

Learning about Others: Pragmatic Social Inference through Ambiguity Resolution

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Abstract

We investigated whether ambiguity resolutions may yield socially-relevant benefits, revealing parts of the privileged ground of the interpreter. In particular, we asked if speakers can (i) use response observations to infer unknown preferences of a listener, and (ii) strategically chose ambiguous utterances for learning about those preferences. We ran experiments in a reference game framework and modeled the data with a pragmatic social inference Rational Speech Act model. Participants were able to infer listeners' preferences when analyzing their choice of objects given referential ambiguity. Moreover, nearly 40% of the speakers were able to strategically choose ambiguous over unambiguous utterances in an epistemic, event-predictive, goal-directed manner. Surprisingly, an equally-large number of participants systematically preferred unambiguous utterances. We conclude that ambiguity resolutions indeed reveal aspects of the knowledge, preferences, and beliefs of our conversation partners and some of us are able to strategically use ambiguous utterances to gain knowledge about these aspects.

Keywords: ambiguity; pragmatics; information gain; event-predictive cognition; Rational Speech Act models; social intelligence

Active inference—that is, the anticipatory, goal-directed, and epistemic invocation of behavior—is closely linked to the predictive mind perspective (Friston et al., 2015; Hohwy, 2013; Clark, 2016). The anticipatory nature of the human mind reveals itself in many domains. With respect to planning and executing manual sensorimotor interactions, it has been shown that we anticipate future events and event boundaries, revealing anticipatory, event-predictive active inference processes (Belardinelli, Stepper, & Butz, 2016; Belardinelli, Lohmann, Farnè, & Butz, 2018; Friston et al., 2015; Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Lohmann, Belardinelli, & Butz, 2019). Also in the language domain, active inference processes seem to continuously unfold (Christiansen

1 & Chater, 2016), compressing information into event-like units of thought (Baldwin &
2 Kosie, 2019; Gärdenfors, 2014). For example, neurophysiological data has shown
3 that listeners predict the semantic category of upcoming words (Federmeier & Kutas,
4 2002). Moreover, the inference process takes the structural properties of sentences into
5 account (Levy, 2008). Dynamic language models show that complex, event-predictive
6 structures guide ambiguity resolution during comprehension and likely also constrain
7 ambiguity generation during language production (Elman & McRae, 2019).

8 When systematic abstractions become relevant, event-predictive biases seem to be
9 at play, invoking the tendency to compress sensorimotor experiences, including lan-
10 guage, into event-predictive encodings (Baldwin & Kosie, 2019; Butz, 2016, 2017;
11 Shin & DuBrow, 2019). Various disciplines associated with cognitive science suggest
12 that our minds develop event-compressed predictive encodings, which are recruited
13 during decision making and action generation, including language production and com-
14 prehension, essentially determining thought itself in a highly active, epistemic, goal-
15 directed manner (Baldwin & Kosie, 2019; Shin & DuBrow, 2019; Elsner & Adam,
16 2019; Knott & Takac, 2019; Ünal, Ji, & Papafragou, 2019; Stawarczyk, Bezdek, &
17 Zacks, 2019). Here, we reveal socially epistemic comprehension and utterance pro-
18 ductions in scenarios where we observe and actively generate social event-predictive
19 interactions.

20 In two main studies, we show how speakers update predictive models of the lis-
21 tener’s preferences and beliefs when watching social event interactions, such as when
22 offering a few objects to choose from and observing the object choice of the conversa-
23 tion partner. We thus show that humans can interpret behavior of other people as driven
24 by their motives, intentions, or personal characteristics. Conceptually, this idea goes
25 back to the attribution theory (Jones & Davis, 1965; Kelley, 1967; Kelley & Stahel-
26 ski, 1970). More recently, Shafto, Goodman, and Frank (2012) developed a Bayesian
27 model of learning that formalizes the process of inferring others’ knowledge about the
28 world based on their actions and goals. They argue that efficient learning is possible
29 if we assume that agents’ actions are driven either by physical (non-social) or commu-
30 nicative goals, but are crucially not random. The authors show that an observer can
31 draw stronger inferences concerning an underlying hypothesis when the acting agent
32 has a communicative goal. The developed model predicts that learners use knowledge
33 of agents’ goals to evaluate how knowledgeable they are, and, as a consequence, how
34 much a learner can trust their actions to be informative about a hypothesis.

35 While our model also pursues Bayesian inference, or “psychological reasoning”,
36 we do not focus on the inference of the actor’s knowledge, that is, on *learning from*
37 *others* (Shafto et al., 2012). Rather, we focus on *learning about others*, that is, learning
38 about listeners’ preferences when observing their disambiguating behavioral responses.
39 We explore interpretive choices and the potential strategic, socially epistemic usage of
40 ambiguous utterances in anticipation of actors’ responses. To formalize our hypothesis,
41 we adapt the Rational Speech Act model framework, reliably modeling the involved,
42 probabilistic interpretation processes and socially epistemic action choice. Interest-
43 ingly, the modeling results reveal good interpretive abilities but also strong individual
44 differences when the task is to choose (ambiguous) utterances strategically for gaining
45 social knowledge.

46 We use ambiguity resolution as a paradigm in which learning about others is possi-
47 ble. Intuitively, ambiguity should make understanding each other difficult. If a speaker
48 and a listener understand an ambiguous utterance differently, communication between
49 them might fail. On rare occasions, such communication failure can even be deadly:
50 Pinker (2015) alludes to the Charge of the Light Brigade during the Crimean War as

1 an example of a military disaster that was caused by vague orders. He also mentions
2 how poor wording on a warning light was responsible for the nuclear meltdown at
3 Three Mile Island. Finally, citing Cushing (1994), Pinker describes how the deadliest
4 plane crash in history resulted from pilots and air traffic controllers arriving at different
5 interpretations of the phrase “at takeoff”.

6 Given that ambiguity can hinder the efficient transfer of information between con-
7 versation partners, it is not surprising that linguists have treated the possibility for am-
8 biguity as a bug in the communication system (Grice, 1975; Chomsky, 2002). The
9 attitude towards ambiguity has been quite different in other disciplines, in part because
10 the term itself can refer to multiple phenomena. For linguistic research, a word is am-
11 biguous if it can have two separate meanings even in the absence of context, simply as
12 a linguistic sign. In that sense, the word “bat” is ambiguous between a winged mammal
13 and a sporting implement. In organizational communication—communication that aids
14 production—ambiguity aligns closely with underspecification: an utterance is ambigu-
15 ous when it does not provide every detail about the intended meaning, leaving room
16 for the listener to interpret it. In the case of referential ambiguity, an ambiguous utter-
17 ance may apply to several possible referents in a scene. For example, a pronoun can be
18 referentially ambiguous if there are multiple potential antecedents in the context. It is
19 the latter type of ambiguity that we are concerned with in this paper.

20 More recent research has begun to take notice of the efficiency ambiguity affords
21 us: by relying on context to fill in missing information, we can reuse lightweight bits
22 of language rather than fully specifying the intended message (Levinson, 2000; Pianta-
23 dosi, Tily, & Gibson, 2012; Wasow, 2015). Viewed in this way, ambiguity serves as
24 a feature—not a bug—of an efficient communication system. This reasoning accords
25 with years of psycholinguistic research documenting that speakers readily produce am-
26 biguous utterances (see Ferreira, 2008, for an overview). Along related lines, Wasow
27 (2015) reviews a large body of evidence and concludes that ambiguity is rarely avoided,
28 even in situations where its avoidance would be communicatively appropriate. This ob-
29 servation stands at odds with the Gricean maxim to avoid ambiguity (Grice, 1975).

30 In search of the communicative purpose of ambiguous language, the current work
31 identifies an additional benefit: the *extra* information we gain from observing how
32 listeners resolve ambiguity. We show that language users learn about each other’s pri-
33 vate knowledge when observing how ambiguity is resolved. When utterances leave
34 room for interpretation, listeners must draw on their opinions, beliefs, and preferences
35 to fill in the gaps; by observing the concrete interpretation, speakers thus learn about
36 the opinions, beliefs, and preferences of their conversation partner. As a result, in a
37 naturalistic conversation, where speakers take turns, ambiguous utterances open in-
38 terpretation spaces and the resulting interpretation choices dynamically and mutually
39 reveal individual opinions, beliefs, and preferences.

40 By way of illustration, take the scenario in Figure 1. Suppose a speaker produces
41 the single-word utterance “blue” – meaning choose a blue object – offering a referential
42 ambiguity, that is, a choice between a blue square and a blue circle to the listener. Sup-
43 pose further that, upon hearing “blue”, the listener selects the blue circle. In observing
44 this choice, the speaker learns something about the private thoughts of the listener:
45 what made her select the blue circle instead of the blue square? Perhaps the circle is
46 more salient to the listener, or the listener has a preference for circles, or the listener
47 may believe that the speaker has a preference for circles; there may even be mutual
48 agreement that circles are to be preferred when possible. Importantly, by observing
49 how the listener resolves the ambiguity in reference, the speaker can learn something
50 about the private thoughts of the listener.

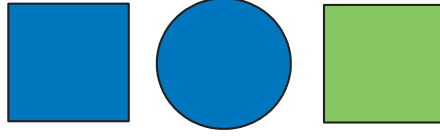


Figure 1: A simple reference game scenario from Frank and Goodman (2012). In the game, speakers are confronted with a collection of objects, which determine the current scenario S , where $S = \{\text{solid blue square}, \text{solid blue circle}, \text{solid green square}\}$ in the depicted example. A speaker may choose a single-word utterance u to signal one of the objects $s \in S$ to a listener. In the shown scenario, the speaker may choose one of the possible utterances $u \in U = \{\text{“blue”}, \text{“green”}, \text{“square”}, \text{“circle”}\}$.

However, accessing this added information requires the speaker to reason pragmatically about the pragmatic reasoning of the listener—a higher-order pragmatic reasoning. In order to select a referent, the listener must interpret the utterance. We follow Frank and Goodman (2012) in treating this interpretation process as active pragmatic, probabilistic reasoning: the listener interprets an utterance by reasoning about the process that generated it, namely the speaker, who selects an utterance by reasoning about how a listener would interpret it. Frank and Goodman model this recursive social reasoning between speakers and listeners introducing a Rational Speech Act (RSA) modeling framework (see Methods section for a detailed formal introduction)

The current paper builds on this foundational, vanilla RSA model of reference games by introducing uncertainty about the prior beliefs of the listener and modeling a speaker who reasons about these beliefs. In particular, the model infers belief posteriors about the hypothetical object type preferences of the listener interpreting their observed referent choices. Moreover, the model actively infers socially epistemic utterance values in anticipation of the potential referent choices considering each possible, partially choice-constraining, utterance.

The main contributions of this paper are two-fold: first, we demonstrate that participants are indeed able to infer hidden beliefs of their conversation partners observing their choices; second, we show that some speakers can actively create situations of uncertainty anticipating the epistemic value when observing the consequent referent choice. We formalize the human communicative behavior in a probabilistic Bayesian model, which approximates the dynamically unfolding reasoning processes, including limits thereof.

Results

Before we report the results and modeling insights from our socially pragmatic and event-epistemic experiments, we introduce our novel pragmatic social inference RSA model.

Pragmatic social inference RSA model

Our model builds on the vanilla version of RSA presented above, modifying the listener’s state prior $P(s)$ and enhancing the reasoning process towards a social component, yielding a *pragmatic social inference RSA* model (PSIRSA). By changing

$P(s)$ to a non-uniform distribution, we essentially model prior beliefs of which object the speaker is more likely to refer to, or—when viewed from a more self-centered perspective—which prior object feature preferences f the listener may have. For example, the listener may like blue things, such that she may be more likely to choose the blue square instead of the green one when hearing the utterance “square” in the scenario shown in Figure 1. As a result, when a pragmatic speaker produces utterance u and observes the listener’s referent choice s , the speaker may infer posteriors over possible feature preferences, attempting to explain the observed object choice in this way.

We use L_0 and S_1 from the vanilla model, but we now parameterize L_1 ’s state prior such that it operates given a feature preference f :

$$P_{L_1}(s | u, f) \propto P_{S_1}(u | s) \cdot P(s | f). \quad (1)$$

We then model a pragmatic speaker S_2 , who updates beliefs about L_1 ’s preferences, $P(f)$. S_2 observes L_1 ’s choice of s given the produced utterance u and then reasons about the likely feature preference f that L_1 used to make the observed choice:

$$P_{S_2}(f | u, s) \propto P_{L_1}(s | u, f) \cdot P(f). \quad (2)$$

We also model the reasoning process by which a speaker may select the best utterance to learn about the preferences of the listener, essentially striving to maximize expected information gain concerning the listener’s feature preferences. Starting with no knowledge of the listener’s preferences, S_2 can be assumed to expect a uniform (i.e., flat) feature preference prior $P(f)$. The more the speaker’s posterior beliefs about the preferences, $P_{S_2}(f | u, s)$ deviate from the uniform prior, the more the speaker will have learned about the listener’s preferences. We can thus model this reasoning in light of expected information gain, which can be equated with the attempt to maximize the KL (Kullback-Leibler) divergence between the speaker’s flat prior and the expected posterior over the listener’s feature preferences f , integrating over all hypothetically possible object choices $s \in S$:

$$P_{S_2}(u) \propto \sum_{s: \llbracket u \rrbracket(s)=1} P_{L_1}(s | u, f) \exp(\lambda \cdot \text{KL}(P(f) || P_{S_2}(f | u, s))), \quad (3)$$

where the factor λ scales the importance of the KL divergence term.

We evaluate two versions of the model. fullPSIRSA assumes the deep reasoning process specified above. It thus assumes that feature preference inference not only considers the current object choices possible, but also differentiates the choice options further with respect to their pragmatic plausibility. For example, fullPSIRSA includes modeling the fact that when a speaker utters “blue” in the object situation depicted in the example in Figure 1 and has the intention to refer to one particular object, she is more likely to refer to the blue square than to the blue circle, because in the latter case the utterance choice “circle” would have been unambiguous and thus a better utterance choice.

Recently, it has been shown that even in the original, simpler reference games, fewer layers of reasoning often perform equally well or better than more complex RSA-based models (Sikos, Venhuizen, Drenhaus, & Crocker, 2019). Accordingly, simplePSIRSA removes the reasoning about alternative utterances and allows the pragmatic speaker to directly tap into the (expected) interpretation of L_0 , augmenting the literal listener’s choice likelihoods with the feature-preference-dependent object prior $P(s | f)$:

$$P_{L_0\text{-simp}}(s | u, f) \propto \llbracket u \rrbracket(s) \cdot P(s | f). \quad (4)$$

1 The pragmatic speaker $S_{1\text{-simp}}$ then reasons directly about the modified literal lis-
 2 tener $L_{0\text{-simp}}$:

$$3 \quad P_{S_{1\text{-simp}}}(f | u, s) \propto P_{L_{0\text{-simp}}}(s | u, f) \cdot P(f). \quad (5)$$

4 As a result, simplePSIRSA ignores any indirect pragmatic reasoning considerations
 5 about which object the speaker may refer to given an utterance and a particular object
 6 constellation. It simply assumes that all objects may be chosen that match the utter-
 7 ance, modifying these choice options dependent on the feature-preference-dependent
 8 object choice priors. The corresponding utterance-selection model also simplifies the
 9 reasoning process:

$$10 \quad P_{S_{1\text{-simp}}}(u) \propto \sum_{s: \llbracket u \rrbracket(s)=1} P_{L_0}(s|u, f) \exp(\lambda \cdot \text{KL}(P(f) || P_{S_{1\text{-simp}}}(f | u, s))), \quad (6)$$


11 In the evaluation section below, we compare the modeling performance of fullP-
 12 SIRSA with simplePSIRSA.

13 Experiment 1

14 Our first task is to check the inferences of the pragmatic speaker having observed that
 15 a listener selects some object s in response to an utterance u . Is it possible to draw
 16 inferences about the most likely preferences the listener had when making her choice?
 17 Can this inference process be modeled by PSIRSA—that is, by recursive, Bayesian
 18 generative modeling? A sample trial is shown in Figure 2.

Progress:

Suppose Maria wants to signal an object in the following scene to Samantha.
 Maria says "red" and Samantha chooses the outlined object:



Based on this choice, do you think Samantha has a preference
 for certain types of objects?

| | very unlikely | very likely | | very unlikely | very likely |
|---------------------|-----------------------|-------------|---------|-----------------------|-------------|
| solid things | <input type="range"/> | | clouds | <input type="range"/> | |
| striped things | <input type="range"/> | | circles | <input type="range"/> | |
| polka-dotted things | <input type="range"/> | | squares | <input type="range"/> | |

Continue

Figure 2: A sample trial from *Experiment 1: Inferring preferences*. Each trial portrays a speaker and a listener: the speaker produces an utterance to refer to one of the objects. The listener picks the object with the orange dotted outline. Participants were tasked with evaluating what preferences of the listener led her to the particular choice of object. They specify their inference by adjusting the sliders for each of the features.

Models with global optimization

We fit the following free parameters to optimized the predictions of the models. First, the full model includes a “greediness” parameter α that controls how likely participants are to choose an optimal utterance to signal an object to a speaker. This parameter is absent in the simple model since it relies on fewer layers of reasoning. The second parameter γ controls how soft the preferences are. Hard preferences enforce the choice of the preferred object type, while increasing softness converges towards no object preference. Similarly, the obedience parameter β allows subjects to choose objects that do not qualify for the utterance. As for the preference parameter γ , the β range includes hard obedience on the one side of the spectrum – for example, definitely choosing a blue object when hearing “blue” – and full ignorance of the utterance at the other extreme – for example, choosing uniformly from all available objects.

simplePSIRSA and fullPSIRSA with softness (γ) optimized globally provide nearly identically good fits to the data (Figure 3). Simple linear regression analysis was used to test whether the model values predicted the human data. simplePSIRSA yields a value of $r^2 = 0.8607^1$ ($F(1, 190) = 1181$)² when only softness parameter γ is optimized ($\gamma = 0.2204$ after optimization). When both parameters are optimized globally, a variance estimate of $r^2 = 0.9788$ ($F(1, 190) = 8823$) is reached ($\gamma = 0.2210$ and $\beta = 0.2693$ after optimization), indicating that participants indeed considered (possibly subconsciously) the option to interpret utterances non-literally. fullPSIRSA yields nearly identical values. When optimizing only the softness parameter γ , a value of $r^2 = 0.8568$ ($F(1, 190) = 1144$) is reached ($\gamma = 0.2231$). Optimizing both, α and γ , a value of $r^2 = 0.8607$ ($F(1, 190) = 1144$) is reached ($\alpha = 0.1797$, $\gamma = 0.2205$). When optimizing all three parameters, fullPSIRSA yields a value of $r^2 = 0.9772$ ($F(1, 190) = 8170$) ($\alpha = 0.2657$, $\gamma = 0.2214$, $\beta = 0.0030$). Overall, the results show that participants are indeed able to infer the feature preferences that lead to the choice of an object. Moreover, the higher model flexibility of fullPSIRSA—controlled via parameter α —does not yield any modeling improvement, implying that an approximation of the more shallow reasoning process modeled by simplePSIRSA typically unfolded in the minds of the participants.

Individually-fitted models

We now compare our two model variants further when fitting the parameters to the individual data of each participant separately. We optimized α and γ in the light of the KL divergence between the individual participants’ slider value choices and the corresponding model predictions for PSIRSA. We then again averaged the individualized model prediction values and participants’ slider values with respect to the particular ambiguity classes and calculated correlations between the data and the model.

The full model optimized at the individual level for the additional parameter α does not improve the fit compared to the simplified model (simplePSIRSA: $r^2 = 0.8631$, $F(1, 190) = 1205$; fullPSIRSA: $r^2 = 0.8627$, $F(1, 190) = 1201$). Seeing that both models again fit the data nearly equally well (if anything, simplePSIRSA performs slightly better), we will henceforth only consider the predictions of simplePSIRSA. Note further that the individually-fitted parameters do not improve the correlation values much, if at all, when compared to the globally-fitted model.

¹Here and throughout the paper we report adjusted r^2 values.

²All results were significant at $p < 0.001$ level if not stated differently in the text.

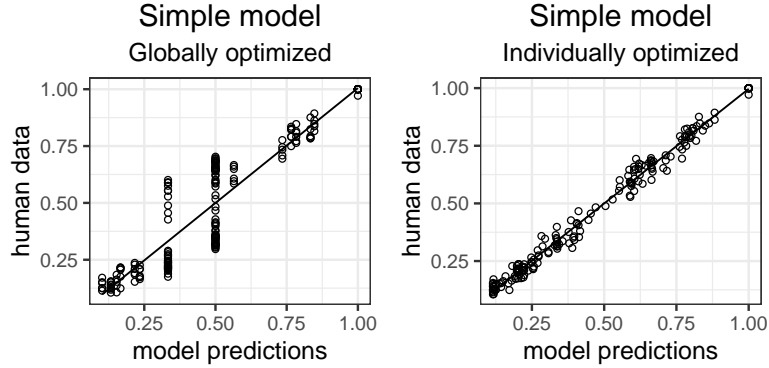


Figure 3: Human data from Experiment 1 plotted against the predictions of simplePSIRSA. Each data point indicates the slider values and model predicted feature preference posteriors for a particular ambiguity class. Left panel: γ optimized globally ($r^2 = 0.8614$); right panel: γ and β optimized individually with leave-one-out cross-validation ($r^2 = 0.9901$).

The model fit improves considerably when we additionally fit the obedience parameter β at the individual level. Here the model explains a large proportion of variance in the human judgments ($r^2 = 0.9919$, $F(1, 190) = 23480$). The likelihood ratio test (two-tailed) revealed that a γ - and β -optimized simplePSIRSA model provides a better fit compared to a model optimized only for γ ($G^2 = 237.36$, $df = 82$, $p < 0.01$). The more complex model contains one additional parameter β fitted for each subject, giving us 82 degrees of freedom. We additionally checked the generalizability of the model by performing leave-one-out cross-validation. Figure 3 shows that the resulting cross-validated model predictions retain the strong fit $r^2 = 0.99$, $F(1, 190) = 18910$.

To appreciate the gains obtained by fitting model parameters, Figure 4 shows the average responses of the human participants and of the individually-, two-parameter-optimized simplePSIRSA model and the non-optimized simplePSIRSA model for the scene type of the sample trial from Figure 2. In that trial, participants saw that the middle object was chosen following the utterance “red”. There are two potential referents for this description: the red striped cloud and the red dotted circle. Since the cloud was chosen, we infer that the person who chose this object has a preference for clouds over circles, and for striped objects over dotted ones. Note that we cannot learn anything about the preference for solid things or squares in this trial because these features are not present, thus we ignore the respective slider values. Moreover, we can definitely not learn anything about color preferences because the color was the uttered, thus sliders for those features were not present. As Figure 4 shows, both humans and the models assign high slider values to clouds and striped things, and low values to circles and dotted things. Indeed, even the non-optimized model fits the qualitative pattern of the results; optimizing β and γ improves the quantitative fit.

We thus find strong empirical support for simplePSIRSA, implying that speakers are indeed able to use listener behavior to acquire information about their preferences. We fail to find that the fullPSIRSA model predicts the data better. This result suggests that the task in our experiments does not require full-blown pragmatic inference about alternative utterances. The question now turns to whether speakers are able to capitalize on this reasoning when it comes to selecting utterances. In other words, are speakers

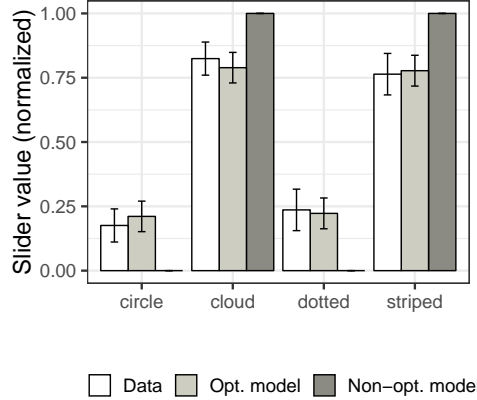


Figure 4: Human data and simplePSIRSA’s (individually-, two-parameter-optimized and non-optimized) feature preference posterior estimates for the scenario S shown in Figure 2.

1 aware that ambiguous language is potentially more informative?


2 Experiment 2: Choosing utterances to learn about others

3 Our next task is to check the predictions of our strategic utterance selection model:
 4 given a set of potential referents S , are participants able to reason pragmatically about
 5 the anticipated potential epistemic utility of utterances $u \in U$ in inferring the listener’s
 6 preferences? Figure 5 shows a sample trial, in which the speaker (“Katie” in the exam-
 7 ple) is to choose an utterance in order to learn about the listener’s preferences (“Eliza-
 8 beth” in the example). While the ambiguous utterances “cloud”, “green”, and “striped”
 9 may allow inferences about color & texture, shape & texture, and color & shape, res-
 10 pectively, the utterances “solid”, “blue”, and “circle” leave only one response option
 11 to the listener, such that the speaker cannot learn about the listener’s preferences when
 12 observing the listener’s response (assuming the listener obeys the speaker’s order).


13 By reasoning about the predictions of S_2 , we are able to use simplePSIRSA to com-
 14 pute the expected most informative utterance for inferring preferences. In other words,
 15 $P_{S_1\text{-simp}}(u)$ calculates the probability that a speaker would choose u for the purpose of
 16 inferring preferences.

17 To generate predictions from $P_{S_1\text{-simp}}(u)$, three free parameters can be identified:
 18 the preference softness γ , the obedience β , and a λ parameter, which factors the impor-
 19 tance of choosing the expected most informative utterance with respect to the expected
 20 KL divergence between preference priors and expected preference posteriors.

21 We compare simplePSIRSA with non-optimized parameters and with several pa-
 22 rameter optimizations with the performance of a uniform base model, which sim-
 23 ply chooses one of the available utterances at random. Seeing that in particular am-
 24 biguity cases with particular constellations S three up to nine utterances are possi-
 25 ble, the base model yields different model predictions for the available utterances in
 26 the respective ambiguity classes. As a result, the the uniform base model is much
 27 better in capturing variance in the data than one would expect without this insight
 28 ($r^2 = 0.7466$, $F(1, 82) = 245.6$, $p < 0.001$). Figure 6 compares this performance to
 29 the non-optimized simplePSIRSA, where we set the parameters to hard preference







Progress: 

Suppose Katie wants to learn about Elizabeth's preferences in the following scenario:



Katie can choose a single utterance and then watch Elizabeth select an object.

What should Katie say?

| | definitely not | definitely |
|-----------|---|------------|
| "cloud" |  | |
| "solid" |  | |
| "green" |  | |
| "striped" |  | |
| "blue" |  | |
| "circle" |  | |




Figure 5: A sample trial from *Experiment 2: Choosing utterances*.

1 and obedience ($\gamma = 0$, $\beta = 0$) and the information gain factor to $\lambda = 1$, thus pre-
 2 ferring to choose those utterances that are expected to yield high information gain.
 3 Surprisingly, this model captures very little variance in the human data ($r^2 = 0.0595$,
 4 $F(1, 82) = 6.253$, $p < 0.05$)

5 To examine the reasons for this failure, we performed additional global parameter
 6 optimization runs. When optimizing all the model parameters, the model accounts for
 7 more variance than the uniform base model ($r^2 = 0.7991$, $F(1, 82) = 331.2$, $p < 0.001$;
 8 optimized model parameters: $\gamma = 0.0006$, $\beta = 0.2758$, $\lambda = 0.3663$). Moreover, the
 9 nested model comparison test with three free parameters yields a G^2 value of 13.6912,
 10 which indicates a more accurate model with $p < 0.01$. Figure 7 shows the correlation
 11 plot. The parameters indicate that the preference strength is rather high, obedience is
 12 not as strong, while the information gain intention is visible. We now turn to individual
 13 parameter optimization, suspecting that there may be fundamental differences between
 14 the individual groups of workers.

15 We compared three single-parameter-individually-optimized simplePSIRSA mod-
 16 els to determine which model provides the best fit to the data. All models have sim-
 17 ilar levels of complexity, with either softness γ , obedience β , or KL-factor λ being
 18 optimized. The results indicate that we get the best fit by optimizing the KL-factor
 19 λ ($r^2 = 0.9059$, $F(1, 82) = 800.2$; leave-one-out cross-validated optimization $r^2 =$
 20 0.8902 , $F(1, 82) = 664.8$, with other models capturing less variance in the data (β -
 21 optimized $r^2 = 0.8015$, $F(1, 82) = 336.1$; γ -optimized $r^2 = 0.8077$, $F(1, 82) = 349.6$).
 22 Two- and three-parameter individual optimizations did not yield any significant model
 23 improvements (best improvement when optimizing γ in addition to λ , with a G^2 value
 24 of 24.72, which is not significant when considering the 82 additional degrees of free-
 25 dom due to individual parameter optimization). Figure 7 shows the resulting correlation
 26 plot.

27 Unlike for Experiment 1 where even the non-optimized models provided a good
 28 linear fit to the data, optimization produces a large effect on the model predictions

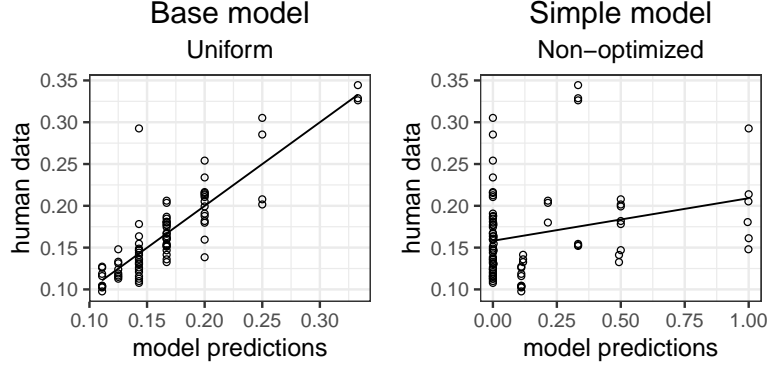


Figure 6: Average human data from Experiment 2 plotted against the predictions of the uniform baseline model and the simplePSIRSA model. Left panel: *uniform model* ($r^2 = 0.7466$); right panel: *non-optimized simplePSIRSA* ($r^2 = 0.0595$).

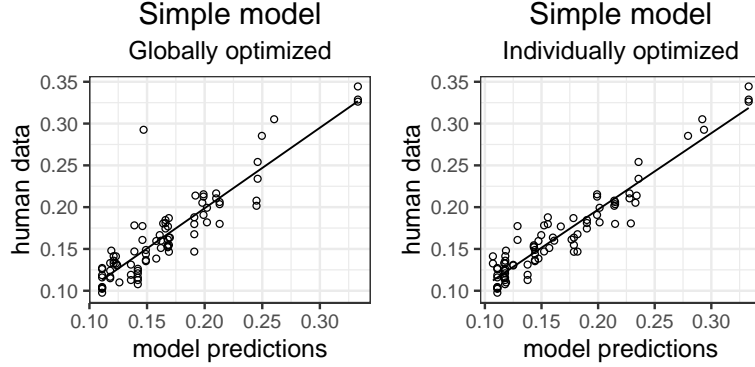


Figure 7: Average human data from Experiment 2 plotted against the predictions of optimized simplePSIRSA models. Left panel: *globally optimized 3 parameter model* ($r^2 = 0.7466$); right panel: *individual KL-factor λ -optimized model* ($r^2 = 0.9059$).

1 in Experiment 2. Figure 8 compares individually-optimized vs. non-optimized model
2 predictions against the human behavior for the sample trial in Figure 5. We see that
3 the non-optimized model strongly favors ambiguous utterances: in a situation with
4 a striped green circle, a blue striped cloud, and a solid green cloud, uttering things
5 like *cloud*, *striped*, or *green* (i.e., the utterances that point to more than one object in
6 the scene) and could let the speaker learn something about the listener’s preferences.
7 However, Figure 8 shows that human behavior deviates quite strongly from the non-
8 optimized, ambiguity-selecting baseline; once we optimize λ , we are able to capture
9 human behavior in the task.

10 When examining the individually optimized parameter values λ , we noticed that
11 three groups of participants could be distinguished. The first one is a “lazy worker”
12 group of 18 participants whose fitted λ values were close to zero (i.e., $-.02 < \lambda <$
13 $.02$), indicating that they were randomly selecting utterances. The second group of
14 32 participants yielded more negative values (i.e., $-7.13 < \lambda < -.02$), indicating that
15 a significant number of participants preferred to systematically choose unambiguous

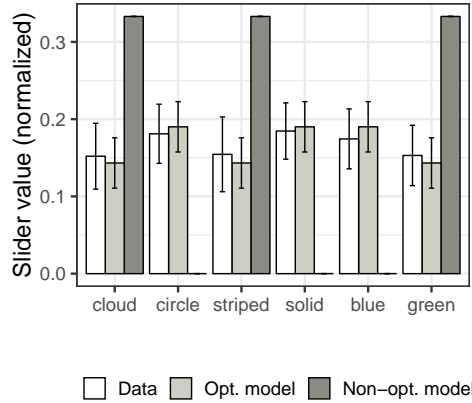


Figure 8: Simple Social Inference model predictions and human data for one of the classes of stimuli *Experiment 2: Picking utterances*. The optimized version of the model is optimized for the KL-factor λ .

1 utterances. The third group of again 32 participants yielded more positive values (i.e.,
 2 $.02 < \lambda < .54$), indicating that these participants indeed chose the most ambiguous
 3 utterance in a strategic manner.

4 Discussion

5 We have found strong support that we can indeed learn about others when observing
 6 their interpretation of ambiguous utterances. The results of Experiment 1 demonstrate
 7 that naïve speakers are able to reason pragmatically about *why* listeners may take the
 8 actions they do. The success of our computational model PSIRSA in predicting the
 9 observed behavior offers an articulated hypothesis about *how* this reasoning proceeds:
 10 when speakers are aware of the ambiguity in their utterances, observing how listeners
 11 resolve that ambiguity provides clues to the preferences listeners use when doing so.
 12 The results of Experiment 2 demonstrate that at least some speakers are able to capi-
 13 talize on this reasoning to strategically select ambiguous utterances that are expected
 14 to improve their understanding of the preferences of their listeners. However, this
 15 group of ambiguity-selecting participants included only about 40% of the participants.
 16 Further experiments with highly similar setups (not reported in detail here) confirmed
 17 this trend. In particular, we ran a complementary study with a blocked design where
 18 participants first completed preference-inferences trials as in Experiment 1 and then
 19 utterance-selection trials as in Experiment 2. Even in such an experimental setup, the
 20 trend stayed the same. Currently, we are transferring the experimental setup to more
 21 naturalistic interaction scenarios. Even in these cases, though, it appears that we still
 22 find participants who consistently prefer to choose unambiguous utterances. Two ex-
 23 planations may be warranted and need to be investigated further. First, it may be the
 24 case that these participants think overly egocentrically, thus having the intention to sig-
 25 nal their own preferences rather than to give options to the listener. Second, it may
 26 simply be the case that these participants do not have access to the required deeper
 27 reasoning process, and thus prefer to give instructions with predictable outcomes.

28 Nonetheless, taken together, the results of our experiments and the success of

1 PSIRSA in modeling these results indicate that humans are aware of the fact that by ob-
2 serving responses to ambiguous utterances, information about the listener’s prior pref-
3 erences can be inferred—that is, they are able to learn about the hidden model states of
4 others, including preferences but probably also other aspects of beliefs. It should also
5 be noted that ambiguous utterances used in this way are closely related to questions,
6 which may ask directly about considered preferences. Ambiguous utterances provide a
7 ready but more subtle, indirect alternative to asking directly. In normal conversations, a
8 speaker might favor the indirect route, given considerations of politeness and possibly
9 also in an effort to keep the conversation open. With ambiguous language, the con-
10 versation partner can choose to disambiguate the ambiguous utterance or, alternatively,
11 choose to continue in a different direction or even change topic.

12 We note that the analyzed preference prior, viewed from a broader perspective, can
13 be closely related to a part of the event-predictive mind of the listener and the speaker
14 (Butz, 2016; Butz & Kutter, 2017). When interpreting an utterance—in our case, open-
15 ing up a set of referent choices—the listener’s mind infers the current choices and
16 integrates them with her preference priors, implicitly anticipating possible choice con-
17 sequences. Moreover, the expected information gain term—computing the utterance
18 choice of the speaker—can be equated with the computation of socially-motivated
19 active inference (Butz, 2017; Friston et al., 2015). It causes the model to strive for
20 an anticipated epistemic value that quantifies the expected information gain about the
21 preferences of the listener—that is, expecting a form of social information gain.

22 More generally, predictive states of mind about others do not only include consid-
23 erations of the preferences of others, but may also concern all imaginable knowledge,
24 opinions, beliefs, current trains of thought, and preferences of the listener. Moreover,
25 during a conversation, the involved “social” priors will dynamically develop depending
26 on the internal predictive models and the generated utterances, actions, and responses
27 of the speaker and listener. The priors dynamically depend on the privileged grounds of
28 the conversational partners, and also on the common ground in which the conversation
29 unfolds. In that sense, ambiguous utterances and resolutions thereof are one device for
30 projecting parts of each other’s privileged grounds into the common ground.

31 **Methods**

32 **Experiment 1: Learning about others’ preferences**

33 **Participants**

34 We recruited 90 participants with US IP addresses through Amazon.com’s Mechanical
35 Turk crowdsourcing service. Participants were compensated for their participation. On
36 the basis of a post-test demographics questionnaire, we identified 82 participants as
37 native speakers of English; their data were included in the analyses reported below. We
38 obtained a confirmation from all the subjects to participate in the study.

39 **Design and methods**

40 We presented participants with a series of reference game scenarios modeled after Fig-
41 ure 1 from Frank and Goodman (2012). Each scenario featured two people and three
42 objects. One of the people served as the speaker, and the other served as the listener.
43 The speaker asks the listener to choose one of the objects, but in doing so she is al-
44 lowed to mention only one of the features of the target object. Participants were told

1 that the listener might have a preference for certain object features, and participants
2 were tasked with inferring those preferences after observing the speaker’s utterance
3 and listener’s object choice.

4 We followed Frank and Goodman (2012) in our stimuli creation. Objects were
5 allowed to vary along three dimensions: color (blue, red, green), shape (cloud, circle,
6 square), and pattern (solid, striped, polka-dotted). The speaker’s utterance was chosen
7 at random from the properties of the three objects present, and the listener’s choice
8 was chosen at random from the subset of the three objects that possessed the uttered
9 feature. By varying the object properties, the targeted object, and the utterance, we
10 generated a total of 2400 scenes. Speaker and listener names were chosen randomly in
11 each trial. Participants saw the speaker’s utterance in bold (e.g., “red” in Figure 2) and
12 the listener’s choice appeared with a dotted orange outline (e.g., the center object in
13 Figure 2). Based on the observed choice, participants were instructed to adjust a series
14 of six sliders to indicate how likely it is that the listener had a preference for a given
15 feature. The sliders specified the six feature values of the two feature dimensions that
16 were not mentioned in the speaker’s utterance (e.g., pattern and shape in Figure 2).

17 Depending on how many features competitor objects share with the chosen object,
18 we were able to identify 48 ambiguity classes, which group the constellations that
19 have the exact same ambiguity constellation. Figure 2 shows a few of those ambiguity
20 classes with particular, exemplary, object-utterance-choice constellations.

21 Participants completed a series of fifteen trials. Objects and utterances were chosen
22 as detailed above, with the constraint that ten trials were potentially informative with
23 respect to listener preferences and five trials were uninformative with respect to listener
24 preferences (e.g., observing that the listener chose one of three identical objects).

25 **Ambiguity classes**

26 To determine model correlations with the gathered data, we partitioned the data into
27 ambiguity classes, similar to Frank and Goodman (2012). The ambiguity classes iden-
28 tified in Experiment 1 distinguish how many objects are referenced by the utterance,
29 how the referenced objects differ in their two non-uttered features, and how the non-
30 referenced objects differ from the referenced objects and from each other. As a result,
31 each ambiguity class yields exact model prediction values for the individual features
32 present (with respect to their “ambiguity role” in the particular ambiguity class) in the
33 respective scenarios S , effectively distinguishing all model-relevant cases. Please see
34 Supplementary materials for examples of different classes.

35 **Experiment 2**

36 **Participants**

37 We recruited 90 participants with US IP addresses through Amazon.com’s Mechanical
38 Turk crowdsourcing service; participants in Experiment 1 were not eligible to partic-
39 ipate in Experiment 2. Participants were compensated for their participation. On the
40 basis of a post-test demographics questionnaire, we again identified 82 participants as
41 native speakers of English; their data were included in the analyses. We obtained a
42 confirmation from all the subjects to participate in the study.

43 Design and methods

44 Participants encountered a reference game scenario similar to Experiment 1 in which a
1 speaker signals an object to a listener who might have a preference for certain types of
2 objects. However, rather than observing the utterance and referent choice, participants
3 were now tasked with helping the speaker choose an utterance that was “most likely to
4 reveal the listener’s color, shape, or pattern preferences.”

5 We used the same sets of objects from Experiment 1, which could vary along three
6 dimensions. Each trial featured a set of three objects, as in Figure 5. After observing
7 the objects, participants adjusted sliders to indicate which single-feature utterance the
8 speaker should choose to learn about the preferences of their listener. Potential utter-
9 ances corresponded to the features of the objects present; depending on the number of
10 unique features, participants adjusted between three and nine sliders. As with Experi-
11 ment 1, we averaged the data and the respective model predictions across specific am-
12 biguity classes, which include all scenes that yield identical utterance choice options.
13 In this case, 14 distinct conditions can be identified, with a total of 84 slider values to
14 set. Membership within an ambiguity class is defined by how many objects in a scene
15 share each of the features: shape, pattern, and color. If objects share a feature, we also
16 consider whether these objects also share other features. For example, in Figure 5, two
17 green objects differ in shape, making the utterance *green* informative. If, on the other
18 hand, both green objects were clouds, uttering *green* would not allow the speaker to
19 update their beliefs about the listener’s shape preferences. In the most extreme case,
20 when all objects share all three features, all utterances are ambiguous since multiple
21 objects can always be picked; but no utterance allows the speaker to learn anything
22 about the listener because the object choice is uninformative. Another extreme case is
23 a situation where all objects are unique and do not share any features. In such a case,
24 any utterance will only pick one object, making learning about preferences impossible
25 unless obedience (β) is not 0—that is, unless listeners have a tendency to disobey the
26 utterance and consider objects that do not satisfy its literal interpretation.

27 Participants completed a series of fifteen trials. As with Experiment 1, objects were
28 chosen at random, with the constraint that ten trials were potentially informative with
29 respect to the listener’s preferences (as in Figure 5) and five trials were uninformat-
30 ive with respect to the listener’s preferences (e.g., observing a set of three identical
31 objects).

32 Ambiguity classes

33 As for Experiment 1, to determine model correlations with the gathered data, we par-
34 titioned the data into ambiguity classes. For Experiment 2, the ambiguity classes dis-
35 tinguish how the three objects in the respective scenario S differ from each other. As a
36 result, the two most extreme classes contain identical objects – in which case exactly
37 three features are present in the scenario – and three objects with all unique features, in
38 which case all nine possible features are present. As for Experiment 1, each ambiguity
39 class yields exact model prediction values for the individual features (with respect to
40 their ambiguity role in the respective ambiguity class) present in the respective sce-
41 narios S , effectively distinguishing all model-relevant cases. Please see Supplementary
42 materials for examples of different classes.

Original RSA Formalization

RSA (cf. Frank & Goodman, 2012; Franke & Jäger, 2016; Goodman & Frank, 2016) formalizes a state space, or scenario, S in the form of a particular set of objects (cf. the example in Figure 1). Moreover, RSA unfolds computations over the corresponding utterance space U , which consists of the set of possible utterances, which in turn contains all object features that are present in a particular scenario S . At the base of the reasoning process, there is a hypothetical, naïve literal listener L_0 , who hears an utterance $u \in U$ and attempts to infer the object $s \in S$ that u is meant to reference. L_0 performs this inference by conditioning on the literal semantics of u , $\llbracket u \rrbracket(s)$, which returns *true* (i.e., 1) for those objects that contain the uttered feature and *false* (i.e., 0), otherwise. As a result, object choice probabilities for the literal listener can be computed by:

$$P_{L_0}(s | u) \propto \llbracket u \rrbracket(s), \quad (7)$$

essentially returning a uniform distribution over those objects in S that contain the uttered feature u .³

One layer up, the speaker S_1 observes the state S and is assumed to have the intention to refer to a particular object $s \in S$. S_1 chooses an utterance u on the basis of its expected utility for signaling s in the scenario S , which is determined by the log-likelihood of this particular object choice $U_{S_1}(u; s)$:⁴

$$U_{S_1}(u; s) = \log(P_{L_0}(s | u)). \quad (8)$$

Depending on a “greediness” factor α , the speaker chooses a particular utterance u with a probability that is exponentially proportional to the utility estimate:

$$P_{S_1}(u | s) \propto \exp(\alpha \cdot U_{S_1}(u; s)). \quad (9)$$

At the top layer of the vanilla RSA model, the *pragmatic* listener L_1 infers posteriors over s on the basis of some observed utterance u . However, unlike L_0 , L_1 updates beliefs about the world by reasoning about the process that *generated* u , namely the utterance choice of speaker S_1 . In other words, L_1 reasons about which object s would have been most likely led S_1 to utter u given the scenario S :

$$P_{L_1}(s | u) \propto P_{S_1}(u | s) \cdot P(s). \quad (10)$$

Frank and Goodman (2012) tested the predictions of RSA against behavioral data from reference games, as in Figure 1. To model production behavior (that is, which utterance should be chosen to communicate a given object), the authors used the probability distributions from S_1 . To model interpretation behavior (i.e., which object the speaker is trying to communicate on the basis of their utterance), the authors generated predictions from L_1 . Frank and Goodman found strong correlations between model predictions and behavioral data in both cases, confirming the validity of their model of pragmatic reasoning in reference games (see also Qing & Franke, 2015 for a fuller exploration of the modeling choices).

³Note that the context S is typically not made explicit, but rather treated implicitly in the specification of the model.

⁴The original model in Frank and Goodman (2012) also includes a term for the utterance cost, $C(u)$. We ignore the term here since we assume uniform cost over all utterances.

Optimization procedure

To compare PSIRSA’s predictions to the human data, we calculated an average value for each slider, binning data into 48 ambiguity classes for Experiment 1 and 14 classes for Experiment 2. We excluded the sliders if their corresponding feature value was not present in a scene. For example, for the trial depicted in Figure 2, we excluded the sliders for solid things and squares since none of these are present, and therefore no learning about them is possible.

We fit the model parameters either at the individual level or at the group level by optimizing the KL (Kullback-Leibler) divergence between the data and the model predictions:

$$\text{KL}(P_{data}(f | u, s) || (P_{model}(f | u, s)), \quad (11)$$

where $P_{data}(f | u, s)$ specifies a participant’s normalized slider value setting, which offers empirical estimates of the feature-preference posterior given object scene S , a particular utterance choice u , and the consequent object choice s ; $P_{model}(f | u, s)$ specifies the corresponding model posterior, either $P_{S_2}(f | u, s)$ in the case of fullPSIRSA or $P_{S_1\text{-simp}}(f | u, s)$ in the case of simplePSIRSA. By minimizing the summed KL divergence between the empirical and model-predicted preference posteriors over all considered trials, we essentially maximize the model fit to the participants’ data. Moreover, we can use the minimized KL divergence values to perform the likelihood ratio test for nested models relying on the G^2 -statistic, because the summed KL divergence values are approximately chi-square distributed (Lewandowsky & Farrell, 2011). Individual vs. global parameter fitting allows us to explore potential differences between participants. In the case of individual model parameter optimization, parameters were optimized for each individual participant separately, determining the KL divergence with respect to the participant-specific set of trials. In the case of global optimization, all trials of all participants were used to determine the summed KL divergence.

We fit three parameters for fullPSIRSA and two for simplePSIRSA. The soft-max scaling factor α is only relevant for fullPSIRSA; it controls how likely speaker S_1 is to maximize utility when choosing utterances. The default value is typically set to $\alpha = 1$ (i.e., no scaling).

The softness parameter γ regulates the strength of individual feature preferences f :

$$P(s | f) \propto \begin{cases} 1 + \gamma, & \text{if } s \text{ contains } f \\ \gamma, & \text{otherwise} \end{cases}, \quad (12)$$

controlling the choice probability of those objects s that contain feature f compared to those that do not. A value of $\gamma = 0$ models a hard preference choice; in this case, the speaker always chooses one of the preferred objects. On the other hand, when $\gamma \rightarrow \infty$, the choice prior becomes uniform over all objects, thus ignoring feature preferences.

For example, in the trial shown in Figure 2, there are two objects that fit the utterance $u = \text{“red”}$: a red striped cloud and a red dotted circle. When $\gamma = 1$, $P(s_{\text{red striped cloud}} | f_{\text{“cloud”}}) = 2/3$, while $P(s_{\text{red dotted circle}} | f_{\text{“cloud”}}) = 1/3$, yielding a soft preference for clouds. We use $\gamma = 0$ —that is, hard preferences—as the default model value.

Finally, we allow for the possibility of noise in our human data introduced by participants not following instructions. Parameter β models the possibility that listeners choose objects that do not pass the semantic filter of the literal listener, allowing for non-literal interpretations that result in choosing objects whose features do not

match the received utterance u . The computation is equivalent to the softness parameter above, in this case softening the object choices of the literal listener L_0 towards a uniform choice over all objects present.

Again, $\beta = 0$ models a hard object choice—that is, full obedience to the uttered instruction u —while $\beta \rightarrow \infty$ models a uniform object choice—that is, full ignorance of u .

For the case of utterance selection, the additional parameter λ becomes relevant (cf. equations 3 and 6). It scales the expected information gain. While a positive value yields the intention to maximize information gain, a negative value results in a tendency to minimize information gain, that is, a preference for no change in the posterior feature preference estimate $P_{S_{1-\text{simp}}}(f | u, s)$ in comparison to the prior estimate $P(f)$. A value of $\lambda = 0$ effectively ignores information gain and a resulting tendency to choose the object that was most likely referenced given the *utterance*.

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Data availability

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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