

Linguistic structure emerges from cognitive mechanisms

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Abstract

People interact with people and, because of shared interest, try to coordinate their behavior. This behavior is governed by the competition of pragmatic pressures. These pressures lead to equilibria. These equilibria become conventionalized over time (Lewis). This convention becomes an additional pressure in the moment of interaction. Language as a paradigm case of these dynamics.

Human society can be viewed as a field which both influences the individual members of the group and is influenced by them.

– G.K. Zipf, 1949

Introduction

“Room for cream?” asked the barista. “Mm, yes – just a bit” replied the customer. Mundane linguistic interactions such as this are the building blocks of daily experience. They are individuals making sounds to each other in an effort to coordinate their behavior in the physical world (H. H. Clark, 2006). These interactions are messy, variable, and highly unconstrained. Indeed it is this variability that gives language its vast expressive power (Hockett, 1960). Yet, despite this appearance of irregularity, rich patterns in linguistic usage are revealed when we aggregate across instances of language use both within and across languages. At the level of syntax, for example, there is a strong bias in English to put subjects before verbs and, across languages, this pattern is attested more often than would be expected by chance alone (Dryer, 2005). These types of probabilistic regularities exist at every level of linguistic structure — from phonology, to semantics, syntax, and discourse — and researchers from a variety of disciplines have taken as their project the goal of characterizing these regularities.

In this paper, I argue that we can gain insight into the character of linguistic structure by considering the dynamics of language use. I will suggest the best way to do this is by framing language use as an instance of a broader phenomenon: social interaction (H. H. Clark, 1996). In particular, I will adopt the formal framework of social interaction proposed by Thomas Schelling, in which social interactions are viewed as acts of solving coordination problems. To illustrate, consider the barista example above. In this example, the agents are the barista and the customer, and they must coordinate how to fill the coffee mug. There are two outcomes — full and almost

full — and the barista’s desired outcome is determined by the preference of the customer. In this case, the barista and the customer rely on language to coordinate their behavior, but this coordination could have been achieved in other ways (e.g. the customer could have shook her head, pointed to the place inside the mug that she wanted the coffee filled to, etc.). Coordination of their behavior is achieved by arriving at the mutually preferred outcome (the customer’s mug is almost full).

A key tenet to the broader argument is that the act of using language is itself an act of solving a coordination problem (H. H. Clark, 1996). When a person speaks, there are many possible ways the utterance could be interpreted, and arriving at the intended interpretation is an act of coordination. For example, in the case of the customer’s interaction with the barista, there are many possible interpretations of the phrase, “Room for cream?.” The barista could mean “Would you like to add cream to your coffee? If so, I will facilitate that by not filling your mug full with coffee.” Or, “We have so much extra inventory of cream! Do you have room in your bag to take some?” Or, “Do you like the band ‘Room for cream’?”. Or, if the speaker is speaking another language, a totally unrelated meaning. The point is that the speaker’s intended meaning is underspecified from the language alone and the interlocutors must work collaboratively to arrive at a shared understanding. Following D. Lewis (1969), I will suggest that we can gain insight into the dynamics of linguistic coordination problems such as this by using Schelling’s formal framework. This perspective on language use will ultimately provide a helpful framework for understanding the relationship between language use and language structure.

It is worth reflecting on the historical relationship between these two aspects of language. Across many schools of linguistics, theorists have made a theoretical cut between language use and language structure: parole vs. langue (Saussure, 1916), token vs. type (Peirce, 1931), and performance vs. competence (Chomsky, 1965). These theorists have different views on the

ontological status of structure — Saussure suggests it is a social fact, while Chomsky argues it is fundamentally a cognitive phenomenon — but they nonetheless agree that there is some sort of invariance in language and it should be the focus of study. Language use has often been seen as an irregular, variant, and epiphenomenal to the true subject of study: structure. However, a number of more recent movements have begun to focus on language use. Labov's (1972) work was an important challenge to exclusionary focus on abstract structure. His work revealed systematicity in the variation of phonology as function of social variables, suggesting that language use was governed by regularities. The study of pragmatics, more generally, can be seen as a step to find regularity in language use. The goal of this paper is to suggest that, not only are these two aspects of language deeply related to each other, the key to understanding linguistic structure may lie in understanding linguistic use.

In Part I, I will outline the linguistic coordination problem as a paradigmatic case of the social coordination problem. I will suggest that coordination problems are solved through the dynamics of two opposing forces — the goals of the one's self and the goal of the other. Following Lewis, I suggest that these opposing forces are resolved by finding an equilibrium point. I will then argue that the equilibria that are reached in language use are reflected in the structure of language, and survey a variety of phenomena in linguistic structure that show this pattern.

In Part II, I will consider the mechanism that might cause linguistic structure to reflect the equilibria reached in linguistic use. Lewis argued that once individuals succeed in solving a coordination problem, there is a tendency to stick with that solution (even though other, equally good solutions exist). This solution is called a convention. I will argue that the key to understanding the link between regularities in linguistic usage and linguistic structure is the process of children's acquisition of these conventions. I will consider how the dynamics of

language acquisition might lead to language change. Finally, I will consider the complementary role of conventions and cognitive forces in solving language coordination problems, and the empirical challenge associated with disentangling the two.

Part I: Linguistic structure reflects pragmatic equilibria

Where does linguistic structure come from? Christiansen and Chater (2008, 2010) propose a compelling theory. They argue that multiple cognitive constraints dynamically influence language evolution. They suggest four constraints: the representational format of thought, properties of the percepto-motor system, learning and processing constraints, and constraints that result from reasoning about others intentions (*pragmatic* constraints). Their argument is that these cognitive constraints influence language at the moment of use, but over time, these biases become instantiated in the structure of language. Although each of these constraints likely plays an important role in the evolution of language, the present paper focuses on the independent contribution of pragmatic constraints. The claim is that pragmatic constraints that play out at the moment of language use become fossilized in the structure of language over time. To develop this claim, we begin by modeling language use as a type of social coordination. We then turn to an analysis of language use as a social coordination problem. Finally, we consider three cases where there are similarities in phenomena between language use and language structure.

Social interaction as a coordination problem

Many theorists of language (Zipf, 1936; D. Lewis, 1969; Grice, 1975; H. H. Clark, 1996) have observed that language is an instance of a much broader class of behavioral phenomena — social coordination. For each, language use is a case of multiple agents making interdependent

rational choices.¹ By adopting work from game theory, D. Lewis (1969) formalized the notion of language as a coordination problem. He defines a *coordination problem* as follows:

Two or more agents must each choose one of several alternative actions. Often all the agents have the same set of alternative actions, but that is not necessary. The outcomes the agents want to produce or prevent are determined jointly by the actions of all the agents (p. 8).

The key feature of these problems is that some combinations of the agents' choices are better than others: there are a set of joint choices in which no agent would have a larger payoff had the agent alone changed her choice. We refer to these as *equilibrium points*.

This broad framing can describe the dynamics of many social interactions. Take the above case of the barista and the customer, for example. We can model this interaction using a payoff matrix (Table 1). In the matrix, we represent the customer's payoff along the rows and the barista's payoff along the columns. There are two possible choices for level of coffee in the cup—full and almost full — and so each agent gets two rows or columns. The agents relative payoffs are indicated in the cells, with the barista's on the left, and the customer's on the right. This happens to be a very simple equilibria — there is one, and only one, possible set of actions in which is an equilibrium. The customer prefers almost full and the barista fills the cup to almost full. The problem is that the barista does not know a priori where this equilibrium lies, i.e. that the customer's pay off for almost full is 1, relative to 0 for full. To solve this coordination problem, the customer and barista make use of language.

¹In outlining his seminal theory of pragmatics, Grice writes: "As one of my avowed aims is to see talking as a special case or variety of purposive, indeed rational, behaviour, it may be worth noting that the specific expectations of presumptions connected with at least some of the foregoing maxims have their analogues in the sphere of transactions that are not talk exchanges" (Grice, 1975, pg. 47).

		customer	
		full	almost full
barista	full	0,0	0,0
	almost full	0,0	1,1

Table 1

A payoff matrix of a context of a simple interaction — a barista trying to determine how full to fill a customers' cup. Given the customer's preference for cream, there lies an equilibrium point at 'almost full' for both barista and customer. To arrive at this equilibrium point, the two must coordinate.

More complicated coordination problems arise when there are multiple possible equilibria. Consider a weekend trip in which food and alcohol must be brought. To distribute the burden, half of the vacationers will bring food and the other half alcohol. In this case, the pay off matrix might look something like Table 2. Neither group — Group A or B — has a strong preference about which of the two commodities each brings. However, what is important is that one group brings food and the other alcohol (no one will be happy on a weekend trip with only food or only alcohol). There are thus two equilibria, one at each set of choices where the two groups bring different things. By chance, the vacationers are equally likely to end up in a non-equilibrium as they are an equilibria. They must therefore coordinate, via language or some other means, to ensure that they end up at an equilibrium.

What are the psychological forces that support these coordination games? Zipf's theory of human behavior (1949) provides insight. He argued that all human behavior could be accounted for by a single principle: people are motivated to minimize their effort (*The Principle of Least*

		Group A	
		food	alcohol
Group B	food	0,0	1,1
	alcohol	1,1	0,0

Table 2

A payoff matrix for a social interaction in which there are two equilibria. Neither group cares who brings what commodity on the vacation; they only care that they bring different things.

Effort). According to this principle, in a context in which individuals need to exert some physical effort, say in walking to a park — they should be motivated to find the solution that minimizes how much effort required. Critically, Zipf argued this simple principle had explanatory power at the level of social groups. He suggested that this principle governs the behaviors of individuals, but with interaction, this principle leads to an equilibrium in behavior at the level of the group.

This simple theory of behavior provides a parsimonious account of a wide range of social phenomena. A particularly clear example is the organization of people into social groups in physical space (Zipf, 1949).² Zipf assumes that every individual in a society is both a consumer and producer of goods. Governed by the Principle of Least Effort, the individual should minimize effort in terms of movement across land, by consuming (i.e. living) and producing (i.e. working)

²A second, well-studied example is economics. At the level of the individual, the consumer tries to minimize something of value, but in this case the valued commodity is money, rather than energy (though these are arguably related in important ways). This is the study of microeconomics. With interaction among consumers, this single force leads to regularities at the level of the social group, or the economy—the study of macroeconomics.

at the same location. However, as the number of raw goods increases this becomes increasingly difficult because the consumer cannot not live at the doorstep of every finishing plant. This creates a conflict. On the one hand there is a force to diversify, so that the population lives at the doorstep of the production line. This creates a force for many separated communities in space, each producing a single good, but with little trade between other communities. On the other hand, there is force to unify so that it is easier to trade final goods. The result is an equilibrium where people live in many different urban centers across the land. This general theory is reflected in more modern theories of urban spatial layouts (Mills, 1967; Brueckner, 1987).

Importantly, Zipf's principle does not provide a description of how individuals come to solve pure coordination problems like the vacationer example above. In that case, it is not clear how two individuals with the exact same payoff structure would arrive at the same, otherwise arbitrary solution. To address this issue, we need the idea of *convention* which will return to in Part II. However, Zipf's principle does provide insight into how a single psychological force, shared by all individuals, can lead to biases for different alternatives (e.g., a preference for the shortest path to a location). When individuals with these same biases interact with each other, we see the emergence of an equilibrium.

Language use as a coordination problem

The coordination framework can be straight-forwardly applied to language use (D. Lewis, 1969). Language use is a paradigmatic case of a coordination problem because it is a tool that is universal in a community, easy to use, and capable of expressing complex ideas. In the case of language, the core of the coordination problem lies in the resolution of reference. Broadly, resolving reference requires interpreting a meaning from some utterance. At the level of individual lexical items, this is a difficult problem because the relationship between linguistic form and meaning is arbitrary (Saussure, 1916; Hockett, 1960). That is, knowing the form of a

		Speaker 1	
		“fep”	“dax”
Speaker 2	Object A	0,0	1,1
	Object B	1,1	0,0

Table 3

A payoff matrix of the mapping problem. Given two words and two referents, the mappings are arbitrary. The only constraint is that no word should map to more than one object, and no object should map to more than one word. Thus, as in the vacationer example, speakers must coordinate.

word does not give a language user any insight into the meaning of that word. Consequently, there is no inherent mapping between form and meaning and speakers must coordinate their behavior.

The arbitrariness of linguistic form leads to a formal equivalence between the problem of reference and the problems of coordination described above. To understand this similarity, consider a case where there are two novel words, “dax” and “fep,” and two novel objects, Object A and Object B. Given this information alone, the listener has no a priori insight into which object each word refers to. This is a problem because the two interlocutors must somehow arrive at the same mappings between words and referents in order to communicate (a system in which you call Object A “fep” and I call it “dax” is a terrible communication system). The interlocutors must therefore coordinate.

The payoff structure for this problem is identical to the vacationer example above (Table 3). Because language is arbitrary, neither speaker cares whether you call Object A “fep” or “dax;” they only care that their mappings are the same. These general dynamics are true not only of individual lexical items, but of all cases of reference. Consider again our example of the barista

and the customer. In interpreting the phrase, “Room for cream?,” the individual lexical items are relatively unambiguous — presumably both know what “room” and “cream” mean. But, the intended meaning of the entire phrase is underspecified, and so the interlocutors must work together to resolve meaning.

In this framework, we can think of *pragmatics* as the study of the psychological processes that lead to an equilibrium in these referential coordination problems. Pragmatics, then, is just a specific case of the dynamics described by (Zipf, 1949). In the case of language, Zipf’s insight was that speech could be thought of as its own economy, similar to any other social system. Speech has a physical cost and could be used as tool. He suggested the speaker and the listener were both governed by the Principle of Least Effort and this lead to an equilibrium. In the case of the speaker, effort could be minimized if there existed a single word w that could be used to refer to the set of all concepts C . In the case of the listener, effort would be minimized (in terms of understanding) if there existed a unique word for each unique concept c . The dynamics of the interaction of these two opposing forces is pragmatics. Many theorists have tried to account for pragmatic regularities in behavior, most notably Grice (1975). However, Horn (1984) presents a particularly parsimonious theory that closely aligns with Zipf’s more general formulation. He posited two principles that describe the manifestation of Zipf’s Principle of Least Effort for the speaker and the hearer each.

SPEAKER: Say no more than you must. (*Principle of Necessity*)

HEARER: Say as much as you can. (*Principle of Sufficiency*)³

These principles are quite straight forward. As a speaker with a necessary meaning to contribute, you want to say a little as possible, while still conveying the intended meaning. In contrast, as a

³Horn refers to these as the R and Q principles, respectively. I’ve opted for less opaque terminology.



Figure 1. Example stimuli from Frank and Goodman (2012). In this case, the intended referent is the middle shape. Both speaker and hearer agree that utterance “circle” is an equilibrium point, as compared to “blue,” even though both terms equally describe the intended referent in truth-functional terms.

listener, you want the speaker to say as much as possible to minimize your effort at arriving at the correct interpretation. That is, you want the speaker to use sufficient language. In the limit, each strategy on its own does not result in a successful communication system. This is because the speaker’s and the hearer’s goal are fundamentally linked: While in the short term, it might be less effort for the speaker to utter a single sound, “blah,” to convey her meaning, this will lead to confusion on the part of the hearer, which the speaker will then have to clarify with additional language. The speaker and hearer must therefore resolve their two opposing forces in what Horn called a “division of pragmatic labor” in order to arrive at an equilibrium point (Horn, 1984, p. 22).⁴

While these principles are simple, the dynamics they give rise to are complex. Frank and Goodman (2012) present a formal model that captures these dynamics in a simple reference game. In their game, there are three possible referents and each referent has two relevant features

⁴Note that there is a super maxim that is also operating here: the cooperative principle (Horn, 1984; Grice, 1975). The cooperative principle is essentially the idea that the interlocutors realize that utterances are the result of an equilibrium from the dynamics these two forces. Put another way, it is a statement that the interlocutors realize that they are playing a coordination game.

(Fig. 1). Given the constraint that a speaker can only utter a single word, there are always two possible words the speaker could utter. For example, if the intended referent is a blue circle, a speaker could use either the word “blue” or “circle” to refer to the object. Critically, both words are equally true of the referent from the perspective of truth functional semantics. The phenomenon that this model captures is that the speakers use different words to refer to an object — and that listeners expect them to — depending on the context in which the word is uttered. In particular, speakers tend to choose a word that most uniquely identifies the intended referent, given the referential context. In other words, they select the word that is most informative. For example, in the example trial pictured in Figure 1, speakers tend to use the word “circle” instead of “blue” to identify the middle referent. Frank and Goodman use a Bayesian framework to formalize this notion of informativity, and their model closely captures the behavioral data in this reference game. This suggests that the behavior of both interlocutors is guided by a tacit understanding of informativity in the referential context.

This notion of informativity falls directly out of Horn’s principles. In this reference game, speakers are constrained by the length of the utterance they can use (one word), but the choice of words is free. From the listener’s perspective, the utterance must be sufficient and so uttering “blue” would be insufficient in the above context because it is ambiguous, and there is a better alternative. From the speaker’s perspective, the utterance must be necessary, but should not be too verbose. This force is enforced by structure of the task — the speaker must contribute something to participate in the task, and the utterance cannot be overly verbose given the single word constraint. Maximal informativity — a sufficient contribution, given the context — is thus the equilibrium between these two forces.

Pragmatic equilibria reflected in the structure of language

Simple reference games like that of Frank and Goodman (2012) are one example of the kind of equilibria that emerges from the interaction of Horn's principles, but there are many others. In the present section, we consider how these pragmatic equilibria points in language use are reflected in the structure of language. We will consider this relationship for three different kinds of linguistic structure: semantics, words, and syntax.

Semantics. Semantics concerns the context-independent meaning associated with a word. The size of the semantic space denoted by particular word reflects an equilibrium point between Horn's speaker and hearer principles. From the hearer's perspective, Horn argues there is a pressure to narrow semantic space (Horn, 1984). This reflects the idea that the hearer's optimal language is one in which every possible meaning receives its own word. One example of this is the word "rectangle." This word refers to a quadrilateral with four right angles. A special case of a "rectangle" is a case where the four sides are equal in length, which has its own special name, "square." Consequently, the term "rectangle" has been narrowed to mean a quadrilateral with four right angles, where the four sides are *not* equal.⁵ From the speaker's perspective, there is a pressure for semantic broadening. This is because the speaker's ideal language is one in which a single word can refer to a wide range of meanings. An example of this is the broadening of brand names to refer to a kind of product. For example, "kleenex" is a name of a product name for facial tissues, but has taken on the meaning of facial tissues more generally.

The opposition of these two semantic forces predicts an equilibrium in the organization of semantic space that satisfies the pressures of both speaker and hearer. A body of empirical work has tested this prediction by examining the organization of particular semantic domains cross-linguistically (Regier, Kemp, & Kay, 2014). Languages show a large degree of similarity in

⁵Horn also points out that there are cases of narrowing that are speaker-based, as in "drink" for "alcoholic drink."

how they partition semantic space for a particular domain, which is likely due to universal cognitive constraints. But, they also show a large degree of variability and these different systems can be shown to all approximate an equilibrium point between speaker and hearer pressures.

Kemp and Regier (2012) demonstrate this systematicity in the semantic domain of kinship. For each language, they developed a metric of the degree to which Horn's speaker and hearer pressures (in their terminology: communicative cost and complexity, respectively) are satisfied. A language that better satisfies the hearer's pressure is one that is more complex, as measured by the length of the description of the system in their representational language. A language that better satisfies the speaker's pressure is one that requires less language to describe the intended referent. To understand this, consider the word "grandmother" in English: this word is ambiguous in English because it could refer to either the maternal or paternal mother, and so referring to one in particular is more costly in English than in a language that encodes this distinction lexically. They find that the set of attested languages is a subset of the range of possible languages, and this subset partition the semantic space in a way that is near the optimal tradeoff between speaker and hearer pressures (Fig. 2). This type of analysis has also been done for the domains of color (Regier, Kay, & Khetarpal, 2007), light (Baddeley & Attewell, 2009), and numerosity (Y. Xu & Regier, 2014).

A second phenomenon that is predicted by these forces is the presence of lexical ambiguity. That is, cases in which there are multiple meanings associated with a word, from a context-independent perspective. Language is rampant with examples. For example, the word "bat" could mean either the instrument used in baseball or the flying mammal. This type of ambiguity in context-independent meaning is tolerated because the meaning is usually easily disambiguated by context. When the word "bat" is uttered while watching a baseball game, the mammal usage of the word is very unlikely. We can view the presence of this ambiguity as an equilibrium in Horn's speaker and hearer principles. If the meaning of a word can be

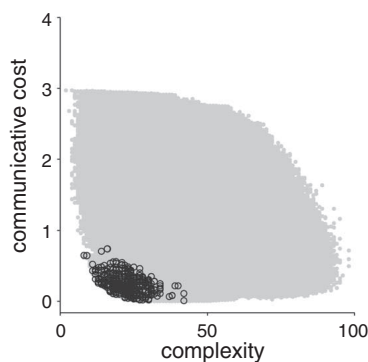


Figure 2. Plot from Kemp and Regier (2012). Languages organize the semantic space of kinship in a way that optimizes both speaker and hearer pressures. The notion of *communicative cost* maps onto Horn’s speaker principle and the notion of *complexity* maps onto Horn’s hearer principle. Gray circles represent possible systems and black circles represented actually attested languages. The key observation is that all of the attested languages are clustered around the bottom left corner that corresponds to an equilibrium between speaker and hearer pressures.

disambiguated by the referential context, then it would violate the speaker’s principle to have an overly-specific term for a meaning.

Indeed, recent work by Piantadosi, Tily, and Gibson (2011a) reveals systematicity in the presence of lexical ambiguity in language. They argue that ambiguity results from a speaker based pressure to broaden the meaning of a word to include multiple possible meanings. In particular, they suggest that this pressure should lead to a systematic relationship between the presence of ambiguity and the cost of a word. According to their argument, costly words (in terms of length, frequency, or any metric of cost) that are easily understood by context violate the speaker’s principle to say no more than you must. Consequently, there should be a pressure for these meanings to get mapped on to a different, less costly word. This word may happen to already have a meaning associated with it, and so the result is multiple meanings being mapped to

a single word. For example, in the case of the word “bat,” a speaker could instead say “baseball bat,” but because this referent is easily disambiguated in context from the mammalian meaning, Horn’s speaker principles leads to a pressure to use the shorter form.⁶ This leads to a testable prediction that shorter words should tend to be more ambiguous. Through corpus analyses, Piantadosi et al. (2011a) find this precise relationship between cost and ambiguity. They find a linear relationship between word length and ambiguity across English, Dutch and German: Shorter words are more likely to have multiple meanings.

An additional case of this lexical ambiguity is found in words that have very little context-independent meaning, known as indexicals or deictics (Frawley, 2003). These words get their meaning from the particular referential context of the utterance, and are therefore highly ambiguous from a context-independent perspective. There are many types of indexicals that are present to varying degrees across languages. An example of a temporal indexical form is “tomorrow.” The context-independent meaning of this word is something like “the day after the day this word is being uttered in.” Critically, abstracted from any context, this word has little meaning; it is impossible to interpret without having knowledge about the day the word was uttered. This phenomenon is also present in person pronouns (e.g. “you” and “I”) and spatial forms, like “here” and “there.” As for lexical ambiguity, this type of ambiguity is a predicted equilibrium point from Horn’s principles: If the hearer can recover the intended referent from context, the speaker would be saying more than is necessary by using an overly-specific referential term (e.g., “December 18th, 2014” vs. “tomorrow”). Language structure reflects this

⁶There are also cases of temporary ambiguity in the meanings of syntactic structures. For example, in a sentence that begins “The coach knew you...” it is unclear whether “you” is a direct object or the subject of a relative clause. Speakers can avoid this ambiguity by inserting a “that,” but this is optional. Work by Ferreira and Dell (2000) suggests that speakers often do not avoid this ambiguity, presumably because the intended meaning can easily be recovered from context.

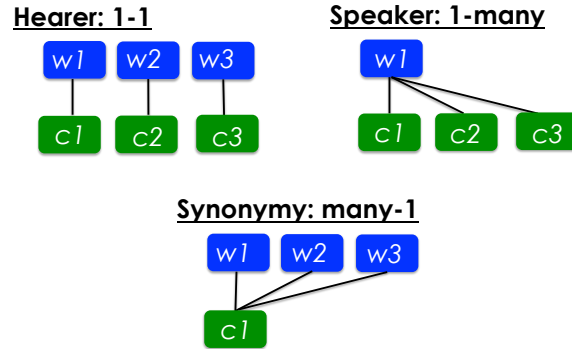


Figure 3. Three possible structures on the organization of lexicon. According to Horn’s principles, the hearer’s optimal language is one in which there is a one-to-one mapping between words and concepts. The speaker’s optimal language is one in which there is one word that maps to many concepts. Synonymy, or a many-1 structure, is thus dispreferred by both interlocutors.

pressure through lexicalized ambiguity in the form of indexicals.

Finally, the relationship between the meanings of different words can be seen as a consequence of Horn’s principles. A number of theorists have noted a bias against two words mapping onto the same meaning — that is, a bias against synonymy (Saussure, 1916; Kiparsky, 1983; Horn, 1984; E. Clark, 1987, 1988). This bias is an equilibrium between Horn’s speaker and hearer principles. Recall that the optimal language for a hearer is one in which each meaning maps to its own word — exactly a language biased against synonymy (see Fig. 3). It turns out that the speaker’s pressure also biases against synonymy. The optimal language for the speaker is a language where a single word maps to all meanings. But, a case where multiple words map to a single meaning is also undesirable because the speaker must keep track of two words. So, for both the speaker and the hearer, there is pressure to avoid synonymy. Thus, when a listener hears a speaker use a second word for an existing meaning, the hearer infers that this could not be what the speaker intended because this would violate the speaker’s principle. The result is an assumption that the second word maps to a different meaning. This pattern is reflected in

language structure by a one-to-one pattern in the lexicon — that is, a structure in which each word maps to exactly one meaning and each meaning maps to exactly one word.

As one kind of evidence for this one-to-one structure in the lexicon, Horn (1984) points to a phenomenon called *blocking*. Blocking refers to cases in which an existing lexical form blocks the presence of a different, derived form with the same root. Horn points to the following examples:

- (a) fury furious *furiosity
- (b) *cury curious curiosity

In both (a) and (b), forms that would be expected, given the inflectional morphology in English, are not permitted. This is presumably because they would have the same meaning as the existing form because they have the same root. Examples such as this provide some evidence for a one-to-one structure in language, but a one-to-one structure is a particularly difficult linguistic regularity to test empirically. Nonetheless, it is an important regularity because it licenses certain inferences in interpreting the meaning of words. In particular, the cognitive representation of a one-to-one regularity has been posited as an explanation of children's bias to map a novel word onto a novel object (Markman & Wachtel, 1988; Markman, Wasow, & Hansen, 2003). We return to this issue in Part II.

Words. Horn's principles make an interesting prediction about the length utterances and their meanings. In many cases, it is possible to use two different utterances to refer to the same meaning (in truth functional terms), and often these utterances differ in length. Horn (1984) presents the following example:

- (1a) Lee stopped the car.
- (1b) Lee got the car to stop.

Both (a) and (b) have the same denotational meaning (the successful stopping of a car), but they differ in length ((b) has two extra words). Horn argues that this asymmetry leads to an inference

on the part of the listener that the two differ in meaning. The logic of this inference is identical to the lexical structure case above. The listener hears a speaker use a more costly phrase to express a meaning that could have been expressed in a less costly way. The listener thus infers that this other meaning could not be what the speaker intended because this would violate the speaker's principle to say no more than is necessary. Horn adds an additional layer to this argument. He suggests that not only do these two forms differ in meaning, but that they map onto meanings in a systematic way. In particular, he argues that the longer form gets mapped on to the more marked meaning, while the shorter form refers to the unmarked meaning. The notion of 'markedness' is underspecified here, but an intuitive definition is related to complexity: more marked things are more conceptually complex, while less marked things are more conceptually simple. Thus, in the above example, (a) would refer to a simple, average case of a car stopping, while (b) might refer to a case where something complex or unusual happened, perhaps Lee was having trouble with the brakes.

The source of the particular mapping between forms of different lengths and meanings of different degrees of markedness is unclear. This is because, in principle, there are multiple equilibrium points in the mapping between form and meaning. Assuming a one-to-one constraint on the mapping, there are two possible equilibria: {short-simple, long-complex} or {short-complex, long-simple} (Table 4). Both satisfy the constraint that each form gets mapped to a unique meaning. So how do speakers arrive at the {short-simple, long-complex}? This is a difficult result to derive from models of pragmatic reasoning. G. Bergen Levy (in prep) successfully derive this result as a consequence of the fact that {short-simple, long-complex} is a more optimal mapping for the speaker (the indirect result of Zipf's Principle of Least Effort). Another possibility relies on iconicity: hearers have a cognitive bias to map more complex sounding forms to meanings that are similarly complex.

Despite the absence of clear theoretical account of this phenomenon, the empirical data suggest that learners do indeed arrive at the predicted equilibrium. L. Bergen, Goodman, and Levy (2012) provide evidence for this type of implicature in a learning game. In their task, partners were told that they are in an alien world with three objects and three possible utterances of different monetary costs. They operationalize the idea of markedness or complexity as frequency, such that participants were instructed that each of the three different objects had three different base rate frequencies associated with them. Participants' task was to communicate about one of the objects using one of the available utterances. If they successfully communicated, they received a reward. The results suggest that both the speaker and hearer expected costlier forms to refer to less frequent meanings. This study provides one of the piece of empirical work suggesting that Horn's predicted equilibrium between word length and meaning emerges in coordination games.

There is a growing body of evidence suggesting this equilibrium is also reflected in the structure of words. One approach to testing this hypothesis is to use the linguistic context of a word to measure the complexity of meaning. The idea is that words that are highly predictable, given the linguistic context, have more complex meanings, while words that are less predictable given the linguistic context, have less complex meanings. Piantadosi, Tily, and Gibson (2011b) measured the the relationship between the predictability of words in context and the length of words. Across 10 languages, these two measures were highly correlated: words that were longer were less predictable in their linguistic context on average. This result held true even control for the frequency of words. Additional evidence for this relationship comes from examining pairs of words that have very similar meanings, but differ in length (e.g. "exam" vs. "examination;" Mahowald, Fedorenko, Piantadosi, & Gibson, 2012). Through corpus analyses, they find that the longer forms are used in less predictable linguistic contexts. In a behavioral experiment, they also

find that speakers are more likely to select the longer word in unsupportive contexts. This body of work points to a systematic relationship between word length and meaning, when complexity is operationalized as predictability in the linguistic context.

Some of our own work provides more direct evidence for this equilibrium. Given a novel word, we find that both adults and preschoolers are more likely to map a longer word to a more complex object, as compared to a short word (Lewis, Sugarman, & Frank, 2014). A key difference between our work from prior work is that we directly manipulate the complexity of word meaning. We have operationalized complexity in three different ways. The first is to directly manipulate the number of object parts the referent has. Second, we have measured complexity by obtaining complexity norms from participants on real objects. Third, we have operationalized complexity through a reaction time measure. In each case, we see a bias to map longer words to more complex referents, as compared to a short word. We also find this bias in natural language. We asked participants to rate the complexity of the meaning of 499 English words, and found that these ratings were highly correlated with word length in both English and 79 other languages. Taken together, this work provides strong evidence that the equilibrium between word length and complexity of meaning that is found in coordination games, such as L. Bergen et al. (2012), is also reflected in the structure of the lexicon.

Syntax. The order of words, or syntax, is another level of language structure that reflects equilibria of language use. Levinson (2000) provides a detailed account of how Chomsky's syntactic binding constraints can be reinterpreted as pragmatic equilibria.

Several experimental finds also suggest that there are pragmatic equilibria reflected in syntax. One of the primary patterns of linguistic structure to be explained is the linear structure of words. In particular, why some word orders are much more prevalent across languages than others. Gibson et al. (2013) offer an account of one aspect of this regularity and this account can

be interpreted as a suggestion that a pragmatic equilibrium is reflected in the structure of language.

Their argument is as follows. There is some evidence that subject-object-verb (SOV) word order is the cognitive default (e.g. Senghas, Kita, & Özyürek, 2004). This proposal reflects the fact that SOV order is the most prevalent word order cross-linguistically (47%). But a puzzle still remains: If there is a SOV bias, why is a second order — SVO — almost equally as prevalent (41%)? Gibson et al. (2013) propose that the move from an SOV to SVO word order reflects a communicative pressure. The idea is that subjects and objects are often semantically confusable (because they are both entities), and thus, it is possible in the “noisy channel” of communication for one of the noun phrases to get deleted. This leads to confusion on the part of the hearer. Thus, they argue that the two should be linearly separated with the verb argument in order to avoid confusion. This is advantageous because if an argument is deleted, the correct grammatical relation of the communicated argument can be inferred from the input in an SVO order, but not an SOV order.

Though they motivate this prediction from an information theoretic perspective, this result can also be derived from Horn’s principles. Both the hearer and the speaker want to minimize effort. If it is indeed the case that SOV order frequently leads to confusion on the part of the hearer, this becomes problematic for the speaker who will have to often expend extra effort to clarify the confusion. Thus, given that there is an alternative word order that requires the same amount of effort —SVO order — there should be a pressure on the part of the speaker to move towards using this order.

To explore this proposal, Gibson et al. (2013) asked speakers to produce sentences describing scenes. A critical prediction of their argument is that confusion should be more likely when both arguments are animate (e.g. “The girl pushed the boy”) compared to a case when there

is an asymmetry in animacy (e.g. “The girl pushed the car”). In their key experiment, speakers of Japanese and Korean viewed brief videos of events. Japanese and Korean speakers were selected because their native languages were not SVO. Following each event, participants used non-verbal gesture to represent the events. Critically, the events involved three nouns that required using an embedded clause structure to describe. The patient of the embedded clause was either animate or inanimate. The measure of interest was the location of the embedded as a function of the confusability of the noun phrases. If participants gesture in accord with their native word order, they should show a SOV ($S_1 [S_2 O_2 V_2] V_1$) pattern in their gestures. However, if this bias is sensitive to the confusability of referents, they should be more likely to show a SVO pattern ($S_1 V_1 [S_2 O_2 V_2]$) when all the noun phrases are animate. Consistent with their prediction, this is exactly what they found: Japanese and Korean speakers were more likely to use the SVO pattern for the embedded events when the entities were all animate, as compared to when the object was inanimate.

Case marking is a second case in which pragmatic equilibria are reflected in syntax. In many languages, case marking is used as a syntactic strategy to indicate grammatical relations, like subject or object. Case markers are affixes that attach to the noun root, and are typically used in languages where word order is not a cue to grammatical relations. Case marking is usually optional but principled in its usage based on semantic properties of the nouns like animacy. For example, speakers often case mark nouns that appear in unpredictable roles, such as when an inanimate noun functions as a subject. Following logic similar to Gibson et al. (2013), Fedzechkina, Jaeger, and Newport (2012) used an artificial learning paradigm to test whether speakers regularize a language to minimize confusion between nouns. They predicted that speakers should be more likely to use case marking when the nouns were all animate, and thus confusable. They exposed learners to a verb-final language with flexible constituent order and

optional case-marking. Critically, case-marking in the input language was not conditioned on animacy. Consistent with the prediction, they found that learners tended to mark animate objects with an overt case marker more frequently than inanimate objects (because animate objects are confusable with animate subjects). This provides another case in which pragmatic pressures are reflected in regularities in language structure.

Part II: A casual link between language use and structure

Why does language structure reflect the patterns that appear in language use? In the present section, I propose a speculative answer to this question. The answer posits an indirect causal link between language use and language structure: Language use over time leads to regularities in linguistic structure. I will outline this answer by relying on an analysis of language separated by five different timescales. To preview, the hypothesis is that linguistic structure reflects language use as a consequence of local dynamics between adjacent timescales.

A *timescale* is a unit of time over which significant changes in state occur. For example, the timescale of dinner is about an hour, where the significant changes in state are walking to the restaurant, sitting down, ordering food, eating the meal, then dessert, etc. In contrast, the timescale of gaining weight occurs over weeks, where the significant changes in state correspond to notable changes in weight. The length of the timescales is determined by the change of interest. Because the changes of interest vary by timescale, the character of the dynamics varies as well.

In the case of language, there are five timescales over which significant changes occur (Fig. 4). The first is the *pragmatic timescale*. The pragmatic timescale corresponds to the processes described by Horn's principles, and addressed in detail in Part I. The *discourse timescale* is a slightly longer timescale. The discourse timescale corresponds to repeated interactions with the same person; a series pragmatic interactions. The third is the *developmental timescale*. The developmental timescale corresponds to the lifetime of an individual. It is composed of many

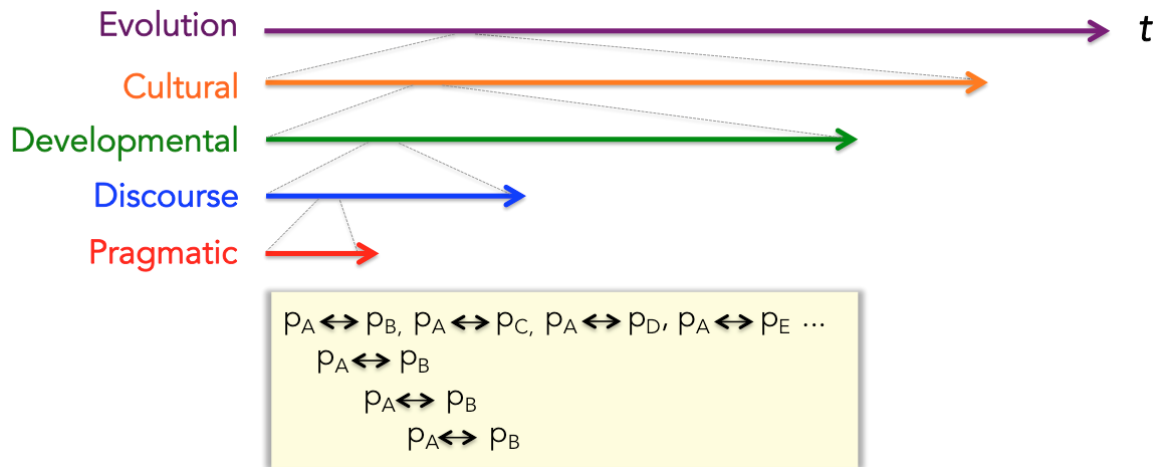


Figure 4.

interactions (on the pragmatic timescale), some of which with the same people (on the discourse timescale). Many people interacting over their lifetimes lead to change at the *cultural timescale*. This is the timescale over which significant changes in language structure occur (sometimes referred to as the “language change” timescale). Finally, at the longest timescale, is the *evolution timescale*. All of the dynamics at lower timescales occur within a small slice in evolutionary time. While I will not have much to say about this timescale, its main significance is to situate the present claims with respect to claims about the innateness of language. Following Christiansen and Chater (2008), the suggestion is that there are aspects of language that are innate and constrain the dynamics of shorter timescales. Importantly, however, not everything is innate — there are also important dynamics that take place at these shorter timescales. These dynamics are the focus of the present section.

The phenomenon to be explained is why dynamics at the pragmatic timescale are reflected in structure at the cultural timescale.

Here are the timescales - diagram - in what follows, consider dynamics between adjacent

timescales (?, ?, ?, ?)

The idea of a causal relationship between use and structure is not new. Particularly in the case of grammar, claims have been made about The key contribution of (?, ?) - emergence

The notion of Emergent Grammar is meant to suggest that structure, or regularity, comes out of discourse and is shaped by discourse as much as it shapes discourse in an on-going process. [...] Structure, then, in this view is not an overarching set of abstract principles, but more a question of a spreading of systematicity from individual words, phrases and small sets. [p. 142]

In what follows, I outline the evidence about the dynamics between each adjacent timescales.⁷

The relationship between pragmatic and discourse timescales

- * Lewis- convention (

- * Conceptual pacts Framing language use as a special case of conformity suggests that language use should be studied in a social context. There is evidence that speakers coordinate their linguistic behavior both in the language used to refer to a particular referent and the use of grammatical structures .

Coordination of reference was demonstrated in an experimental task by H. H. Clark and Wilkes-Gibbs (1986). In this task, pairs of naive subjects were brought into the lab and randomly assigned to either the role of director or matcher. They were seated across from each other with an opaque wall in between them. Each subject had a set of 12 cards with ambiguous images (an identical set of 12 as their partner). The director had their 12 cards arranged in a 6-by-2 grid, and her task was to direct the matcher to organize her cards in the same way using only verbal

⁷talk about form so far, but this is all vary related to whorf where the ideas that habits about thinking about semantics lead to regularities over time.

instruction. They were allowed to interact as much as they desired. After repeatedly completing this task with the same partner, it was found that directors used overall fewer words to describe the cards over successive trials. This was achieved through developing shared conceptualizations of different cards. For example, in trial 1, one director used the phrase “the next one looks like a person who’s ice skating, except they’re sticking their arms out in front,” but by trial 6 the same director simply used the phrase “the ice skater” to refer to that same card. This pattern suggests that interlocutors coordinate how they conceptualize the world through language, and this coordination increases over time. R. M. Krauss and S. Weinheimer (earlier referring (Scott-Phillips, Kirby, & Ritchie, 2009)

Pacts in linguistics structure. Similar patterns have been observed in the coordination of linguistic structure. In a study by Branigan, Pickering, and Cleland (2000), participants completed a picture description task in pairs. They alternated using a single sentence to describe the event depicted on different cards. Critically, one of the participants was a confederate. Sometimes the confederate used a prepositional object structure (e.g. “The girl is throwing the ball to the dog.”) and sometimes she used a double-object construction (e.g. “The girl is throwing the dog the ball.”). The results revealed that subjects tended to use the syntactic structure used by the confederate to describe their own picture (even though there was no semantic overlap between the two). This result suggests that, within conversations, speakers may not only conform in how they conceptualize the world but also in the grammatical structures they use.

(e.g. Trude & Brown-Schmidt, 2012) perceptual coordination

daniel mathews (kids), metzing

What are the psychological process supporting this behavior? When language use is couched in the context of the broader phenomenon of social interaction, old studies of social interaction become relevant.

There is evidence for this emergent view of conformity from the original Sherif (1935) study. In one version of the study, a group of three subjects were first tested individually in the light movement task. They were then tested three additional times as a group. The group context was identical to the individual paradigm except that other subjects were also making judgements about the movement of the light at the same time. As in the Asch studies, subjects did not know each other prior to the experiment. Figure 1a plots the results of one group of three subjects. When tested individually, the three subjects were highly variable in their distance judgements. However, when tested together, their judgements tended to converge, and this convergence increased over iterations of the experiment. The inverse of this experiment was also conducted, in which subjects were first tested in a group and then individually. In this design, subjects showed conformity when tested together, and some divergence from the social norm once tested individually. Critically, however, they showed much less variability in the individual test in this design, as compared to the design in which they were tested individually first. This result provides additional evidence for the tendency of groups to converge at an (arbitrary) solution to a problem. In the case of linguistic meaning, this suggests that groups may arrive at shared (but theoretically arbitrary) ways of conceptualizing referents.

* unconcioncious, but increases with awareness (?, ?)

The relationship between discourse and developmental timescales

*cached equilibrium, generalization problem, learning to learn, overhypothes (Smith, Goodman, & Frank, 2013) - important for thinking about timescales over development - different rates of learning.

The relationship between development and cultural timescales

- christiasen and chater (Smith et al., 2013) (Fedzechkina et al., 2012)

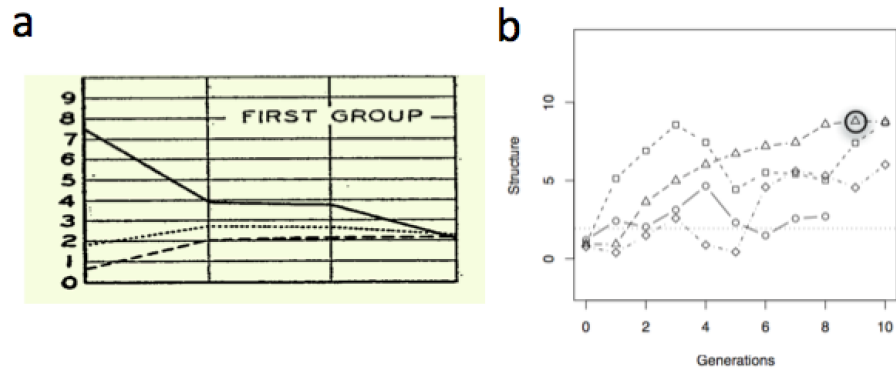


Figure 5. Plots reproduced from (a) Sherif (1935) and (b) Kirby, Cornish, and Smith (2008). Plot (a) shows the median distance judgement (in inches) for three different subjects. The x-axis plots subjects performance on the task when completed individually, and then three subsequent periods in which the task was completed as a group (of 3 subjects). Plot (b) shows the emergence of systematicity in the language across generations in the labeling task. Each line corresponds to a different set of people. Both plots suggest the emergence of systematicity, or conformity, within the group as a function of time.

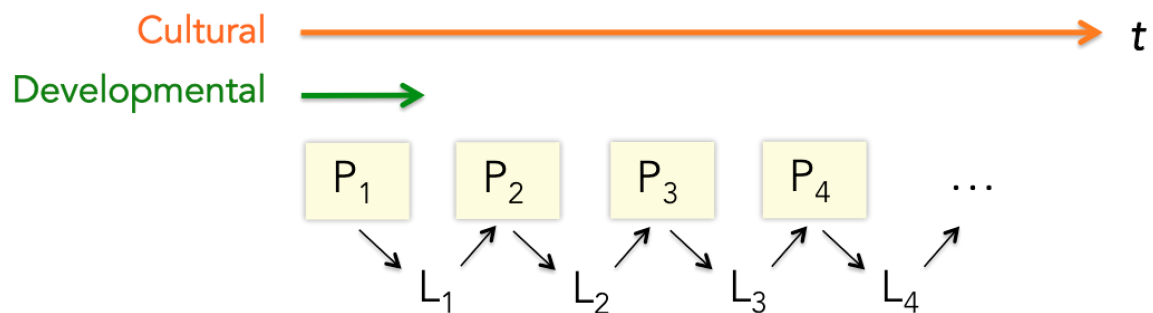


Figure 6.

Recent work using an artificial language paradigm tests this prediction. In a study by Kirby, Cornish, and Smith (2008), participants were presented with a novel language and asked to learn the pairings between words to novel images. For the first subject, the mappings between words and images was randomly generated. In the training phase, the subject was presented with an image and a label for that image. In the testing phase, they were shown a new image and asked to guess what word they thought was associated with that image. This first subject's responses were recorded, then divided into half (one half for training and one half for testing), and presented to a subsequent subject. This process repeated for a total of 10 subjects. Consistent with the Sherif (1935) results, it was predicted that language use would become more systematic over time. In particular, it was predicted that a pattern should emerge in the mapping between features of the stimuli (e.g. color, shape, etc.) and syllables in the novel words. This is exactly what was found (Figure 1b). As the number of generations increased, the language became more systematic. This pattern was observed across a four different "strings" of participants.

It suggests that the conformity that takes place in the context of particular conversations (as demonstrated by Brennan and Clark, 1996) has larger consequences when aggregated across time and across a linguistic community. While conversations are the locus of conformity, many small instances of conformity lead to highly regularized language patterns at the level of linguistic communities.

Consequences for learning

While not the focus of this paper, it is worth noting the consequence of this broader argument for learning. (Chater & Christiansen, 2010) Frank - Inferring word meaning by assuming speakers are informative (Smith et al., 2013) Alis adjective paper (F. Xu & Tenenbaum, 2007)

An empirical challenge: Sufficient but not necessary mechanisms

Parallels between development and language structure, and development and pragmatics in the moment of language use - ontological status of regularities just because they exist doesn't mean we represent them. ontological status of these regularities – difference between this and other laws of nature (e.g. physics) is that we can represent them – general abstract rules (connect to symbol literature). The question is: do we represent these regularities explicitly? (unlike macroeconomics) Just because we behave in away that is constant with macro economics, doesn't mean we = represent the regularity.

Conclusion

What this is not – totally reductionist to pragmatis. As Christiansen and Chater argue, multiple factors (most notable things like memory)

References

- Baddeley, R., & Attewell, D. (2009). The relationship between language and the environment information theory shows why we have only three lightness terms. *Psychological Science*, 20, 1100–1107.
- Bergen, G., Levy. (in prep). Pragmatic reasoning through semantic inference.
- Bergen, L., Goodman, N. D., & Levy, R. (2012). That's what she (could have) said: How alternative utterances affect language use. In *Proceedings of the thirty-fourth annual conference of the cognitive science society*.
- Branigan, H. P., Pickering, M. J., & Cleland, A. A. (2000). Syntactic co-ordination in dialogue. *Cognition*, 75, B13–B25.
- Brueckner, J. K. (1987). The structure of urban equilibria: A unified treatment of the muth-mills model. *Handbook of regional and urban economics*, 2, 821–845.

- Chater, N., & Christiansen, M. H. (2010). Language acquisition meets language evolution. *Cognitive Science*, 34, 1131–1157.
- Chomsky, N. (1965). Aspects of the theory of syntax cambridge. *Multilingual Matters: MIT Press*.
- Christiansen, M. H., & Chater, N. (2008). Language as shaped by the brain. *Behavioral and Brain Sciences*, 31, 489–509.
- Clark, E. (1987). The principle of contrast: A constraint on language acquisition. *Mechanisms of language acquisition*. Hillsdale, NJ: Erlbaum.
- Clark, E. (1988). On the logic of contrast. *Journal of Child Language*, 15, 317–335.
- Clark, H. H. (1996). *Using language*. Cambridge University Press Cambridge.
- Clark, H. H. (2006). Social actions, social commitments. *The roots of human sociality: Culture, cognition, and interaction*, 126–150.
- Clark, H. H., & Wilkes-Gibbs, D. (1986). Referring as a collaborative process. *Cognition*, 22, 1–39.
- Dryer, M. S. (2005). Order of subject, object, and verb. *The world atlas of language structures*, 330–333.
- Fedzechkina, M., Jaeger, T. F., & Newport, E. L. (2012). Language learners restructure their input to facilitate efficient communication. *Proceedings of the National Academy of Sciences*, 109, 17897–17902.
- Ferreira, V. S., & Dell, G. S. (2000). Effect of ambiguity and lexical availability on syntactic and lexical production. *Cognitive psychology*, 40, 296–340.
- Frank, M., & Goodman, N. (2012). Predicting pragmatic reasoning in language games. *Science*, 336, 998–998.
- Frawley, W. (2003). International encyclopedia of linguistics. In (Vol. 2, chap. Deixis.). Oxford

University Press.

Gibson, E., Piantadosi, S. T., Brink, K., Bergen, L., Lim, E., & Saxe, R. (2013). A noisy-channel account of crosslinguistic word-order variation. *Psychological Science*, 24, 1079–1088.

Grice, H. (1975). Logic and conversation. 1975, 41–58.

Hockett, C. (1960). The origin of speech. *Scientific American*, 203, 88-96.

Horn, L. (1984). Toward a new taxonomy for pragmatic inference: Q-based and R-based implicature. *Meaning, form, and use in context*, 42.

Kemp, C., & Regier, T. (2012). Kinship categories across languages reflect general communicative principles. *Science*, 336, 1049–1054.

Kiparsky, P. (1983). Word-formation and the lexicon. In *Proceedings of the 1982 mid-america linguistics conference* (Vol. 3, p. 22).

Kirby, S., Cornish, H., & Smith, K. (2008). Cumulative cultural evolution in the laboratory: An experimental approach to the origins of structure in human language. *Proceedings of the National Academy of Sciences*, 105, 10681–10686.

Labov, W. (2006). *The social stratification of english in new york city*. Cambridge University Press.

Levinson, S. C. (2000). *Presumptive meanings: The theory of generalized conversational implicature*. MIT Press.

Lewis, Sugarman, E., & Frank, M. C. (2014). The structure of the lexicon reflects principles of communication. In *Proceedings of the 36th Annual Meeting of the Cognitive Science Society*.

Lewis, D. (1969). *Convention: A philosophical study*. Harvard University Press, Cambridge, Mass.

Mahowald, K., Fedorenko, E., Piantadosi, S., & Gibson, E. (2012). Info/information theory:

- speakers actively choose shorter words in predictable contexts. *Cognition*.
- Markman, E., & Wachtel, G. (1988). Children's use of mutual exclusivity to constrain the meanings of words. *Cognitive psychology*, 20, 121–157.
- Markman, E., Wasow, J., & Hansen, M. (2003). Use of the mutual exclusivity assumption by young word learners. *Cognitive Psychology*, 47, 241–275.
- Mills, E. S. (1967). An aggregative model of resource allocation in a metropolitan area. *The American Economic Review*, 197–210.
- Peirce, C. (1931). *The collected papers of charles s. peirce* (P. W. C. Hartshorne & A. Burks, Eds.). Cambridge: Harvard University Press.
- Piantadosi, S., Tily, H., & Gibson, E. (2011a). The communicative function of ambiguity in language. *Cognition*.
- Piantadosi, S., Tily, H., & Gibson, E. (2011b). Word lengths are optimized for efficient communication. *Proceedings of the National Academy of Sciences*, 108, 3526–3529.
- Regier, T., Kay, P., & Khetarpal, N. (2007). Color naming reflects optimal partitions of color space. *Proceedings of the National Academy of Sciences*, 104, 1436–1441.
- Regier, T., Kemp, C., & Kay, P. (2014). Word meanings across languages support efficient communication.
- Saussure, F. (1916). Course in general linguistics, trans. *London: Peter Owen*.
- Scott-Phillips, T. C., Kirby, S., & Ritchie, G. R. (2009). Signalling signalhood and the emergence of communication. *Cognition*, 113, 226–233.
- Senghas, A., Kita, S., & Özyürek, A. (2004). Children creating core properties of language: Evidence from an emerging sign language in Nicaragua. *Science*, 305, 1779–1782.
- Sherif, M. (1935). A study of some social factors in perception: Chapter 3. *Archives of Psychology*, 27, 23-46.

- Smith, N. J., Goodman, N., & Frank, M. (2013). Learning and using language via recursive pragmatic reasoning about other agents. In *Advances in Neural Information Processing Systems* (pp. 3039–3047).
- Trude, A. M., & Brown-Schmidt, S. (2012). Talker-specific perceptual adaptation during online speech perception. *Language and Cognitive Processes*, 27, 979–1001.
- Xu, F., & Tenenbaum, J. B. (2007). Sensitivity to sampling in bayesian word learning. *Developmental Science*, 10, 288-297.
- Xu, Y., & Regier, T. (2014). Numeral systems across languages support efficient communication: From approximate numerosity to recursion. *Proceedings of the 35th Annual Meeting of the Cognitive Science Society*.
- Zipf, G. (1936). *The psychobiology of language*. Routledge, London.
- Zipf, G. (1949). Human behaviour and the principle of least effort. *Cambridge, Mass*.