Communicative pressures at the semantics-pragmatics interface: Learning biases may prevent the lexicalization of pragmatic inferences

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Abstract

Mutual reasoning endows speakers with the ability to convey information that goes beyond the literal meaning of expressions. A particularity of certain classes of lexical meanings is that they enable for such pragmatic enrichments in a notably productive fashion. This raises the challenge to justify their regular selection over other alternatives that, e.g., do not require such enrichments. We suggest that such an account can be provided by an analysis of the linguistic pressures that apply at the semantics-pragmatics interface. To this end, we lay out a general model that combines functional pressure on language use and a pressure for learnability in acquisition in populations of probabilistic language users with varied degrees of pragmatic sophistication. We then use this model in a case study on the (lack of) lexicalization of scalar implicatures. The results suggest that such inferences fail to lexicalize when languages are pressured towards simpler semantic representations in learning, provided that pragmatic reasoning can compensate for the disadvantage in expressivity that users of such languages otherwise incur. We argue this result to shed light on the lack of lexicalization of scalar inferences, as well as the semantics-pragmatics distinction more generally.

1 Introduction

What is conveyed usually goes beyond what is said. A request for a blanket can be politely veiled by uttering “I'm cold”, a temporal succession of events conveyed by the order in which conjunts appear, as in“I traveled to Paris and got married”, or an invitation be declined by saying “I have to work”. An influential explanation of the relation between the literal meaning (semantics) of such expressions and what they are intended and interpreted to convey (pragmatics) sees the latter as a product of a process of mutual reasoning (Grice 1975). For instance, under the assumption that the speaker is cooperative and strives to be relevant, “I have to work” may be interpreted as providing a reason why the speaker will not be able to accept the invitation – why would she have said so otherwise?

Nowadays, it is common to draw a distinction between semantics and pragmatics in linguistic theorizing. Importantly, many classes of lexical meanings allow for pragmatic enrichments in a notably productive fashion. For instance, while John can eat all the cookies and still truthfully claim “I ate some cookies”, the use of *some* over *all* is usually taken to convey that the latter does not hold. That is, “I ate some cookies” is pragmatically strengthened to convey that *some but not all* were eaten (citations for experimental evidence). This inference is not restricted to quantifiers such as *some* and *all* but can be licensed for a large class of natural language expressions ranging from numerals such as *four* and *five* to adjectives such as *cold* and *big*.

These pragmatic inferences, so-called *scalar implicatures*, have been the focus of many theoretical and experimental studies at the semantics-pragmatics interface (citations). However, an issue that has received little attention is the justification of semantic structure in light of the systematic enrichment offered by pragmatics. The present investigation seeks to fill this gap by analyzing the effects linguistic pressures have on the selection and pervasiveness of particular lexical meanings under consideration of their possible pragmatic enrichments.

1.1 Linguistic pressures at the semantics-pragmatics interface

The emergence and change of linguistic structure is influenced by many intertwined factors. These range from biological and socio-ecological to cultural (Steels 2011, Tamariz and Kirby 2016). Social and ecological pressures determine communicative needs, while biology determines the architecture that enables and constrains the means by which they can be fulfilled. In the following, our focus lies on the remaining cultural aspect, wherein processes of linguistic change are viewed as shaped by language use and its transmission. That is, as a result of a process of cultural evolution.

The idea that language is influenced by communicative pressures has played a pivotal role in synchronic and diachronic analyses at latest since Zipf's (1949) rationalization of the approximation of word frequency rankings by a power law distribution as competing hearer and speaker preferences (e.g. in Martinet 1962, Horn 1984, Jäger and van Rooij 2007, Jäger 2007, Piantadosi 2014, Kirby et al. 2015). In recent years this line of research has led to a surge of approaches that seek to analyze the effects of such pressures on language from multiple angles ranging from simulations to experiments with human and robotic agents (see Steels 2015 and Tamariz and Kirby 2016 for recent overviews). Our starting point is given by the overarching argument that has crystalized from the accumulated mathematical, experimental and cross-linguistic evidence in this literature: Natural languages need to be well-adapted to communicative needs within a linguistic community, but also need to be learnable to survive their faithful transmission across generations. More succinctly; natural languages are pressured for expressivity and learnability.

The opposition of expressivity and learnability becomes particularly clear when considering their consequences in the extreme (cf. Kemp and Regier 2012, Kirby et al. 2015). A language with a single form is easy to learn but lacking in expressivity. Conversely, a language that associates a distinct form with all possible meanings its users may want to convey is maximally expressive but challenging to acquire. The most prominent problem that arises from this tension is that of acquiring a language to express a potentially infinite set of meanings through finite means (Kirby 2002). However, this is not the only challenge learners confront. A more central issue to our explanandum is that of selecting particular hypotheses out of a potentially infinite space of alternatives compatible with the data learners are exposed to. At the semantics-pragmatics interface this concerns the selection between functionally (near-)equivalent lexical meanings. Put differently, what is systematically conveyed through pragmatics could alternatively be codified lexically. However, lexical meanings that allow interlocutors to draw these inferences seem to resist their lexicalization. The question is why. We assume an integral part of the answer to be that learners are a priori biased towards simpler, more compressed, lexical representations. That is, rational learners should prefer simpler over more complex explanations of the data they witness (Feldman 2000, Chater and Vitányi 2003, Piantadosi et al. 2012a, Kirby et al. 2015, Piantadosi et al. under review). In a nutshell, our hypothesis is that codifying more semantically is a priori dispreferred by learners. Crucially, in cases where pragmatics offers conventional means of enrichment, the communicative disadvantage that speakers would otherwise incurr is leveled. In this way, semantics and pragmatics play a synergic role in overcoming linguistic pressures for expressivity and learnability which may prevent the lexicalization of pragmatic inferences.

In the following, we model these components using the replicator-mutator dynamics, combining functional pressure on successful communication with effects of learning biases on (iterated) Bayesian learning (Griffiths and Kalish 2007). The semantics-pragmatics distinction and its effect on production and comprehension are captured by a probabilistic model of rational language use with different degrees of pragmatic sophisitication and languages (Frank and Goodman 2012, Franke and Jäger 2014, Bergen et al. 2016). The remainder of this section introduces these components individually together with the assumptions underlying them. These are: the representation of languages and their use (§1.2), pressures towards expressivity (§1.3) and learnability (§1.4), regulated by the replicator and mutator dynamics, respectively, as well as a bias towards simpler semantic representations, codified as the learners' prior. After laying out the model, we analyze its predictions in a case-study on the lack of lexicalization of scalar implicatures in §2.

1.2 Lexica and linguistic behavior

Lexica codify the truth-conditions of a language's expressions, i.e., its semantics. Following e.g. Franke and Jäger (2014), a convenient way to represent lexica is by $(|S|, |M|)$-Boolean matrices, where S is a set of states of affairs (meanings) to convey and M a set of messages (forms available in the language). For example, the following two fragments determine the truth-conditions of two messages, m_1 and m_2, for two states, s_1 and s_2.

$$L_a = \begin{array}{c} \\ s_1 \\ s_2 \end{array} \begin{array}{c} \begin{array}{cc} m_1 & m_2 \end{array} \\ \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \end{array} \qquad L_b = \begin{array}{c} \\ s_1 \\ s_2 \end{array} \begin{array}{c} \begin{array}{cc} m_1 & m_2 \end{array} \\ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \end{array}$$

According to lexicon L_a the message m_1 is true of state s_1 as well as of s_2. In contrast, m_1 is only true of s_1 in L_b. Otherwise, the two languages are truth-conditionally equivalent.

While these representations are very coarse and simple, they suffice to make the distinction between semantics and pragmatics precise. We distinguish between two kinds of linguistic behavior. *Literal interlocutors* produce and interpret messages literally. That is, their linguistic choices are guided only by their lexica. In contrast, *pragmatic interlocutors* engage in mutual reasoning to inform their choices. For instance, a rational speaker of L_a who reasons about her addressee may use m_1 to exclusively signal state s_1 since s_2 can unambiguously be conveyed through m_2. Accordingly, rational hearers that expect their interlocutor to reason along these lines will interpret ambiguous m_1 as s_1. An important consequence of this process of mutual reasoning for our purposes is that it can render L_a (nearly) indistinguishable from L_b in terms of language use.

Following models of rational language use such as Rational Speech Act models (Frank and Goodman 2012) and their game-theoretic predecessors, the Iterated Best/Quantal Response models (Franke 2009, Franke and Jäger 2014), this kind of signaling behavior is captured by a reasoning hierarchy. The hierarchy's bottom, level 0, corresponds to literal language use. Pragmatic language users of level $n + 1$ behave rationally according to expected level n behavior of their interlocutors. Below, (1) and (3) specify the behavior of literal and pragmatic hearers of a language L. Literal and pragmatic speakers are specified in (2) and (4).

$$H_0(s|m; L) \propto pr(s) L_{sm} \tag{1}$$

$$S_0(m|s; L) \propto \exp(\lambda \, L_{sm}) \tag{2}$$

$$H_{n+1}(s|m; L) \propto pr(s) S_n(m|s; L) \tag{3}$$

$$S_{n+1}(m|s; L) \propto \exp(\lambda \, H_n(s|m; L)^{\alpha}) \tag{4}$$

According to (1), a literal hearer's interpretation of a message m as a state s depends on her lexicon and her prior over states, $pr \in \Delta(S)$. In the following this prior is assumed to be uniform across hearers. The behavior of literal speakers, given in (2), is regulated by a soft-max parameter λ, $\lambda \geq 1$ (Luce 1959, Sutton and Barto 1998). As λ increases, choices made in production are more rational in that higher values lead to behavior that is increasingly in line with expected utility maximization.

Pragmatic behavior is similar to its literal counterparts. As hinted at in the informal sketch above, their difference lies in that level $n+1$ speakers/hearers reason about level n hearer/speaker behavior instead of solely relaying on their lexicon. That is, they reason about the way a rational level n interlocutor would use or interpret a message, and behave according to these expectations. Pragmatic production is further regulated by a parameter α which controls the tension between semantics and pragmatics, $\alpha \in (0, 1]$. Lower values lead to more literal production whereas higher values lead to stronger pragmatic behavior.

We call the combination of a lexicon with its use, i.e., a level in the reasoning hierarchy, a type. These are the basic units on which our population dynamics operate.

1.3 Replication & expressivity

Expressivity has received particular attention from investigations using evolutionary game theory (e.g. Nowak and Krakauer 1999, Nowak et al. 2000; 2002). Under this view, a type's ability to convey and interpret information successfully confers it a higher fitness, a measure that is relative to the success of other types in the population. In the simplest models fitness directly translates into the proportion of types present in the population after a generational turnover. As a consequence, fitter types flourish while unfit ones are driven out. This association of communicative success within a population with changes in the proportion of types present in it creates a feedback loop that pressures the population towards greater expressivity.

The replicator equation gives us the means to make these dynamics precise. The proportion of types in a given population is codified in a vector x, where x_i is type i's proportion. As noted above, the fitness of type i is equal to its relative communicative success within this population, $f_i = \sum_j x_j \mathrm{EU}(t_i, t_j)$. That is, its fitness is the sum of its expected communicative success in interacting with other types weighted by the latter's population share. Communicating well with types that appear often thusly confers a higher fitness than doing so with underrepresented ones. The expected communicative success of i and j is obtained by considering the average success of i conveying information to j and vice versa: $\mathrm{EU}(t_i, t_j) = [U_S(t_i, t_j) + U_R(t_i, t_j)]/2$. $U_S(x, y)$ and $U_R(x, y)$ are, respectively, $\sum_s P(s) \sum_m S_n(m|s; L) \sum_{s'} R_o(s'|m; L)\delta(s, s')$ and $U_S(y, x)$, for n and o being the reasoning level of x and y, and $\delta(s, s') = 1$ iff $s = s'$ and 0 otherwise. This quantity is symmetric, reflecting the probability of two types' mutual understanding. The average fitness of the population is given by Φ, $\Phi = \sum_i x_i f_i$. This term serves as a normalizing constant for the discrete replicator equation: $\dot{x}_i = \frac{x_i f_i}{\Phi}$

Under its biological interpretation, this equation captures the idea of fitness-relative selection whereby fitter types produce more offspring, leading to their propagation in subsequent generations. As noted in §1, many aspects of language are subject to processees of transmission and change that can be likened to these biological dynamics. Amongst others, replication can be construed as modelling language acquisition, as e.g. in Nowak et al. 2002, but also as a process of horizontal adaptation in a single generation (see Benz et al. 2005b:§3.3 for discussion).

In their series of papers on language evolution, Nowak and colleagues did not only consider expressivity but also recognized the central role played by the fidelity by which languages are transmitted. Linguistic production can be prone to errors and multiple languages may be compatible with the data learners are exposed to. These sources of uncertainty introduce variation in their faithful acquistion. In keeping the analogy to evolutionary processes this variation can be likened to mutation to the effect that a type's offspring may adopt a different type than that of its parent. Importantly, the resulting generational turnovers should depend on the relative learnability of a type. For this purpose, we turn to a different strand of research in cultural evolution: *iterated learning.*

1.4 Mutation & learning

Iterated learning is a process in which the behavior of one individual serves as learning input for another. This learner, upon acquisition of this behavior, then goes on to produce behavior that serves as input for a new learner. This process can be thought of as a progression through chains of parents and children; the parent produces linguistic data from which the child infers a language. The latter, now a parent, goes on to produce linguistic data for a new generation of naïve learners. Following Griffiths and Kalish (2007) we model iterated learning as a repeated process of Bayesian inference in which learners combine the likelihood of a type producing the received learning input with prior inductive biases.

Due to the pressure towards learnability it exherts, iterated learning generally leads to simpler and more regular languages (see Kirby et al. 2014 and Tamariz and Kirby 2016 for recent surveys). Importantly, experimental and mathematical results suggest that the outcome of this process reflects learners' a priori biases. In a Bayesian setting these biases can be codified in a prior $P \in \Delta(T)$. A way to think about this prior is as the amount of data a learner would require in order to adopt a language (cf. Griffiths and Kalish 2007:450). Or, in our case, a combination of a lexicon and a signaling behavior.

As touched upon in §1 we assume learners to be biased towards simpler semantics. That is, learners have a preference for types that can explain the data by codifying less in their lexical representations. More generally, a drive for simplicity has been argued to underpin speaker preferences for brevity and ease of articulation, as well as to pressure languages towards lexical ambiguity and grammatical compression (Zipf 1949, Grice 1975, Piantadosi et al. 2012b, Kirby et al. 2015). As shown by Chater and Vitányi (2003) simplicity not only provides a solution to problems of induction by allowing for the distinction between equally explanatory hypotheses, but it has also proven its empirical worth as a predictive principle in cognitive modelling.

The extent of the prior's influence has been shown to heavily depend on the learning strategy assumed to underly the inference process. On the one hand, simulation results suggested that weak biases could be magnified by exposing learners to only small data samples (Brighton 2002). On the other, Griffiths and Kalish's (2007) mathematical characterization showed that iterated learning converged to the prior. That is, the distribution over languages obtained from this process corresponded to the learners' prior distribution and was independent of the amount of input given to them. This difference in predictions can be traced back to differences in the selection of hypotheses from the posterior. Griffith & Kalish's convergence to the prior holds for learners that sample from the posterior. More deterministic strategies such as the choice for the type with the highest posterior probability, so-called *maximum a posterior estimation* (MAP), increase the influence of both the prior and the data (Griffiths and Kalish 2007, Kirby et al. 2007). In the following, we parametrize the posterior by $l \geq 1$. In doing so, we obtain a range of learning strategies that live between posterior sampling and MAP. When $l = 1$ learners sample from the posterior. As l increases towards infinity their propensity to maximize the posterior grows as well.

The data learners are exposed to is described by a set D containing sequences of state-message pairs, e.g., $\langle\langle s_i, m_v\rangle, ... \langle s_j, m_w\rangle\rangle$. These correspond to sequences of of language use witnessed by the learners. In the following, we denote the length of these sequences by k. Put differently, each datum $d \in D$ contains k members of the set $\{\langle s_i, m_v\rangle \,| s_i \in S, m_v \in M\}$.

To summarize, the parametrized posterior, $P(d|t)^l$, is obtained from combining the prior $P(t)$ and the likelihood $P(d|t)$. Since types are combinations of a lexicon and its use, the latter can be computed straightforwardly from the type's production. We combine the replicator dynamics with iterated learning by codifying these components in a transition matrix Q. Q_{ij} indicates the probability that a child of a parent of type i adopts type j. This quantity is proportional to the probability of i producing the learning data and that of inferring j given the data:

$$Q_{ij} \propto \sum_{d \in D} P(d|t_i) F(t_j, d),$$

where $F(t_j, d) \propto P(t_j|d)^l$ and $P(t_j|d) \propto P(t_j)P(d|t_j)$.

1.5 Summary

Drawing from past research, we argued that expressivity, learnability and simplicity are central to the cultural evolution of language. In the present setup they are modelled as communicative efficiency-relative replication, iterated Bayesian learning, and a prior that biases learners for compressed lexical meanings. Taken together their dynamics are described by the replicator-mutator dynamics (Hofbauer and Sigmund 2003):

$$\hat{x}_i = \sum_j Q_{ji} \frac{x_j f_j}{\Phi}$$

The units that the dynamics operate on are a combination of a lexicon and a degree of pragmatic sophistication which determines its use. We call this combination a type. A type's expressivity depends on its communicative efficiency within a population while its learnability depends on the fidelity by which it is infered by new generations of naïve learners. With this model at hand we turn to the analysis of the lack of lexicalization of productive pragmatic inferences.

2 Scalar implicatures

Scalar implicatures are a particularly well-studied type of conventional pragmatic inference. They are licensed for groups of expressions ordered in terms of informativity, here understood as an entailment induced order. For instance, *some* is entailed by *all.* If it were true that 'All students came to class', it would also be true that 'Some students came to class'. However, as already noted in §1, while weaker expressions such as *some* are truth-conditionally compatible with stronger alternatives such as *all*, this is not what their use is normally taken to convey. Instead, the use of a less informative expression when a more informative one could have been used can license a defeasible inference that stronger alternatives do not hold (cf. Horn 1972, Gazdar 1979). That is, a hearer who assumes the speaker to be able and willing to provide all relevant information can infer that stronger alternatives do not hold since the speaker did not use them. In this way, 'Some students came to class' is strengthened to convey that some but not all students came to class. Conversely, speakers can rely on their interlocutors to draw this inference. The bound that rules out stronger alternatives is thusly not codified in the lexical meaning of weak alternatives but instead pragmatically supplied.

This kind of strengthening corresponds to our previous description of the pragmatic use of lexicon L_a. A pragmatic hearer who reasons about a speaker's use of message m_1 will associate it more strongly with s_1 than with s_2 since the latter is already unambiguously associated with

s_2. Conversely, a pragmatic speaker will reason about her interlocutor's interpretation and use the messages accordingly.

$$L_a = \begin{array}{c} \\ s_1 \\ s_2 \end{array} \begin{array}{c} \begin{array}{cc} m_1 & m_2 \end{array} \\ \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \end{array} \qquad L_b = \begin{array}{c} \\ s_1 \\ s_2 \end{array} \begin{array}{c} \begin{array}{cc} m_1 & m_2 \end{array} \\ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \end{array}$$

Our initial question can now be narrowed in terms of scalar implicatures by asking for a justification for the lack of lexical upper-bounds in weak scalar alternatives. That is, why semantics such as those of message m_1 in L_a are regularly selected for over the alternative of codifying the bound semantically as in L_b. More poignantly, would it not serve language users better if weak(er) expressions such as *warm*, *or*, *some* and *big* were truth-conditionally incompatible with stronger alternatives such as *hot*, *and*, *all* and *huge*? This question is particularly striking considering the number of expressions suggested to license such inferences across languages.

We see two main explanations for the lack of upper-bounds in the lexical meaning of weak scalar expressions. The first is that their truth-conditional compatibility with stronger expressions endows them with a broader range of applicability by allowing them to occur in contexts in which their upper-bounded reading is absent. This can happen when embedded in downward-entailing contexts, when the speaker is likely uncertain about whether the upper bounded reading is true, or when the distinction between an upper-bounded reading and the simple, only lower-bounded reading, is not relevant. For instance, if for all the speaker knows 'Some students came' but she doesn't know whether all came, then the use of unbounded *some* succinctly conveys her uncertainty. This may suggest a functionalist argument for why upper-bounded meanings do not conventionalize: should contextual cues provide enough information to the hearer to identify whether a bound is intended to be conveyed pragmatically, then this is preferred over expressing it overtly through longer expressions. For example, by saying *some but not all* explicitly. Importantly, although morphosyntactic disambiguation is dispreferred due to its relative length and complexity, it allows speakers to enforce an upper-bound and override contextual cues that might otherwise mislead the hearer. In a nutshell, this explanation posits that scalar implicatures fail to lexicalize because, all else being equal, speakers prefer to communicate as economically as possible and pragmatic reasoning enables them to do so. Compare this with a hypothetical language that lexicalizes two expressions for each weak scalar expression – one with and one lacking an upper-bound. Along this functionalist explanation, we see four conditions that may pressure languages for English-like semantics over this alternative. First, contextual cues are very reliable. Second, morphosyntactic disambiguation is seldom necessary. Third, morphosyntactic disambiguation is only marginally dispreferred. Fourth, larger lexica are costly. Overall, neither condition is convincing as a pivotal explanatory device for such a wide-spread phenomenon. The first two conditions put a heavy burden on the ability to retrieve contextual cues to a degree that seems unlikely to undercut the benefit of unambiguous communication. It is likely that human language users are very good at retrieving cues from context, but to stipulate that they are so good as to undercut the benefit of safe communication provided by our hypothetical alternative strikes us as too strong of an assumption. As for the third and fourth condition, these seem mostly like technical solutions without a proper empirical basis.

Taking the regularity and spread of scalar implicatures together with the observation that monomorphemic expressions that lexically rule out stronger alternatives are unattested across languages (Horn 1984:252-267,Horn 1972, Traugott 2004, van der Auwera 2010) suggests that other forces may be play. In what follows we investigate the hypothesis that the lack of lexicalization of scalar inferences can be accounted for through the relative simplicity of lexical meanings lacking an upper-bound over those that explicitly codify it. While we do not want to argue that functionalist pressure may not play a role, we do see a clear benefit in exploring whether matters

$$L_1 = \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} \quad L_2 = \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix} \quad L_3 = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

$$L_4 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad L_5 = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \quad L_6 = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$$

Table 1: Space of possible lexica.

of learnability would not give us additional leverage.

Note however that we do not represent the contrast between lexical representations explicitly. Instead, the learning bias towards a lack of upper-bounds in weak scalar alternatives is directly encoded in the learners' prior over types. In principle this difference could be made precise with an adequate representational language, e.g., through measures over representational complexity such as minimal description length. There is a growing effort to develop such empirically testable representational languages. For instance, the so-called language of thought has been put to test in various rational probabilistic models that show encouraging results (see e.g. Katz et al. 2008, Piantadosi et al. under review; 2012b and references therein). We think that our assumption is well-warranted as a working hypothesis and decide against such an enrichment given that the introduction of a larger framework would also require further assumptions and justifications.

2.1 Analysis

We analyze the model's predictions in populations of types with two signaling behaviors; literal or pragmatic. The former correspond to level 0 reasoners who only take their lexica into consideration and the latter to level 1 reasoners. Higher level reasoning is not required to derive scalar implicatures from the lexica we consider here nor would it provide substantial pragmatic refinement.

The space of possible lexica is given in Table 1. As in the preceding examples, lexica are $(2,2)$-Boolean matrices. These are the simplest matrices that allow us to make the contrast between the presence or lack of an upper-bound and the use of scalar implicatures precise. As implicit in the discussion so far, one may think of s_1 as a "some but not all"-state and of s_2 as an "all"-state. The literal meaning of weak scalar expressions such as English *some* then corresponds to a message true of both s_1 and s_2 in these fragments. Following our assumption for a preference for simple lexical representations, the prior biases learners against lexica in which a message holds true only of state s_1. That is, those messages that lexicalize an upper-bound that rules out the "all"-state s_2. All other semantics are assumed to be a priori equally probable. Accordingly, this prior is captured by $P(t_i) \propto n - c \cdot r$, where n is the total number of states and r is the number of messages only true of s_1 in t_i's lexicon, $c \in [0,1]$. In short, increments in parameter c bring about a stronger preference against languages that lexicalize upper-bounds, i.e., L_2, L_4 and L_6.

While there is a total of 16 possible $(2,2)$-lexica, a number of them are identical both in terms of expressivity and the learning bias. The competition between such types is determined by the initial configuration of a population, i.e., the proportion with which each type starts out. However, this fact can be obscured when averaging across simulations. We therefore focus on a smaller representative subset.[1] Lexica L_1 to L_3 are not optimal for communication because they assign the same state to all their messages. This failure to associate a single form to a meaning both semantically and pragmatically inevitably leads to their disadvantage in language use. L_4

[1] Simulations conducted with the full space of possible lexica confirm that the results reported here do not hinge on their exclusion.

parameter	explanation	locus
$\lambda \geq 1$	rationality parameter	$S_{n+1}(m\|s; L) \propto \exp(\lambda \; H_n(s\|m; L)^{\alpha})$
$\alpha \in [0, 1)$	semantics-pragmatics tension	$S_{n+1}(m\|s; L) \propto \exp(\lambda \; H_n(s\|m; L)^{\alpha})$
$\|D\|$	number of data produced per parent type	$P(d\|t_j)P(t_i\|d)$
$k = \|d\|$	number of observations per datum	$P(d\|t_j)P(t_i\|d)$
$l \geq 1$	posterior parameter from sampling to MAP	$P(t_i\|d) \propto [P(t_i)P(d\|t_i)]^l$
$c \in [0, 1]$	learning bias for lack of upper-bounds	$P(t_i)$

Table 2: Summary of model parameters.

and L_5 are our target lexica, previously labeled as lexica L_b and L_a. They codify upper-bounded semantics for message m_1 and a lack thereof, respectively. Lastly, L_6 is similar to L_5 in that two messages are true of the same state but differs from it in assigning upper-bounded semantics to m_1.

Combining a signaling behavior with each of these 6 lexica yields a total of 12 distinct types. Note in particular that a type that has conventionalized upper bounds to realize a (quasi-)partition of the relevant semantic space, such as L_4, will produce speaker behavior that is *almost* indistinguishable from that of a language that lacks upper bounds, but with pragmatic speakers, such as L_5. Almost, because there may be slight differences between the probability with which speakers would (erroneously) use a semantically false description and the probability with which speakers would (erroneously) use a pragmatically suboptimal description. Due to this possibly marginal difference between pragmatic L_4 and L_5, the selection of one type over the other is expected to mainly depend on the learning bias. Things are less clear for literal L_5 contrasted with literal/pragmatic L_4. The former has a learning advantage but is expected to fare worse in communicative terms in virtue of ambiguous m_1.

The dynamics are initialized with an arbitrary distribution over types, constituting the population's first generation. The results for each parameter setting were obtained from 1000 independent runs, each consisting of 20 generations. This corresponds to a developmental plateau after which no noteworthy change was registered. As specified in §1.4, the learning matrix Q can be obtained by considering all possible state-message sequences of length k. Given that this is intractable for large k, matrices were approximated by sampling 10 sequences from each type's production probabilities and a type's children being exposed only to this subset. For convenience, the model's parameters are summarized in Table 2.

According to our hypothesis, functional pressure on successful communication combined with learning pressures in the form of a bias against upper-bounds may lead to the selection of L_5-like semantics. It is instructive to first inspect the effect of these pressures in isolation. For this purpose we focus our attention on three pragmatic types.[2] Pragmatic L_3, a type that is lacking in expressivity but is a priori preferred for its lack of upper-bounds. Pragmatic L_4, a type that is functionally advantageous but biased against. And pragmatic L_5, combining virtues of the latter two.

Expressivity only. Recall that the replicator dynamics are sensitive to λ and α as both have a bearing on a type's fitness. In particular, low α disadvantages types that rely on pragmatic reasoning to the gain of those that codify more semantically. The rationality parameter λ has a similar effect for different reasons: Low rationality leads to a less pronounced preference for the choice(s) expected to succeed best in communication. That is, λ regulates the strength by

[2] Pragmatic reasoning allows language users to refine their (possibly erroneous) choices. Therefore, it is advantageous even for those types that codify an upper-bound lexically.

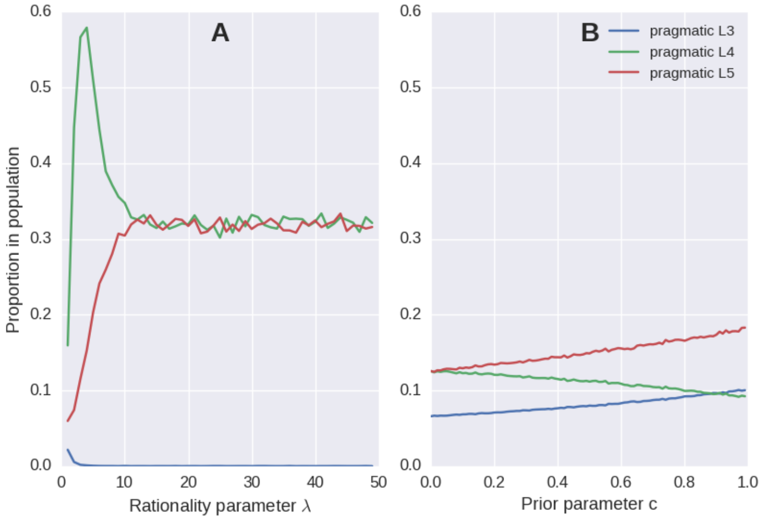

Figure 1: Mean proportions of target types after 20 generations in 1000 populations with only replication (A; $\alpha = 1$) and only mutation (B; $\alpha = 1, \lambda = 30, k = 5$).

which users of L_5 associate non-upper-bounded m_1 exclusively with the "some"-state s_1 over the "all"-state s_2. Speakers of L_4 need not rely on λ for this, as as the association of m_1 with s_1 is already part of their language's semantics.

The effect of the rationality parameter for $\alpha = 1$ is depicted in Figure 1.A. As expected, the less expressive L_3 speakers fare the worse and are influenced the least by variations in λ. In contrast, low values of λ result in a higher proportion of L_4 speakers relative to L_5. This is expected given role of rationality in producing more deterministic linguistic behavior in users of L_5-like languages. As the rationality parameter increases the functional difference between L_4 and L_5 is levelled. Overall, the final populations that result only from a pressure towards expressively come close to an even share of pragmatic L_4, L_5 and L_6 types (the latter follows the same trajectory as L_5 in Figure 1). That is, expressivity alone can not differentiate between these lexica in populations of rational pragmatic language users.

Learnability only. The effect of iterated learning without a pressure for expressivity is shown in Figure 1.B with posterior sampling. In line with our expectations, the share of L_4 speakers decreases as the bias against this lexicon increases. In turn, this benefits L_3 and, in particular, L_4. However, note that even a strong bias against lexical upper-bounds leads only to a moderate advanage for L_5 over L_4. Furthermore, a pressure only towards learnability can promote functionally defective languages L_3.

Inspecting these pressures separately not only gives some intuitions about the parameters' influence, but also highlights some of their broader implications. First and foremost, neither dynamic comes close to converging to a monomorphic population under most parameter configurations. For instance, while L_4 speakers can come to take over a substantial proportion of the population, this only happens in a restricted range of low degrees of rationality. Apart from polymorphy, both pressures make undesirable predictions. A pressure only towards expressivity leads to the selection of types using L_4 to L_6 and to the ejection of L_1 to L_3. However, it can not explain the regular selection of L_5-like semantics over either of these functionally similar alternatives. In contrast, a pressure only towards learnability has a modest but clear effect in

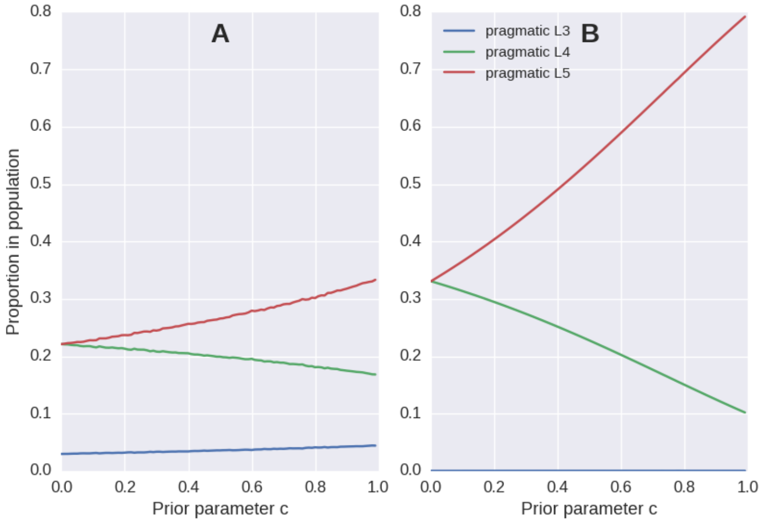

Figure 2: Mean proportions of target types after 20 generations in 1000 populations across bias values $c \in [0, 1]$ with $l = 1$ in A and $l = 3$ in B ($\alpha = 1, \lambda = 20, k = 5$).

differentiating L_5 from these alternatives but fails to rule out functionally suboptimal types such as tautological L_3. In sum, neither dynamic on its own is a suitable candidate to provide a justification for the predicted prevalence of L_5-like semantics.

Expressivity and learnability. Figure 2 illustrates the effect of the learning bias for posterior sampling (2.A) and slightly more MAP-like learning (2.B). More detailed results for all types across a sample of c-values are presented in Table 3. Overall, these results suggest that in the present setup a weak bias is sufficient to lead to a selection of L_5 over L_4. As in the simulations that only considered learnability, this effect increases with the bias' strength provided L_5 users are pragmatic. Importantly, the addition of a pressure towards expressivity magnifies this effect and dampens the proliferation of functionally suboptimal types advantaged by the learning bias. As stressed above, this suggests that neither the learning bias nor functional pressure alone but their combination may lead to the lack of upper-bounds in the lexical meaning of scalar expressions.

The resulting proportion of pragmatic L_5 speakers primarily hinges on three parameters. First, the degree to which linguistic behavior is deterministic, controlled by λ and α. As stressed before, this plays a role both for expressivity as well as for producing data that allows learners to discriminate this type from others. Second, the learning bias c which controlls the learners preference for simpler lexical representations – leading to the selection of L_5 over L_4. Lastly, the posterior parameter l which magnifies the effects of the learning bias in tandem with replication.

As discussed in relation to Figure 2.A, posterior sampling can lead to the incumbency of pragmatic L_5. However, not even a strong favorable learning bias combined with a pressure for expressivity completely drives out competing types. This is not so for more posterior maximizing behavior. Crucially, as shown in Figure 3 the range of bias values within which L_5 takes over the population increases with MAP-like learning. In other words, the strength of the learning bias required for a given final proportion of L_5 speakers strongly depends on the learning strategy adopted evinced by it. As for the effect of the other parameters not mentioned so far, changes in sequence length influence the population in a predictable way: smaller values lead to more

	$l = 1$					$l = 3$				
c	0	.1	.5	.8	.9	0	.1	.5	.8	.9
lit. L_1	.03	.03	.04	.04	.04	ϵ	ϵ	ϵ	ϵ	ϵ
lit. L_2	.03	.03	.02	.01	.04	ϵ	ϵ	ϵ	ϵ	ϵ
lit. L_3	.03	.03	.04	.04	.04	ϵ	ϵ	ϵ	ϵ	ϵ
lit. L_4	.07	.07	.06	.06	.05	ϵ	ϵ	ϵ	ϵ	ϵ
lit. L_5	.04	.05	.05	.06	.06	ϵ	ϵ	ϵ	ϵ	ϵ
lit. L_6	.04	.04	.04	.04	.03	ϵ	ϵ	ϵ	ϵ	ϵ
prg. L_1	.03	.03	.04	.04	.04	ϵ	ϵ	ϵ	ϵ	ϵ
prg. L_2	.03	.03	.02	.01	.04	ϵ	ϵ	ϵ	ϵ	ϵ
prg. L_3	.03	.03	.04	.04	.04	ϵ	ϵ	ϵ	ϵ	ϵ
prg. L_4	.22	.22	.2	.18	.17	.33	.31	.23	.15	.12
prg. L_5	.22	.23	.27	.3	.32	.33	.37	.54	.7	.75
prg. L_6	.22	.22	.2	.18	.17	.33	.31	.23	.15	.12

Table 3: Mean proportions of types in 1000 populations after 20 generations across bias values $c \in [0, 1]$ with $l = 1$ and $l = 3$ ($\alpha = 1, \lambda = 30, k = 5$), $\epsilon < 0.005$.

heterogeneous populations that reflect the learner's prior more faithfully whereas larger ones lead to more pronounced differences amongst equally preferred types. This is expected insofar as the likelihood that a sequence of length 1 was produced by any type is relatively uniform (modulo prior) whereas the likelihood of types with lexica L_1 - L_3 to produce, for instance, a sequence of 10 observations consistently with the same state-message combination is less likely than for pragmatic types using L_4 - L_6, or literal L_4. Thus, while noteworthy, sequence length has no direct bearing on the contrast of interest.

2.2 Discussion

Broadly speaking these results suggest that a lack of semantic upper-bounds coupled with pragmatic reasoning can overcome selective pressures and stabilize in a population provided there is a bias for simpler representations. This outcome is particularly encouraging in light of other advantages a lack of semantic upper-bounds may confer.

This predictions hinges on three assumptions. First, that language is pressured toward both expressivity and learnability. Second, that language use is not too unpredictable: low α or λ values renders languages that rely on pragmatics too prone to miscommunication and more difficult to learn. Third, that learners prefer simpler over more complex lexical representations. Importantly, a combination of rationality in learning and choice requires a weaker bias towards simpler representations. Under these conditions the selection of lexical meanings lacking upper-bounds in populations of pragmatic speakers is robust against parameter perturbations.

While a great representation of non upper-bounded lexical meanings is predicted by the literature, it is less clear to what extent other types should be represented – if at all. There are reasons to expect functionally suboptimal types L_1-L_3 to be ruled out since they fail to enable their users to communicate effectively. However, this is not true of L_4.[3] Notwithstanding, it is possible that natural language communities are composed of homogeneous populations or that

[3] L_6 presents a special case. In our current setup, it mirrors L_5 in enabling for a pragmatic strenghtening of message m_2 rather than m_1. However, this association of s_2 with m_2 under favourable parameter conditions is achieved by ruling out the "some but not all"-state s_1 and not, as with scalar implicatures, the "all"-state s_2. L_6 speakers therefore strenghten a "some"-message to convey something paraphrasable as 'some but not [some but not all]'. However, our present setup is blind to this redundancy.

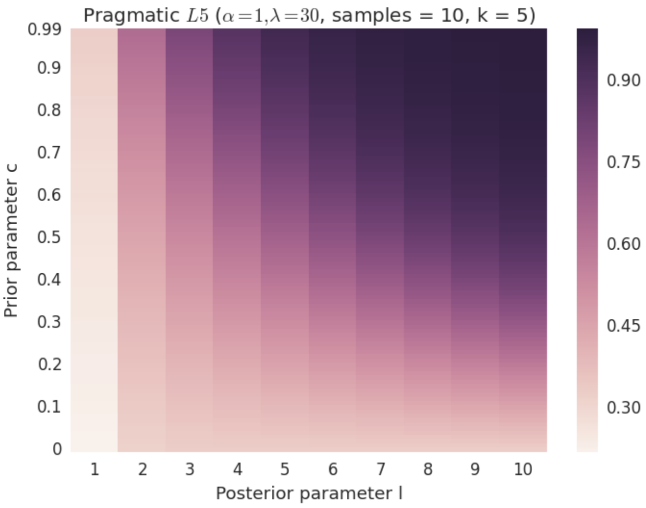

Figure 3: Mean proportion of pragmatic L_5 in 1000 populations after 20 generations ($\alpha = 1, \lambda = 30, k = 5$)

a single speaker may entertain L_4-like semantics for one scalar expression and L_5-like semantics for another.

This empirical issue relates to two aspects left undiscussed in our present analysis: disadvantages of pragmatic reasoning and the effect of state frequencies on the fossilization of pragmatic inferences. We tacitly assumed pragmatic reasoning to come at no cost. However, there is experimental evidence that suggests that the pragmatic derivation of upper-bounds costs effort and takes additional processing time (cf. Neys and Schaeken 2007, Huang and Snedeker 2009. This raises the question at which point such usage-based cost undercuts the learnability advantage of simpler semantic representations. Should cost play a role, it's effect is bound to depend on the frequency with which a given scalar expression is used. We speculate that frequently drawn scalar implicatures might fossilize to avoid cost, while infrequent ones could still be computed on-line.

3 General discussion

We laid out a model that combines game-theoretical models of functional pressure towards efficient communication (Nowak and Krakauer 1999), effects of learning biases on (iterated) language learning (Griffiths and Kalish 2007), probabilistic speaker and listener types of varied degrees of pragmatic sophistication (Frank and Goodman 2012, Franke and Jäger 2014) as well as different lexica (Bergen et al. 2012; 2016). This model generates predictions about lexicalization patterns found in natural language. We argued that, while the puzzle raised by semantics in light of pragmatics is hard to explain on purely functional grounds, part of the answer lies in learnability: Simpler semantic representations are more likely to be learned while pragmatic reasoning can counteract functional disadvantages otherwise incurred. This result is of particular relevance for the longstanding assumption of a divide and interaction between semantics and pragmatics by offering an account of why (certain) pragmatic inferences are not part of the literal meaning of expressions.

Summarize main predictions: Only expressivity, only learnability, both together; expressivity nudging learning in the right direction and learning leading to a uniform preference for thing in the population

Discussion about expressivity as external to learning (cf. Stadler, replicator-papers by Kenny Smith, Kirby et al 2015). Possibly add appendix with direct comparison between IL and RMD.

Kirby et al. (2015) propose dynamics that involve expressivity and learnability. In contrast to our proposal, the former pressure is not fully decoupled from the latter in that is restricted to the production of learning data as a form of ambiguity avoidance (cf. brighton+etal:2005b cited on p.89l, who make render such ambiguity avoidance as a "expressivity bias" in learning). That is, a measure of the degree of understanding achieved by interlocutors is not a part of the theoretical model. [4]

In contrast to past research using the replicator-mutator dynamics, the Bayesian setting afforded by iterated learning allows for a straightforward integration of a learning prior. Furthermore, less idiosyncratic assumptions about the variation introduced by learning without having to resort to similarity matrices between vocabularies (Nowak and Krakauer 1999) nor languages (Nowak et al. 2002).

Following **?** we assumed that, at some level, lexical meanings are expressed in a representational language and that the learners' task is to infer the lexicon that best explains the linguistic data they witness. We go beyond this by inferring type of use

4 Conclusion

Language change is affected by intertwined pressures. We investigated the selection of non-upper-bounded lexical meanings as a case study on role of semantics and pragmatics in satisfying such pressures. We showed that, when pressured for learnability and expressivity, the former drives for simpler semantic representations inasmuch as pragmatics can compensate for their lack of expressivity in use. That is, the relative learnability advantage of simpler semantics may offer an answer to why natural languages do not lexicalize certain pragmatic inferences. More broadly, we argued that semantic patterns can be explained by taking into consideration the way in which they are used in interactions as well as their representational complexity.

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[4] We could say more about this

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