Communicative pressure can leads input that supports language learning

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Abstract

Infants prefer to listen to and learn better from child-directed speech. This speech might support learning in part due to communicative pressure: parents must use language that their children understand. We designed a Mechanical Turk study to experimentally validate this idea, putting Turkers in the role of parents talking with children who knew a novel language less well. Participants could communicate in 3 ways: pointing—expensive but unambiguous, labelling—cheap but knowledge-dependent, or both. They won points only for communicating successfully; using pointing and labelling together was costly, but could teach, allowing cheaper communication on later trials. Participants were modulated their communicate behavior in response to their own and their partner's knowledge and teaaching emerged when the speaker had substanially more knowledge of the lexicon. While language is more than reference games, this work validates the hypothesis that communicative pressure alone can lead to supportive language input.

Keywords: Language; Child-Directed Speech; POMDP.

Introduction

One of the most striking aspects of children's language learning is just how quickly they master the complex system of their natural langauge (Bloom, 2000). In just a few short years, children go from complete ignorance to conversational fluency that is the envy of second-language learners attempting the same feat later in life (Newport, 1990). What accounts for this remarkable transition?

One possiblility is that children's caregivers deserve most of the credit; that the language parents produce to their children is optimized for teaching. Although there is some evidence that aspects of child-directed speech support learning, other aspects–even in the same subproblem, e.g. phoneme discrimination–appear to make learning more difficul (Eaves Jr, Feldman, Griffiths, & Shafto, 2016; McMurray, Kovack-Lesh, Goodwin, & McEchron, 2013). In general, parents rarely explicitly correct their children, and children are resistant to the rare explicit language correction they do get (Newport, Gleitman, & Gleitman, 1977). Thus while parents may occasionally offer a supervisory signal, the bulk of the evidence suggests that parental supervision is unlikely to explain rapid early language acqusition.

Alternatively, even the youngest infants may already come to language acquisition with a precocious ability to learn the latent structure of language from the statistical properties of speech in their ambient environment (Saffran & 2003, 2003; L. B. Smith & Yu, 2008). While a number of experiments clearly demonstrate the early availability of such mechanisms, there is reason to be suspicious about just how precocious they are early in development. For example, infants' ability to track the co-occurrence information connecting words to their referents appears to be highly constrained by both their developing memory and attention systems (L. B. Smith & Yu, 2013; Vlach & Johnson, 2013). Further, computational models of these processes show that the rate of acquisition is highly sensitive to variation in environmental statistics (Blythe, Smith, & Smith, 2010; Vogt, 2012). Thus precocious unsupervised statistical learning also appears to fall short of an explanation for rapid early language learning.

We explore the consequences of a a third possibility: The language that children hear is neither designed for pedagogy, nor is it random; it is designed for communication (Brown, 1977). We take as the caregiver's goal the desire to communicate with the child, not about language itself, but instead about the world in front of them. To succeed, the caregiver must produce the kinds of commincative signals that the child can understand, and thus might tune the complexity of their speech not for the sake of learning itself, but as a byproduct of in-the-moment pressure to communicate successfully (Yurovsky, 2017).

We explore the emergence of tuning in a simple model system: an iterated reference game in which two players earn points for communicating successfully with each-other. On each round of the game, participants can point–a signal which is costly to produce but always communicatively effective, or can use language–a cheaper signal which is cheap to produce but successful only if both players share a common lexicon. Crucially, participants can point and speak together–paying the cost of both, but effectively establishing a shared label for this referent that they can exploit on later trials of the game.

In a series of experiments on Mechanical Turk, we show that people tune their communicative to choices to varying cost and reward structures, and also critically to their partner's linguistic knowledge–teaching when partners are unlikely to know language and many more rounds remain. We then show that human behavior can be explained by a rational planning model that seeks to optimize its total expected utility over the course of the game. Together, these these data show that pedagogically-supportive input can arise from purely selfish motives to maximize the cost of communicating successfully while minimizing the cost of communication. We take these results as a proof of concept that both the features of child-directed speech that support learning as well as those that inhibit it may arise from a single unifying goal: The desire to communicative efficiently.

Experimental Framework

To study the emergence of pedagogy from communicative pressure, we developed a simple reference game in which participants would be motivated to communicate successfuly.

After giving people varying amounts of training on novel names for 9 novel objects, we asked them to play a communicative game in which they were given one of the objects as their referential goal, and they were rewarded if their partner successfully selected this referent from among the set of competitors (Figure 1). Participants could choose to refer either using the novel labels they had been exposed to, or they could use a deictic gesture to indicate the referent to their partner. Deixis was unambiguous, and thus would always succeed. However, in order for language to be effective, the participant and their partner would have to know the correct novel label for the referent. Across participants, we varied the relative cost of using these two communicative signals.

If people are motivated to communicate successfully, their choice of referential modality should reflect the tradeoff between the cost of producing the commmunicative signal with the likelihood that the communication would succeed. We thus predicted that peoples' choice of referential modality would reflect this calculus: People should be more likely to use language if they have had more exposures to the novel object's correct label, and they should be more likely to use language as gesture becomes relatively more costly.

Over the course of three experiments, 705 participants were recruited to play our reference game via Amazon Mechanical Turk, an online platform that allows workers to complete surveys and short tasks for payment. In these studies, all particpants were placed in the role of speaker and listener responses were programmed.

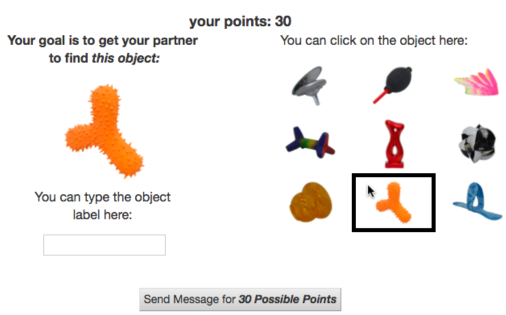

Figure 1: Screenshot of speaker view during gameplay.

Experiment 1

In this experiment, we explicitly implemented strategy utility by assigning point values to each strategy.

Participants, Materials, Methods 60 particpants were recruited though Amazon Mechanical Turk and received a small payment for their participation. Data from 9 participants was excluded from subsequent analysis for failing the manipulation check or for producing psedoenglish labels (e.g., 'pricklyyone').

Participants were told they would be introduced to novel object-label pairs and then asked to play a communication game with a partner wherein they would have to refer to a particular target object. Particpants were exposed to nine novel objects, each with a randomly assigned pseudoword label. We manipulated the degree of exposure within subjects, such that, during training, particpants saw three of the nine object-label mappings four times, two times, or one time, resulting in a total of 21 training trials. Participants were then given a simple recall task to establish their baseline knowledge of the novel lexicon.

After being introduced to the rules of the game, participants were told they would be asked to communicate about each object three times. During gameplay, speakers saw the target object in addition to an array of all nine objects. Speakers had the option of either directly selecting the target object from the array (gesture)- a higher cost cue but without ambiguity- or typing a label for the object (speech)- a lower cost cue but contingent on the listener's knowledge. After sending the message, speakers are shown which object the listener selected.

If the speaker clicked on on object (gesture message), the listener was coded to simply make the same selection. If the speaker typed an object label, the listener evaluated the Levenshtein distance (LD) between the typed label and each of the nine possible labels and selected the candidate with the smalles edit distance. If none of the nine object labels had an LD less than or equal to two, the listener always selected an incorrect object.

Speakers could win up to 100 points per trial if the listener correctly selected the target referent based on their message. If the listener failed to identify the target object, the speaker received no points. We manipulated the relative utilities of each of the strategies between-subjects. In the 'Talk is Cheap' condition, speakers recieved 30 points for gesturing and 100 points for labeling, while in the 'Talk is Less Cheap' condition speakers recieved 50 points for gesturing and 80 points for labeling.

Results As expected, particpants were sensitve to both the exposure rate and the relative utilities of the communication strategies. A simple logistic regression was used to predict whether speakers chose to produce a gesture or a label during a given trial. There was a signficant effect of exposure rate such that the more exposures to a particular object-label pair during training, the more likely a speaker was to produce a label (...). The more exposures to a given object-label pair during training, the more likely participants were to recall that label at pretest (...). The effect of exposure rate on modality choice held even after controlling for pretest knowledge, indicating the effect was more than the result of being constrained by knowledge of the label (...).

Participants also modulated their communicative behavior on the basis of the utility manipulation. Speakers in the Talk is Cheap condition produced significantly more labels than particpants in the Talk is Less Cheap condition (...). Thus, participants are senstive to our manipulations- altering their choices about how to communicate with their partner on the basis of their own knowledge, the degree of training, and the imposed utilities.

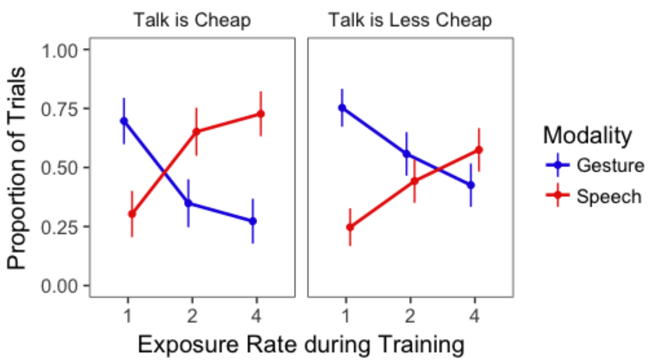

Figure 2: Plot of modality choice as a function of exposure, split by utility condition.

Experiment 2

XX planning figure HERE

Thus far, we have focused on relatively straightforward scenarios to demonstrate that a pressure to communicate successfully in the moment can lead speakers to trade-off between gesture and speech sensibly. However, critical to these repeated interactions is the ability to learn about an interlocuter and potentially influence their learning. In Experiment 2, particpants were told about a third type of message using both gesture and speech within a single trial to effectively teach the listener an object-label mapping. This strategy necessitates making inferences about the listner's knowledge state, so we also manipulated listner knowledge in Experiment 2.

Participants, Materials, Methods

240 particpants were recruited though Amazon Mechanical Turk and received a small payment for their participation. 40 participants were run in each of 6 different condtions, crossing our utility manipulation (the same descirbed in Experiment 1) and our partner knowledge manipulation (where we told speakers that the listner had seen the object-label pairs zero times, half as many times as the speaker, or twice as many times as the speaker). 39 participants were excluded from the final analysis for failing to respond correctly to the manipulation check, producing pseudoenglish labels, or producing nonsense labels (e.g., "xhlfjh").

In order to produce teaching beahvior, speakers had to pay the cost of producing both cues, yeilding 30 points in either conditon of our explicit points framework. Our communicative game was designed to reward in-the-moment communication, and teaching required the speaker paying a cost upfront. However, rational communicators may understand that if one is accounting for future trials, paying the cost upfront to teach the listener allows a speaker to use a less costly message strategy on subsequent trials.

Incorporating teaching means that our speaker must now reason about their interlocuter's knoweldge state more explicitly, in order to make rational decisions about what to teach and when. To address this added dimension, we also manipulated participants expectations about their partner's knowledge. Prior to beginning the game, participants were told that there partner had no experience with the lexicon, had half the experience of the speaker, or had twice the experience of the speaker.

Listeners starting knowledge state were also initialized accordingly. Listners with no exposure were given no knowledge of the lexicon to start. Listners with half the exposure of the speaker began with knowledge of three object-label pairs (2 high frequency, 1 mid frequency), based the average retention rates found previously. Lastly, the listener with twice as much exposure as the speaker began with perfect knowledge of the lexicond, again based on the average retention rates. Through gesture-speech co-occurance, the speaker could effectively teach the listener a novel mapping. Listners could learn a novel mapping from one teaching event in this game and integrate it into their set of candidate words when evaluating the LD of subsequent labels.

Results

As predicted, mixed effects logistic regression predicting whether or not teaching occured on a given trial revealed that teaching rates across conditions depend on all of the same factors that predict speech and gesture. There was a signficant effect of intial exposure to the mapping on the rates of teaching, such that more exposures to a word predicted higher rates of teaching behavior (B = 0.09, p = 0.045). There was also a signficant effect of the utility manipluation such that being in the Talk is Less Cheap condition predicted lower rates of teaching than being in the Talk is Cheap condtion (B = -0.98, $p < 0.01$), a rational response considering the eventual benefit for teaching a novel word is less strong in this former condition.

We also included whether this was an objects first, second, or third appearance as a predictor in our model. The expected utility of teaching on a given trial should decrease as there are fewer subsequent trials for that object, thus we predicted that teaching rates would drop dramatically. Indeed, this is consistent with the results from our model; compared with the first appearance of an object, speakers were significantly less likely to teach on the second appearance (B = -1.11, $p < 0.001$) or the third appearance (B = -2.01, $p < 0.001$).

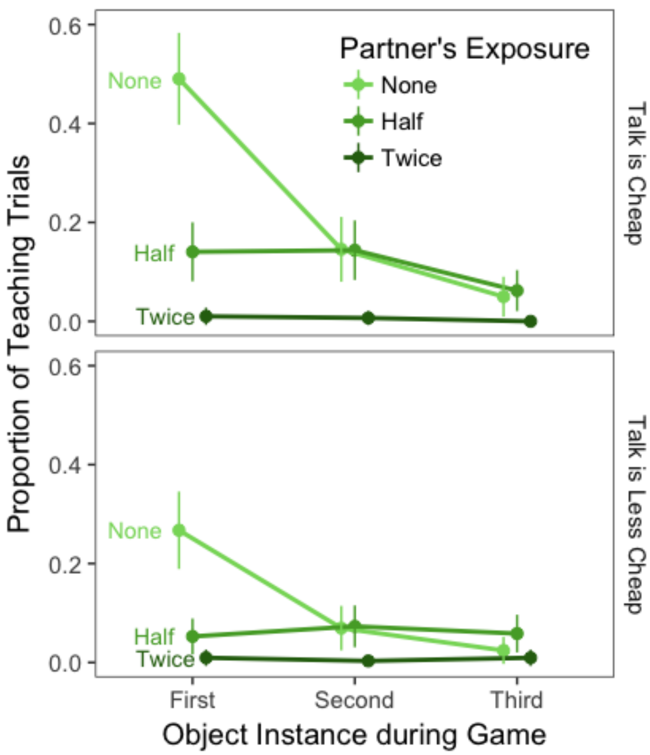

Figure 3: Proportion of teaching behavior as a function of whether it was the first, second, or third appearance of a given target, split by partner's level of exposure.

Interestingly, as we expected, there was a signficant effect of our manipulation of listener knowledge. Compared with listner's with no experience with the lexicon, speakers were signifcantly less likely to teach when they were told the listner had half as much exposure (B = -1.19, $p < 0.01$) or twice as much exposure as they themselves did (B = -4.64, $p < 0.001$).

Experiment 3

As a replication and extension of experiments 1 and 2, we sought to embed the relative utilites of the communicative strageies in the gameplay more implicitly. In experiment 3, we used the same procedure described above; however, a timer controlled the number of points that were earned on each trial of gameplay (Figure 4). Rather than impose an explicit point system as in experiments 1 and 2, we set the relative utilities of communication strategies by manipulating the speed with which particpants could respond.

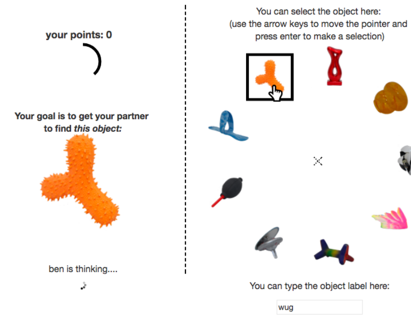

Figure 4: Screenshot of speaker view during gameplay in the Experiment 3 version.

Participants, Materials, Methods

405 particpants were recruited though Amazon Mechanical Turk and received a small payment for their participation. 45 participants were run in each of 9 conditions, again crossing partner knowledge (none, half as much, twice as much) with our utility manipulation (pointing is normal, slow, or slowest). The responses from 128 participants were excluded for failing to meet our manipulation check, using pseudoenglish labels, or using non-sense labels.

Experiment 2 utilitzed the same training and pretest procedures, but gameplay differed in a number of ways. During the game, the nine novel objects were arranged in a circle around a cartoon pointer (see Figure 4). To manipulate the relative speeds of gesturing and labeling, we required speakers to move the small pointer with the arrow keys on their keyboards in order to select an object with gesture. With this method we could directly manipulate the speed of the pointer while holding the arrow keys to effectively set maximum possible utility of using gesture.

If the listner correctly identified the target object, speakers recieved points determined by the amount of time remaining on the timer. For successful communications, speakers always recieved a minimum of 10 points, regardless of the time elapsed. Based on pilot response times, the timer was set to 6.5 seconds and points were scaled to match experiments 1 and 2. Participants were randomly assigned into one of three conditions, where the pointer was set to either a normal, slow, or slowest setting.

This framework allowed us to implement the point system as an implicit extension of gameplay and resulted in each partipcant having unique gesture-speech utilities, based on their speed of responses across the two methods.

Results

As expected, the same patterns emerge as experiments 1 and 2. Speakers again labeled signifcantly more (TBD) and gestured significantly less (TBD) on high exposure targets, relative to low exposure targets. Particpants were signficantly more likely to recall the high exposure labels than the low exposure labels at pretest (TBD), and this effect did not account the effect of exposure rate on modality choice (TBD).

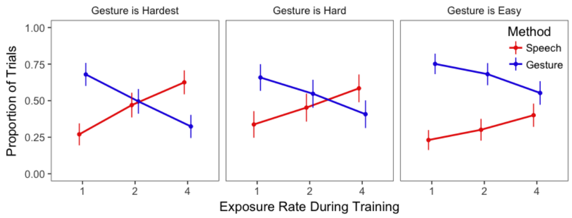

Figure 5: Screenshot of speaker view during gameplay in the Experiment 3 version.

Critically, there was a main effect of our utility manipulation, such that speakers in the fast pointer condition produced signficantly more gestures than particpants in the slowest pointer condition (TBD). The pattern is reveresed for labeling (TBD). In the absence of an explicit framework for assigning utilities based on method, speakers continue to adapt their communicative choices taking into account the expected utility of possible strategies.

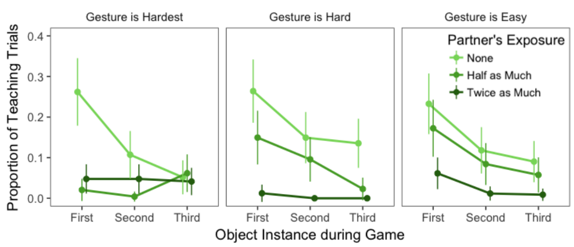

Figure 6: Screenshot of speaker view during gameplay in the Experiment 3 version.

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We investigated the emergence of teaching in both a paradigm with an explicit points system (Experiment 2) and an implicit points system (Experiment 3).

Model: Iterated Communication as Rational Planning

The results from these experiments are qualitatively consistent with a model in which participants make their communicative choices to maximize their expected utility from the reference game. We next formalize this model to determine if these results are predicted quantitatively as well.

In a one-shot reference game, like Experiment 3, maximizing expected utility is simply choosing the action (a) that has the highest expected utility ($\mathbb{E}[U]$). The expected utility depends both on the action itself, and on the state of the two partners (s): For pointing, this expected utility is independent of referent, defined entirely by our experimental manipulation. In contrast, for speech, the utility varies with the probability of partners sharing a common label for the referent. Following other models in the Rational Speech Act framework, we use the Luce Choice Axiom, in which each choice is taken in probability proportional to its exponentiated utility (Frank & Goodman, 2012). This choice rule has a single paramter α that controls the noise in this choice–as α approaches 0, choice is random and as α approaches infinity choice is optimal:

$$C(a;s) \propto e^{\alpha \mathbb{E}[U(s,a))]}$$

To use this rule, agents have to estimate how likely they are to share a common label (s). In our simulation, we assume for simplicty that people have an accurate representation of their own knowledge. We thus set each simulated participant's knowledge to the explicit recall judgement made by a real participant in our experiments. To estimate their partner's knowledge, participants can reason about their own learning. Again for simplicity we model learning as a simple Bernoulli process: Each exposure to novel label is like a flipping a coin with weight p, if it comes up heads, the label is learned. Having observed their own learning outcomes, agents can infer their own learning rate by determining the weight p' under which their observed learning is most likely. Assuming that their partner would have learned at the same rate, participants can then generate a probabiliy with which their partner would have learned each label by estimating the probability that at least one of its n came up heads given learning rate p': $P(s^+) = 1 - p'(1-p')^n$.

In an iterated game, however, because actions taken on the current trial can influence the state (s) on future trials, the optimal action to take is not the one that optimizes the single trial's rewards, but rather the one that optimizes the expected rewards that will accumulate over all future trials (Kaelbling, Littman, & Cassandra, 1998).

For the results reported here, we set $\alpha = 2$ based on hand-tuning, but other values produces similar results.

We implemented a two-agent model of speaker and listener behavior in this game based on partially observable Markov decision processes. The speaker is given a target referent each trial and must signal to the listener which object to select. Speakers send messages to the listener by speaking, a low cost cue that relies on the listener's knowledge, or by pointing, a higher cost cue that is unambiguous.

The speaker estimates the listener's knowledge. First, the speaker uses Markov chain Monte Carlo to infer their own learning rate based on how well they were able to learn a novel lexicon after N exposures. Then, given the listner's degree of exposure, the speaker can use their own learning rate to infer the probability that the listener would know any given object-label mapping. Across trials, the speaker gains further information about the listener through their selections, allowing them to update their beliefs about the listener's knoweldge state.

The model specifies the relative costs for each communicative modality. On each trial, the speaker estimates the expected utility of each modality by accounting for these costs, their own knowledge of the object's label, and the probability that the listner knows the object's label. The speaker then uses Luce's choice axiom to select a communicative modality based on the expected utilities.

When estimating expected utility, the model sums the expected utility of a given trial and any remaining trials for that particular object. This allows the speaker to engage in planning by accounting for the way a given message may induce knowledge changes and thus affect subsequent expected utilities. Utilites were scaled using an exponential discounter as a function of delay (Do we want to cite a precedent for this?) to give greater weight to immediate rewards than subsequent rewards.

Crucially, speakers can also combine both communication cues, paying the upfront cost of both, to produce a message that is both unambiguous and informative. In this way, speakers are able to teach their partners object-label mappings. A speaker that plans may thus infer that teaching the listener, especially if there is an asymmetry in their knowledge states, may have a high expected utility after accounting for remaining trials where the speaker could use a less costly cue (i.e. speech). After producing both cues, the speaker also updates their own beliefs about the partner's knowledge state to reflect this exposure.

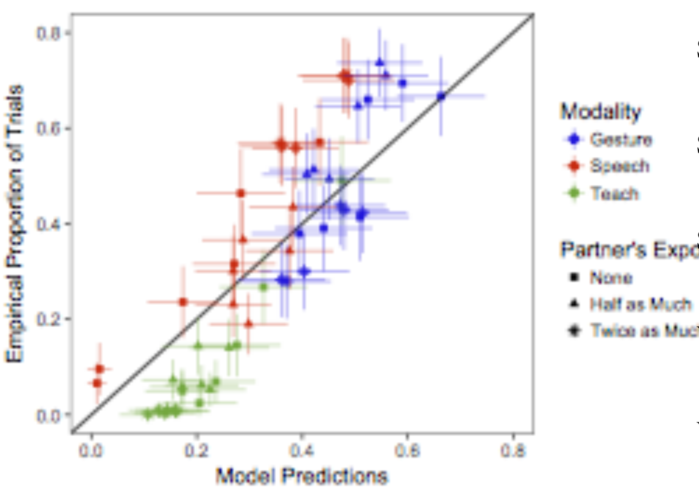

Figure 7: Plot of the fit between model predictions and empirical data.

Discussion

Acknowledgements

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