red corn and avoiding pink corn. Those
17 young individuals never tasted bitter corn, and yet they adopted the group’s norm with high
18 levels of conformity (van de Waal et al., 2013).

19
20 At the other extreme, one may imagine unstable, or chaotic cultures. Highly chaotic
21 cultures are probably common, but difficult to study. A milder form of cultural instability is a
22 drifting culture (**Fig. 1C**). Drifting cultures were observed in whale songs (Garland et al.,
23 2011): Male humpback whales produce highly stereotyped, repetitive songs. All males within a
24 population conform to a certain song type, but not for very long. Song types spread rapidly, like
25 cultural ripples, over thousands of miles, resulting in a strong annual fluctuation in songs
26 produced within a region.

27
28 Perhaps the most fascinating cultures are between those two extremes (**Fig. 1B**):
29 cultures that exhibit many shared behavioral components (polymorphism), but also stability,
30 even over hundreds of generations, despite the constant flow and spreading of multiple
31 behavioral patterns. For example, in white-crowned sparrows (*Zonotrichia leucophrys*)
32 (Tamura, 1962), juveniles acquire their songs by imitating songs from their neighbors, which
33 collectively lead to the establishment of local song dialects. When listening to a white-crowned

1 sparrow singing, it is often possible to recognize both the dialect and the individual bird. This
2 is because each dialect has several distinct features, or a shared syllable vocabulary. For
3 example, in a certain forest, songs typically begin with a few down-sweeps and include a long
4 'buzz', whereas in a nearby forest, songs typically begin with a single down-sweep and include
5 a prolonged pure tone. An individual bird may produce only a sub-set of the shared vocabulary
6 and therefore have a unique song. However, collectively, the vocabulary remains stable at the
7 population level over decades (García et al., 2015). Local song dialects can have an important
8 role in courtship and in territorial behaviors. Evidence from a few birdsong species suggest
9 that females prefer males whose song includes syllables from the shared vocabulary (Maney et
10 al., 2003; O'Loghlen and Rothstein, 1995). Males can signal different levels of aggression by
11 matching the song types of their rivals to various extents during territorial disputes (Akçay et
12 al., 2013; Stoddard et al., 1992). The song culture is therefore an accumulation of shared
13 behavioral patterns, which are acquired through social learning. Local dialects allow singing
14 behavior to communicate both individual identity and group identity, so that birds can
15 distinguish between local and foreign individuals (Mammen and Nowicki, 1981), and resolve
16 territorial disputes without fighting (Akçay et al., 2013). Note that these functions require the
17 retention of stability and polymorphism in the shared vocabulary: the stability facilitates the
18 retention of group identity, while polymorphism provides sufficient 'bandwidth' for signaling
19 individual identity (Mundinger, 1970) and for communicating different levels of aggression by
20 varying the degree of song matching.

21
22 What features can sustain stable polymorphic cultures and prevent them from
23 collapsing into either chaotic or highly conforming states? One may start by asking, more
24 generally, what sort of interactions between elements would accumulate to create a stable and
25 complex structure? In the physical world, for example, macro structures are often formed by
26 the balance between different forces: some promote cohesion by attracting particles through
27 long distance, while others prevent implosion by repelling them over short distances (Badii
28 and Politi, 1999). In a similar vein we will suggest that the combined influences of converging
29 and diverging social forces may either promote or infringe stable polymorphism at the macro
30 level of culture (**Figure 1D**).

31
32 The accumulation of social interactions into culture can be studied at two levels: at the
33 level of dyadic interactions between individuals who influence each other, or learn from each

1 other, and at the level of signal propagation through the social network. We will review these
2 levels by integrating studies across two model systems: the emergence of song culture in birds,
3 and the spread of public opinion and social conventions in humans. In songbirds we will focus
4 on how vocal learning (through dyadic interaction) shapes culture. Studying this process in
5 songbirds has two important advantages: first, birds can be kept socially isolated and their
6 developmental experience can be fully controlled (Tchernichovski et al., 2004). Second, the
7 songbird brain is highly accessible for experimental manipulations, allowing mechanistic
8 investigation of social and vocal coordination (Benichov et al., 2015). As discussed above,
9 convergence through learning and interaction may result in stable polymorphic vocal cultures
10 in songbirds. Similar interactive mechanisms have been studied in humans: convergence has
11 been shown in natural dialog (Levelt and Kelter, 1982), and experimentally demonstrated in
12 both linguistic (Brennan and Clark, 1996; Pickering and Garrod, 2006) and non-linguistic
13 (Galantucci, 2005; Garrod et al., 2007) communication. However, only recent studies have
14 began to explore how local mechanisms scale up to the level of stable cultures (Centola and
15 Baronchelli, 2015). In this review, in order to complement the mechanistic strength of
16 birdsong research, we focus on integrating between song learning studies in birds and human
17 studies at the social network level, where controlled experiments show how the structure
18 (topology) of social networks can shape public opinion and social conventions.

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How song learning sustains polymorphic dialects

23 Social influence and peer learning are widespread, but song culture is the rare example
24 where acquired behaviors can accumulate over decades (García et al., 2015; Tamura, 1962).
25 Although song learning is ubiquitous in songbirds, local song dialects were detected only in a
26 few species (Podos and Warren, 2007). Song imitation can be more or less accurate depending
27 on genetic, ecological, and social factors: Song similarity between birds decreases with genetic
28 distance, and therefore high genetic flow between populations may also promote
29 polymorphism in song structure within a group (MacDougall-Shackleton and MacDougall-
30 Shackleton, 2001). Ecological factors may further contribute to polymorphism. For example,
31 juvenile birds that are subject to even a mild nutritional stress during song learning often fail
32 to accurately imitate the song of their adult tutor (Nowicki et al., 2002). Finally, at the social
33 level song learning may be shaped by interactions with peers, such as affiliative and aggressive

1 interactions between siblings (Derégnaucourt and Gahr, 2013) and female guidance during
2 song development (West and King, 1988).

3
4 We do not know how convergence (due to learning), and divergence due to the
5 accumulation of song-copying errors (Lachlan et al., 2016) add up to explain how local cultures
6 are formed. Only a handful of multigenerational studies documented the evolution of local
7 song dialects over time. One such example is in the saddleback (*Philesturnus carunculatus*), a
8 semi-flightless songbird. The males sing highly diverse songs, which are shared within a group
9 of up to 20 individuals occupying contiguous territories. New song groups (local dialects) are
10 thought to emerge from errors in song learning (Jenkins, 1978). But when the rate of errors in
11 song learning is too high, song dialects may fail to emerge and stabilize. For example, the high
12 frequency of song copying errors in zebra finches can explain why different domesticated
13 colonies show only weak local dialects (Lachlan et al., 2016). But interestingly, even in cases
14 where diverging forces are strong enough to prevent the establishment of local song dialects,
15 birds still maintain their species-specific song features. What sort of 'long distance' converging
16 forces can account for this?

17
18 Songbirds are capable of imitating a broad range of vocalization, including songs of
19 other species, even though most species are unlikely to do so in the wild (Soha and Marler,
20 2000). Given the broad range of vocalizations that songbirds can learn to produce, song-
21 copying errors and improvisations should accumulate over time and with geographic distance.
22 Therefore, one would expect song dialects to diverge with geographical distance without
23 bound. However, Marler (Marler and Nelson, 1992; Marler and Pickert, 1984) observed that
24 song cultures diverge only over short geographical distances, and converge over very large
25 distances, even across continents. Since production constraints could not explain the global
26 convergence toward species-specific song cultures, he suggested that perceptual biases, e.g., in
27 female song preference, could stabilize species-specific song features via sexual selection. But
28 it appears that, in some respects, species-specific song culture can be explained by biases in
29 song learning at the individual level (Fehér et al., 2009). Here we focus on three features of
30 song learning that can potentially explain how a stable and polymorphic song culture can be
31 sustained over generations.

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1 1. Transition from a graded to a categorical signal

2 Vocal communication signals can be either graded or categorical. Graded signals are
3 characterized by a continuum of broadly distributed features (without clear ‘bumps’, **Fig. 2C**,
4 left panel). An example of a graded signal is crying behavior in human infants: acoustically,
5 crying is highly complex, and it can transfer important information about urgency and severity.
6 Mothers can often identify the type of distress (hunger versus pain) expressed in their infant’s
7 cry (Gustafson and Harris, 1990), but by and large, the signal lies on a continuum (Stewart et
8 al., 2013). On the other hand, categorical signals are characterized by a narrow or highly
9 clustered distribution of features (**Fig. 2C**, right panel). For example, when zebra finches can
10 see their peers, they tend to produce short calls. When an individual loses sight of its
11 neighbors, it produces a long and loud contact call. In aggressive situations, it produces harsh
12 (hiss-like) calls (Zann, 1996). Each of these call types is acoustically distinct and can be
13 recognized as a distinct cluster in acoustic space. Acoustic variability within each of those call
14 types is also meaningful, forming a rich, graded signal within each category, allowing birds to
15 share a wide variety of behavioral states with their peers (Elie and Theunissen, 2015).

16
17 Across many vocal learner species, vocal development begins with a broad range of
18 exploratory sounds called vocal babbling (Doupe and Kuhl, 1999; Knörnschild, 2014; Oller et
19 al., 2008). In many songbirds, vocal babbling is characterized by graded signals, which develop
20 into highly stereotyped syllable types found in adult song (**Fig. 2A-B**). We suspect that the
21 developmental transition to categorical signal tend to be weaker in vocal-learning mammals.
22 Even in human, where there is a clear developmental transition from vocal babbling to
23 categorical speech, acoustically the signal remains surprisingly variable (Oller et al., 2013),
24 which is why automatic speech recognition is so difficult. Songbirds are therefore unique in
25 their strong developmental transition from highly variable to highly stereotyped vocalization
26 (**Figure 2A-B**). This transition has been studied extensively at both behavioral and neuronal
27 levels (Aronov et al., 2008; Lipkind and Tchernichovski, 2011), and we suggest that it
28 facilitates both vocal learning and song culture: The wide and continuous range of early vocal
29 babbling is optimal for vocal exploration, namely for matching the ‘sensory templates’ of song
30 syllables produced by an adult bird ‘tutor’. As song imitation progresses during development,
31 distinct syllable types (clusters) emerge and differentiate (**Figure 2D**). Although in the case of
32 birdsong the sensory input is highly stereotyped and categorical, the emergence of clusters in
33 the developing songs takes place even in the absence of categorical sensory input. Song

1 development is delayed in socially isolated birds, but even isolate songs eventually stabilize
2 and show distinct syllable types (Morrison and Nottebohm, 1993; Price, 1979). Further, we
3 recently found that providing birds with delayed self-input, namely, training a bird with its
4 own developing song, induce rapid emergence of clusters, similar to birds who were trained
5 with categorical songs (Fehér et al., *In Press*). Therefore, song imitation can be seen as a
6 modulating factor, rather than the cause of this transition, which is internally driven
7 (Tchernichovski and Marcus, 2014).

8
9 The early generation of distinct syllable types has implications at the level of song culture.
10 Cultural transmission of a highly stereotyped signal with distinct categories (or symbols)
11 should be easier, and it is more likely to remain stable over iterations compared to a graded
12 signal. Interestingly, spontaneous emergence of a categorical signal has been reported in
13 language evolution studies (Carr et al., 2016). In these experiments, human subjects were
14 instructed to learn an artificial language, composed of arbitrary words, each representing
15 objects differing in a visual feature (such as color and shape) and in movement. Using the
16 learning outcome of one individual as the training set for the next individual in a transmission
17 chain (in an iterated fashion, as in a telephone game), resulted in rapid emergence of
18 structured languages (Kirby et al., 2008; Scott-Phillips and Kirby, 2010), even when the initial
19 “meaning space” (the mapping from words to objects) was entirely continuous [32].

20
21 The developmental transition from graded to categorical signaling is analogous to signal
22 compression. At the extreme, compression could collapse the entire distribution into a single
23 category. A more useful compression would cluster the signal into several categories. In many
24 songbird species, mature songs are composed of about three to 10 syllable types. But there are
25 extreme cases: in chipping sparrows the broad distribution of song features collapses into a
26 very simple song including a single (bird specific) syllable type over the course of development
27 (Liu and Nottebohm, 2007), whereas the songs of an adult California thrasher remain complex
28 and variable (Sasahara et al., 2012). We suspect that a strong compression, resulting in fewer
29 and more stable syllable types, should make song cultures more stable. Podos and Warren
30 (Podos and Warren) performed meta-analysis of song dialects across species, which appear to
31 support this notion: in songbirds that learn prior to dispersal (namely in the territory of their
32 parents), song dialects are more common and more stable in species with smaller song
33 repertoires.

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2. Adaptive balance between convergence and divergence

As noted earlier, convergence in singing behavior might be counterbalanced by the accumulation of song-copying errors. But errors in song imitation are not entirely random: the accuracy of song imitation varies with environmental (Nowicki et al., 2002) and social (Chen et al., 2016; Tchernichovski and Nottebohm, 1998) conditions. Furthermore, there is evidence that the accuracy of song imitation may change adaptively—i.e. to counterbalance a strong convergence. For example, adult zebra finches typically produce a highly stereotyped song, including several repetitions of a single motif. Each motif is composed of 2-8 syllable types, produced in a fixed order (**Figure 2B**). A juvenile zebra finch, raised singly with an adult male (tutor), will typically acquire a nearly perfect replica of his tutor’s song. However, in a family setting, where a few siblings are interacting with a single tutor (their father), typically only one of them (the first one to imitate the father’s song) will develop an accurate imitation. In the other siblings, song imitation is partially inhibited, resulting in divergence (Tchernichovski and Nottebohm, 1998). This is not due to lack of opportunity to learn from a busy tutor: A recent study showed that the rate at which tutors produced song is inversely related to pupil attention and to song learning (Chen et al., 2016). Therefore, divergence appears to be an active process. Furthermore, zebra finches accurately imitate song playbacks that they heard for several seconds per day, but imitation accuracy decreases with further exposure to song playback (Tchernichovski et al., 1999).

Figure 3 presents an outcome of song learning in a social arena, where ten cages with juvenile pupils were arranged around a single adult tutor. As shown in **figure 3B**, only one pupil (P2) acquired an accurate replica of the tutor’s song. A group of three pupils (P3, P10 & P6) developed songs that were only partially similar to the tutor. One bird (P4) improvised an entirely new song, consisted of call-like syllables. Another bird (P7) produced a hybrid song, with some syllables copied from his tutor, and other syllables copied from his peers (Derégnaucourt and Gahr, 2013) including from the abnormal ‘call-like’ song of P4. Interestingly, in cases where a tutor song is abnormally ‘monopolized’ by a single syllable type (as in birds P4 and P7 in **Fig. 3**), pupils imitate the song with a twist: **Figure 4A** shows a song of zebra finch tutor who was raised in isolation and has developed an abnormal song. His song was dominated by a single syllable type (syllable B), which was repeated back-to-back and

1 occupied about 80% of the song bout. His pupil copied syllable B, but its abundance decreased
2 to 27%, and the distribution of syllable types in the pupil song became more diverse. A
3 systematic investigation across birds showed that song imitation is sensitive to the abundance
4 of syllable types (**Figure 4B**)(Tchernichovski and Marcus, 2014).

5
6 In general, juvenile songbirds tend to copy not only the structure of song syllables, but
7 also the abundance (relative frequency) of each syllable type from their tutor. However, once
8 the abundance of a tutor song syllable is higher than 30%, we see a ceiling effect in the
9 imitation, such that the abundance of syllable types copied from the tutor rarely exceed 30%
10 (Fehér et al., 2009). This ceiling effect alone can explain why wild zebra finch songs are
11 typically composed of at least three syllable types. It is analogous to a negative (balancing)
12 frequency dependent selection (Fitzpatrick et al., 2007), which is a specific type of natural
13 selection that can explain the retention of polymorphism in phenotypes (**Figure 4C**). In sum,
14 an accurate song imitation is only one aspect of vocal learning in songbirds. Deviations from
15 accurate imitation might reflect an adaptive balance between convergence and divergence.
16 Divergence might be regulated by social inhibition of song imitation, which we observed in
17 cases where a particular song is highly abundant across birds (**Figure 3**), and by negative
18 frequency dependent selection of syllable types that are highly abundant within a song (**Fig.**
19 **4**).

20
21 Evidences for active divergence via balancing selection were documented only in
22 domesticated zebra finch, who do not establish stable song dialects in nature. It is therefore an
23 open question if and to what extent may balancing selection play any role in natural song
24 dialects. This is a difficult problem because tracking social interactions during song
25 development in the wild is extremely challenging.

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29 *3. Directional biases in song learning stabilize feature distribution*
30 We now return to the question that puzzled Marler: what converging forces may prevent song
31 cultures from drifting apart along geographical distances without bound? The mechanism of
32 convergence toward species-typical songs can be studied by tracking song learning across
33 generations, starting from the abnormal song of an isolate founder. Interestingly, convergence
34 toward wild type distribution of song features can be detected within three to four generations

1 (Fehér et al., 2009). The imitation of isolate song syllables appears to be fairly complete:
2 namely, almost every song syllable was copied from the isolate tutors (**Fig. 4D**). However,
3 directional biases in the imitation process can be easily identified. For example, isolate songs
4 often include abnormally long syllables (**Fig. 4D** top, red bar), but the copies of such syllables
5 in pupil songs tend to be shorter. Analysis across several birds (**Fig. 4E**) shows that syllable
6 duration is copied accurately in the range of 30- 270ms, but above this range, the pupils' copies
7 are always of shorter duration. The accumulation of this bias leads, within a few generations,
8 to an upper bound of 270ms, which is similar to the upper bound of syllable durations of zebra
9 finches in our database. Such biases are analogous to directional signal filtering, which can,
10 over generations, stabilize the distribution of song features within species-specific boundaries.
11 In sum, at least some of the species-specific convergence that Marler observed across song
12 cultures might be explained by directional biases during song learning.

13

14

15 **Integration: from birdsong cultures to human public opinion**

16

17 Earlier we suggested that polymorphic cultures are sustained by a balance between
18 converging and diverging forces (**Fig. 1**). We have identified such forces in song learning: i)
19 Early developmental transition to categorical signals (clustering), which may ease cultural
20 transmission and promote stability; ii) Negative (balancing) frequency-dependent filtering,
21 which may promote cultural polymorphism; and iii) Directional filtering, which may sustain
22 stable cultural boundaries. Overall, the process of song learning is more interesting than
23 simply providing a mechanism for transferring information (Rendall et al., 2009): when songs
24 are learned, the signal is compressed and filtered. We will now show that signal compression
25 and filtering may also take place at the macro level, while 'traveling' through a social network.

26

27 Social structure inevitably impacts on the formation and maintenance of song dialects
28 in birds. For example, European starling populations that live in colonies exhibit more complex
29 dialect patterns than those nesting individually, where certain song elements completely lack
30 variation (Snowdon and Hausberger, 1997). However, although a few studies have
31 investigated birdsong at the social network level (Sasahara et al., 2012; Weiss et al., 2014),
32 linking network structure to natural dialects is challenging. In contrast, social networks in
33 humans have been studied extensively in many fields (Jackson, 2008). The most relevant

1 studies focus on identifying mechanisms that can determine the emergence and retention of
2 social conventions or public opinion. Interestingly, these studies show that the connectivity
3 pattern (topology) of social networks can shape cultural forms, including their stability and
4 polymorphism.

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Cultures of social conventions and public opinion

10 There are many examples of stable but polymorphic social conventions in humans. To
11 name one, ethnic groups often coordinate shared linguistic conventions on accepted names for
12 children and a distinct conventions for naming pets (e.g., in the US, Buddy and Coco are
13 commonly used for naming dogs and parrots, but rarely for naming children) (Ullmann-
14 Margalit, 2015). Like song dialects, the shared vocabulary for naming pets can remain stable
15 over decades despite frequent innovations of alternative options (Centola and Baronchelli,
16 2015). Semantic coordination can stem from dyadic interactions (Garrod and Anderson, 1987),
17 but shared social conventions may also emerge from centralized authority, social leadership
18 and aggregated information (Kearns et al., 2009; Salganik et al., 2006). Dyadic interactions and
19 central authority both exert an influence on social networks through which information
20 travels, and the structure of the network can affect the saliency of that influence (Dunbar,
21 2004; Nettle, 1997). For example, dissenters may pay a higher price if they live in a highly
22 clustered social network, which therefore constrain the level of local divergence.

23
24 Centola & Baronchelli (Centola and Baronchelli, 2015) recently demonstrated
25 experimentally that the structure of social networks has a critical role in allowing or
26 preventing the emergence of global conventions from dyadic coordination between
27 individuals. Strikingly, this effect was demonstrated in conditions where the social networks
28 were completely invisible to the subjects. They trained pairs of subjects to coordinate terms by
29 presenting them with images, and rewarded them when they managed to simultaneously use
30 the same terminology to describe them. In one experiment, subjects played repeatedly with
31 virtual neighbors, who played with their neighbors and so on, in a so-called ‘spatial social
32 network’ (as in **Fig. 5A**, a chain-like network). Within a few iterations, many ‘neighbors’
33 managed to coordinate terms. However, competing conventions across the neighborhoods

1 kept offsetting each other, and a global convention was never achieved. Interestingly, global
2 social convention did emerge, and became universally adopted, in experiments when subjects
3 were paired *homogenously* (as in **Fig. 5B**, in a sparse equidistant arrangement of connections).
4 In sum: the homogeneously connected social network acted as a converging force, whereas the
5 spatial network promoted diversity and instability. These results were scale-invariant,
6 namely, the topology but not the size of the social networks determined if a stable culture
7 could emerge or not.

8
9
10 In the Centola & Baronchelli study (Centola and Baronchelli, 2015), the outcome was
11 either instability or a global consensus with a high conformity level. What network topology, if
12 any, can promote a stable polymorphism? This is of particular importance to political scientists
13 who are interested in the problem of retaining minority opinion ‘alive’ in online debates. A
14 recent experimental study by Klar & Shmargad examined how underrepresented viewpoints
15 can ‘survive’ while traveling through experimentally-designed social networks of different
16 topologies (Klar and Shmargad, 2016). They found that spatial (highly clustered) networks
17 promote consensus, quickly eliminating underrepresented viewpoints (**Fig. 5C**), whereas more
18 homogeneously connected social networks, called ‘small world networks’ (Watts and Strogatz,
19 1998) retained minority viewpoints across many iterations (**Fig. 5D**). Therefore, as opposed to
20 the Centola & Baronchelli study (Centola and Baronchelli, 2015), here the spatial network
21 induced consensus whereas the more homogeneously connected network promoted
22 polymorphism.

23
24 The discrepancy between these studies is probably due to different constraints on
25 interactions at the dyadic (micro) level: in the social conventions experiment, subjects
26 constantly innovated novel names for the pictures presented, whereas in the minority
27 viewpoints experiment subjects choices were binary (between two competing views). In both
28 studies the spatial network acted as a local filter, eliminating minority viewpoints or rare
29 conventions before those could travel very far. However, with a narrow (binary) space of
30 behaviors, similar local clusters can easily merge, and a global consensus is quickly reached
31 (**Fig. 5C**). In contrast, with a broad space of behavioral options, clusters of local consensus are
32 highly diverse and are therefore likely to collide rather than to merge, resulting in instability
33 (**Fig. 5A**). Similarly, in both studies, the more homogenous networks made it easier for rare

1 morphs (e.g., two people holding the same minority viewpoint) to find each other, hence
2 keeping their views alive. But here too, differences in signal bandwidth can lead to different
3 outcomes: in a binary space, a majority is immediately apparent and links between rare
4 morphs evolve slowly. In a broadband space all morphs are initially a minority, and a majority
5 evolves slowly.

6
7 Earlier we presented evidence for signal filtering during dyadic social song learning in
8 birds, and here we discuss signal filtering at the social network level in humans. But there are
9 interactions between those two levels. For example, the results of the human studies suggest
10 that the outcome of network-level filtering depends strongly on the bandwidth of the dyadic
11 behavioral interactions. Can this also apply to birdsong culture? Many songbirds are territorial,
12 and their communication networks are naturally spatial. In species where the song repertoire
13 size is small and song copying is highly accurate, the situation might be similar to that of the
14 Klar & Shmargad study (Klar and Shmargad, 2016). If this analogy is correct, the spatial
15 network topology is likely to filter out rare syllable types over iterations, potentially imploding
16 the local dialect. In songbird species where song repertoire is rich, or when error and
17 improvisation rates are high, the scenario might be more similar to that of the Centola &
18 Baronchelli study (Centola and Baronchelli, 2015), namely the spatial communication
19 network might promote instability in the shared repertoire.

20
21 Note that according to the hypotheses presented above, an evolutionary change in the
22 bandwidth of signing behavior may flip the effect the spatial network – turning it from a
23 converging force into a diverging force. Can this be beneficial for the birds? Assuming that
24 local song dialects are advantageous, what evolutionary forces may maintain them in different
25 scenarios? The evolution of different territorial, dispersal or migratory behaviors could
26 potentially alter network topology between the spatial and homogeneous extremes, hence
27 counterbalancing converging or diverging tendencies to maintain a stable polymorphic song
28 dialect. However, changes in territorial or migratory behaviors have strong ecological
29 consequences. Evolutionary changes at the level of song learning are more likely to be less
30 costly. For example, the evolution of higher improvisation rates or of a mechanism for *negative*
31 (balancing) *frequency-dependent filtering* we discussed earlier could counteract convergence
32 due to spatial network topology. Therefore, relatively minor changes in features of song

1 learning could potentially balance converging and diverging forces to retain a stable and
2 polymorphic song dialect.

3
4 In sum, although birdsong dialects, social conventions, and public opinion, are studied
5 by disjointed scientific disciplines, it might be useful to integrate knowledge across them: In the
6 case of birdsong culture, the learning process is more readily available for mechanistic
7 investigation, while human studies provide the opportunity to investigate cultural mechanisms
8 at the social network level, where topology can be experimentally controlled. In both cases, the
9 manner in which signals are compressed and filtered – either during learning, or while
10 traveling through the social network – can shape cultures by shifting the balance between
11 convergence and divergence. We think that understanding cultures across the levels of dyadic
12 social interaction and social networks may have far reaching implications. We conclude by
13 briefly outlining such implications, focusing on how manipulating signal compression and
14 filtering could be used to promote stable polymorphism in online communication systems.

15
16

17 **Practical implications for improving online communication systems**

18

19 During the last decade, social media and crowd-sourcing platforms have transformed how
20 public opinion is shared, guiding everyday decisions from picking a restaurant to expressing
21 support by ‘liking’ posts and signing petitions. Looking at online platforms through the lens of
22 cultural stability and polymorphism, they often seem unbalanced: either too chaotic, or highly
23 biased and monolithic. Such outcomes could be unintended social consequences of recent
24 advances in communication technology. Centola & Baronchelli (Centola and Baronchelli,
25 2015) suggested that the increase in social connectedness via social media could potentially
26 facilitate the convergence of public opinion among people who do not even know that they are
27 implicitly coordinating with one another (Centola and Baronchelli, 2015). Other studies show
28 that such convergence can induce a phase transition (or non-linearity), shifting public opinion
29 from moderate views towards extremism (Ramos et al., 2015), causing community
30 disconnection (Gil and Zanette, 2006), and echo chamber effects, particularly in domains with
31 high emotional salience (Cowan, 2014; Jasny et al., 2015; Pentland, 2014). We will conclude by
32 presenting a coarse outline for technical approaches to counteract imbalances in online
33 communication systems.

1
2 We noted earlier that converging and diverging forces can shape cultures at two levels:
3 social learning and network topology. It is rarely practical (or desired) to modify the social
4 networks of citizens engaged in online communication platforms. However, information-
5 sharing protocols are easy to manipulate, and such manipulations can potentially influence
6 how social learning spreads and accumulates. Take for example the Klar & Shmargad study we
7 discussed earlier (Klar and Shmargad, 2016): they found that spatial social networks filtered
8 out underrepresented viewpoints, whereas small world networks promoted their survival.
9 Instead of manipulating social network topology, online platforms could manipulate the way
10 information is presented to users. For instance, social media sites automatically organize each
11 post into categories, or into topics that emerge from trends across posts (Hong and Davison,
12 2010). We wonder if different strategies for clustering underrepresented viewpoints could
13 potentially affect their survival rate. Is there any simple equivalence between the effects of
14 manipulating the topology of information presentation vs. network topology with respect to
15 cultural outcomes?

16
17 Consider the design of online petition systems: the US White House petition platform is
18 designed to efficiently filter petitions: a petition must receive > 100,000 signatures within 30
19 days to be considered. The platform provides no mechanism of similar petitions to merge or to
20 evolve. We suspect that different methods for compression and filtering information may
21 result in very different cultures. Stable polymorphic cultures cannot easily emerge in highly
22 competitive and rapid turnover platforms, or in 'timeline' based social media platforms.
23 However, there is some preliminary evidence that regulating the filtering and presentation of
24 information in online reviewing platforms can induce incremental improvement in public
25 service quality via distributed social learning:

26
27 Crowd-sourced reviewing platforms are highly popular (Mackiewicz, 2009; Zhu and
28 Zhang, 2010). For example, Yelp owns a database with about 100-million anonymous
29 restaurant reviews, which is used by about 135 million monthly visitors. Mean scores are
30 presented by star rating, and even a moderate change from 3.5 to 4 stars in Yelp increases the
31 chances of a restaurant being booked by about 19% (Anderson and Magruder, 2012). Clearly,
32 biases and fraud (Luca and Zervas, 2013; Racherla and Friske, 2012) are serious concerns in
33 such 'learning from the crowd' platforms. Even with potential fraud set aside, cumulative star

1 rating provides little opportunity for social learning across clients and providers of services:
2 For a new venue, a random (or malicious) cluster of a few negative reviews is likely to drop the
3 mean score strongly enough to ruin a business. For a highly popular venue, the
4 unresponsiveness of the cumulative score to incremental changes may fail to provide adequate
5 motivation for enhanced efforts. In sum, we suggest that the ubiquitous 5-star rating system
6 compress rating information too strongly. Evidence from a recent field study suggests that
7 adjusting the level of temporal granularity (i.e., compression) of the presentation of service
8 rating can potentially keep a crowd-sourced reviewing platform in an agile state, where client
9 feedback can drive incremental improvement in services over timescales of years
10 (Tchernichovski et al., 2016). Instead of star rating, the study presented service clients with
11 short-term trends of client satisfaction with service outcome. Those trends were presented on
12 the service request forms, making them apparent to both service clients and service providers.
13 Presenting trends allowed the regulation of the compression level: larger bins pooled more
14 data, providing more robust estimates at the cost of lower sensitivity to change, and vice versa.
15 For social learning to be efficient, the granularity of the trends, namely their sensitivity to
16 changes in service quality, should correspond to timescales of service responsiveness. That is,
17 trends should be presented in a temporal resolution that can allow service workers sufficient
18 time to adjust, and prevent discouragement. The positive outcome of the field study, although
19 in a small scale, suggested that synchronizing social learning across networks of service
20 workers and clients might promote a culture of engagement in service improvement.

21
22 Overall, we presented a preliminary framework for studying how features of social
23 learning and of distributed communication systems may shape culture. We integrated findings
24 and ideas across the scientific disciplines of birdsong and human social networks with the goal
25 of outlining some common threads. For birdsong culture, we suggest that the results of large-
26 scale human social network studies provide a framework for understanding how features of
27 territorial networks may cause convergence or divergence of song dialects. For human online
28 cultures, we suggested that it may be useful to consider features of birdsong learning, which
29 were optimized over millions of generations to give rise to stable polymorphic cultures.
30 Experimenting with implementing similar features in online communication system could
31 potentially facilitate the design of more stable and balanced information systems, which can
32 potentially promote distributed self-governance.

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Figure legends

Figure 1: From social learning to culture. A-C, Social learning may add up to difference types of cultures, with vary in their stability. In stable monolithic culture strong convergence can lead to high conformity (A). In stable polymorphic cultures, individuals show different combinations of cultural traits, however, at the population level those traits remain stable (B). In drifting cultures (C) cultural traits are unstable at both individual and population levels. **D,** Converging and diverging social forces may add up to shape cultures of different stability levels.

Figure 2: Transition from graded to categorical signal. A. sonogram of a juvenile zebra finch showing highly variable syllables. **B,** a song of an adult zebra finch showing distinct syllable types (denoted by letters), repeated in a fixed order (ABCDE...). **C.** a schematic view of the developmental transition. **D.** Scatter plot of syllable features during early (left), middle (center) and late (right) song development of a zebra finch male. Each dot represents a song syllable. We plot the duration of each syllable versus its frequency modulation (which distinguishes between call-like syllables and frequency modulated syllables). Early in development, song features are broadly distributed. Distinct syllable types appear during development, and eventually the song becomes crystalized.

Figure 3: Song imitation in a social arena: A, a circular arena of cages, where an adult zebra finch (tutor) is placed at the center, and ten cages with juvenile birds (pupils). **B,** sonograms of the tutor song (top) and sonograms of six of his pupils. Only one pupil (P2) imitated the tutor's song accurately. Three pupils (3, 6 & 10) copied only a subset of their tutor's song syllables and modified others. Two pupils (P4 & P7) did not appear to imitate the song of their tutor, and instead improvised an atypical song composed on call-like syllables.

1 **Figure 4: Biases in song imitation: A**, An imitation of an abnormal isolate song. The isolate
2 tutor song (top) is composed on a rare syllable type (syllable A) and a highly abundant syllable
3 type (Syllable B). The pupil's song (bottom) is composed on the same syllable types but with
4 different abundance. **B**, Imitation of syllable abundance from isolate tutors across birds. The
5 correlation line at abundance level < 30% indicate imitation of abundance below that level. **C**.
6 An illustration of a negative (balancing) frequency dependent selection, where relative
7 frequencies of rare morphs is amplified. **D**. An example of a biased imitation of syllable
8 duration. The tutor (top) is an isolate. E. Imitation of syllable durations from isolate tutors.

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11 **Figure 5: From network topology to cultural forms. A**, Propagation of a broadband signal
12 through a spatial network may result in clusters of nodes with converging conventions, but
13 globally, competition between those clusters may cause instability (Centola and Baronchelli,
14 2015). **B**, In a homogeneous network, a slow convergence due to interactions between distant
15 nodes (red lines) may eventually result in a global adoption of a single convention. In the case
16 of a binary signal (**C**), a spatial network topology may quickly filter out rare morphs, and
17 converge globally. However, in a homogeneous network (**D**) interactions between distant
18 nodes may sustain the rare morph (blue lines).

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