

Learning about Others: Pragmatic Social Inference through Ambiguity Resolution

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Abstract

We investigated whether ambiguity resolution 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 resolution 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 fu-

1 ture events and event boundaries, revealing anticipatory, event-predictive active
2 inference processes (Belardinelli, Stepper, & Butz, 2016; Belardinelli, Lohmann,
3 Farnè, & Butz, 2018; Friston et al., 2015; Hayhoe, Shrivastava, Mruczek, & Pelz,
4 2003; Lohmann, Belardinelli, & Butz, 2019). Also in the language domain, active
5 inference processes seem to continuously unfold (Christiansen & Chater, 2016),
6 compressing information into event-like units of thought (Baldwin & Kosie, to ap-
7 pear; Gärdenfors, 2014). For example, neurophysiological data has shown that
8 listeners predict the semantic category of upcoming words (Federmeier & Kutas,
9 2002). Moreover, the inference process takes the structural properties of sentences
10 into account (Levy, 2008). Dynamic language models show that complex, event-
11 predictive structures guide ambiguity resolution during comprehension and likely
12 also constrain ambiguity generation during language production (Elman & McRae,
13 2019).

14 When systematic abstractions become relevant, event-predictive biases seem
15 to be at play, invoking the tendency to compress sensorimotor experiences, includ-
16 ing language, into event-predictive encodings (Baldwin & Kosie, to appear; Butz,
17 2016, 2017; Shin & DuBrow, to appear). Various disciplines associated with cog-
18 nitive science suggest that our minds develop event-compressed predictive encod-
19 ings, which are recruited during decision making and action generation, including
20 language production and comprehension, essentially determining thought itself in
21 a highly active, epistemic, goal-directed manner (Baldwin & Kosie, to appear; Shin
22 & DuBrow, to appear; Elsner & Adam, 2019; Knott & Takac, to appear; Ünal, Ji,
23 & Papafragou, to appear; Stawarczyk, Bezdek, & Zacks, 2019). Here, we reveal
24 socially epistemic inferences and utterance productions in scenarios where we ob-
25 serve and actively generate social event-predictive interactions.

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

42 While our model also pursues Bayesian inference, or “psychological reason-
43 ing”, we do not focus on the inference of the actor’s knowledge, that is, on *learning*
44 *from others* (Shafto et al., 2012). Rather, we focus on *learning about others*, that is,

1 learning about listeners' preferences when observing their disambiguating behav-
2 ioral responses. We explore interpretive choices and the potential strategic, socially
3 epistemic usage of ambiguous utterances in anticipation of actors' responses. To
4 formalize our hypothesis, we adapt the Rational Speech Act model framework,
5 reliably modeling the involved, probabilistic interpretation processes and socially
6 epistemic action choices. Interestingly, the modeling results reveal good inter-
7 pretive abilities but also strong individual differences when the task is to choose
8 (ambiguous) utterances strategically for gaining social knowledge.

9 We use ambiguity resolution as a paradigm in which learning about others is
10 possible. Intuitively, ambiguity should make understanding each other difficult. If
11 a speaker and a listener understand an ambiguous utterance differently, communi-
12 cation between them might fail. On rare occasions, such communication failure
13 can even be deadly: Pinker (2015) alludes to the Charge of the Light Brigade dur-
14 ing the Crimean War as an example of a military disaster that was caused by vague
15 orders. He also mentions how poor wording on a warning light was responsible for
16 the nuclear meltdown at Three Mile Island. Finally, citing Cushing (1994), Pinker
17 describes how the deadliest plane crash in history resulted from pilots and air traffic
18 controllers arriving at different interpretations of the phrase "at takeoff".

19 Given that ambiguity can hinder the efficient transfer of information between
20 conversation partners, it is not surprising that linguists have treated the possibil-
21 ity for ambiguity as a bug in the communication system (Grice, 1975; Chomsky,
22 2002). The attitude towards ambiguity has been quite different in other disciplines,
23 in part because the term itself can refer to multiple phenomena. For linguistic
24 research, a word is ambiguous if it can have two separate meanings even in the
25 absence of context, simply as a linguistic sign. In that sense, the word "bat" is am-
26 biguous between a winged mammal and a sporting implement. In organizational
27 communication—communication that aids production—ambiguity aligns closely
28 with underspecification: an utterance is ambiguous when it does not provide ev-
29 ery detail about the intended meaning, leaving room for the listener to interpret it.
30 In the case of referential ambiguity, an ambiguous utterance may apply to several
31 possible referents in a scene. For example, a pronoun can be referentially ambigu-
32 ous if there are multiple potential antecedents in the context. It is the latter type of
33 ambiguity that we are concerned with in this paper.

34 More recent research has begun to take notice of the efficiency ambiguity
35 affords us: by relying on context to fill in missing information, we can reuse
36 lightweight bits of language rather than fully specifying the intended message
37 (Levinson, 2000; Piantadosi, Tily, & Gibson, 2012; Wasow, 2015). Viewed in
38 this way, ambiguity serves as a feature—not a bug—of an efficient communication
39 system. This reasoning accords with years of psycholinguistic research document-
40 ing that speakers readily produce ambiguous utterances (see Ferreira, 2008, for an
41 overview). Along related lines, Wasow (2015) reviews a large body of evidence
42 and concludes that ambiguity is rarely avoided, even in situations where its avoid-
43 ance would be communicatively appropriate. This observation stands at odds with
44 the Gricean maxim to avoid ambiguity (Grice, 1975).

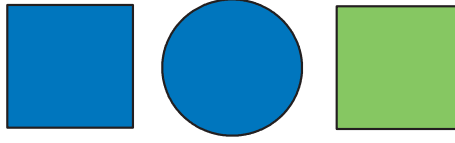


Figure 1: A simple reference game scenario from Frank and Goodman (2012). In the game, speakers are confronted with a collection of objects, which determine the current scenario S , where $S = \{\text{solid blue square}, \text{solid blue circle}, \text{solid green square}\}$ in the depicted example. 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 following set of utterances is available: $U = \{\text{“solid”}, \text{“blue”}, \text{“green”}, \text{“square”}, \text{“circle”}\}$.

1 In search of the communicative purpose of ambiguous language, the current
2 work identifies an additional benefit: the *extra* information we gain from observ-
3 ing how listeners resolve ambiguity. We show that language users learn about
4 each other’s private knowledge when observing how ambiguity is resolved. When
5 utterances leave room for interpretation, listeners must draw on their opinions, be-
6 liefs, and preferences to fill in the gaps; by observing the concrete interpretation,
7 speakers thus learn about the opinions, beliefs, and preferences of their conversa-
8 tion partner. As a result, in a naturalistic conversation, where speakers take turns,
9 ambiguous utterances open interpretation spaces and the resulting interpretation
10 choices dynamically and mutually reveal individual opinions, beliefs, and prefer-
11 ences.

12 By way of illustration, take the scenario in Figure 1. Suppose a speaker pro-
13 duces the single-word utterance “blue” – meaning: choose a blue object – creat-
14 ing referential ambiguity for the listener, that is, offering a choice between a blue
15 square and a blue circle. Suppose further that, upon hearing “blue”, the listener se-
16 lects the blue circle. In observing this choice, the speaker learns something about
17 the private thoughts of the listener: what made her select the blue circle instead
18 of the blue square? Perhaps the circle is more salient to the listener, or the lis-
19 tener has a preference for circles, or the listener may believe that the speaker has
20 a preference for circles; there may even be mutual agreement that circles are to be
21 preferred when possible. Importantly, by observing how the listener resolves the
22 ambiguity in reference, the speaker can learn something about the private thoughts
23 of the listener.

24 However, accessing this added information requires the speaker to reason prag-
25 matically about the pragmatic reasoning of the listener—a higher-order pragmatic
26 reasoning. In order to select a referent, the listener must interpret the utterance. We
27 follow Frank and Goodman (2012) in treating this interpretation process as active
28 pragmatic, probabilistic reasoning: the listener interprets an utterance by reasoning
29 about the process that generated it, namely the speaker, who selects an utterance by
30 reasoning about how a listener would interpret it. Frank and Goodman model this

1 recursive social reasoning between speakers and listeners introducing a Rational
 2 Speech Act (RSA) modeling framework (see Methods section for a detailed formal
 3 introduction).

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

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

18 Results

19 Before we report the results and modeling insights from our socially pragmatic
 20 and event-epistemic experiments, we introduce our proposed pragmatic social in-
 21 ference RSA model.

22 Pragmatic social inference RSA model

23 Our model builds on the vanilla version of RSA (see Methods section for de-
 24 tails), modifying the listener’s state prior $P(s)$ and enhancing the reasoning pro-
 25 cess towards a social component, yielding a *pragmatic social inference RSA* model
 26 (PSIRSA). By changing $P(s)$ to a non-uniform distribution, we essentially model
 27 prior beliefs of which object the speaker is more likely to refer to, or—when viewed
 28 from a more self-centered perspective—which prior object feature preferences f
 29 the listener may have. For example, the listener may like blue things, such that she
 30 may be more likely to choose the blue square instead of the green one when hear-
 31 ing the utterance “square” in the scenario shown in Figure 1. As a result, when a
 32 pragmatic speaker produces utterance u and observes the listener’s referent choice
 33 s , the speaker may infer posteriors over possible feature preferences, attempting to
 34 explain the observed object choice in this way.

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

$$37 \quad P_{L_1}(s \mid u, f) \propto P_{S_1}(u \mid s) \cdot P(s \mid f). \quad (1)$$

38 We then model a pragmatic speaker S_2 , who updates beliefs about L_1 ’s prefer-
 39 ences, $P(f)$. 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 integrating the full RSA formalism. 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 shown 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 $P(s | f)$:

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

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

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

As a result, `simplePSIRSA` ignores any indirect pragmatic reasoning considerations about which object the speaker may refer to given an utterance and a particular object constellation. It simply assumes that all objects may be chosen

that match the utterance, modifying these choice options dependent on the feature-preference-dependent object choice priors. The corresponding utterance-selection model simplifies the reasoning process accordingly:

$$P_{S_1\text{-simp}}(u) \propto \sum_{s: \mathbb{I}(u)(s)=1} P_{L_0}(s|u, f) \exp(\lambda \cdot \text{KL}(P(f) || P_{S_1\text{-simp}}(f | u, s))). \quad (6)$$


In the evaluation section below, we compare the modeling performance of fullPSIRSA with simplePSIRSA.

Experiment 1

Our first task is to check the inferences of the pragmatic speaker having observed that a listener selects some object s in response to an utterance u . Is it possible to draw inferences about the most likely preferences the listener had when making her choice? Can this inference process be modeled by PSIRSA—that is, by recursive, Bayesian inference? 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"/>	<input type="range"/>	clouds	<input type="range"/>	<input type="range"/>
striped things	<input type="range"/>	<input type="range"/>	circles	<input type="range"/>	<input type="range"/>
polka-dotted things	<input type="range"/>	<input type="range"/>	squares	<input type="range"/>	<input type="range"/>

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 may have led her to the particular object choice, specifying their inference by adjusting the sliders for each of the features.

Models with global optimization

We fit the following free parameters to optimize the predictions of the models. First, the full model includes a “greediness” parameter α that controls how likely

1 it is that speakers choose the best-suited utterance to signal a particular object to a
2 listener. This parameter is absent in the simple model since it relies on fewer layers
3 of reasoning. The second parameter γ controls how soft the preferences are. Hard
4 preferences enforce the choice of the preferred object type, while increasing soft-
5 ness converges towards no object preference. Similarly, the obedience parameter
6 β allows subjects to choose objects that do not qualify for the utterance. As for the
7 preference parameter γ , the β range includes hard obedience on the one side of the
8 spectrum – for example, definitely choosing a blue object when hearing “blue” –
9 and full ignorance of the utterance at the other extreme, choosing uniformly from
10 all available objects.

11 simplePSIRSA and fullPSIRSA with softness (γ) optimized globally provide
12 nearly identically good fits to the data (Figure 3). Simple linear regression analysis
13 was used to test whether the model values predicted the human data. simpleP-
14 SIRSA yields a value of $r^2 = 0.8607^1$ ($F(1, 190) = 1181$)² when only softness
15 parameter γ is optimized ($\gamma = 0.2204$ after optimization). When both parameters
16 are optimized globally, a variance estimate of $r^2 = 0.9788$ ($F(1, 190) = 8823$) is
17 reached ($\gamma = 0.2210$ and $\beta = 0.2693$ after optimization), indicating that partic-
18 ipants indeed considered (possibly subconsciously) the option to interpret utter-
19 ances non-literally. fullPSIRSA yields nearly identical values. When optimizing
20 only the softness parameter γ , a value of $r^2 = 0.8568$ ($F(1, 190) = 1144$) is reached
21 ($\gamma = 0.2231$). Optimizing both, α and γ , a value of $r^2 = 0.8607$ ($F(1, 190) = 1144$)
22 is reached ($\alpha = 0.1797$, $\gamma = 0.2205$). When optimizing all three parameters, fullP-
23 SIRSA yields a value of $r^2 = 0.9772$ ($F(1, 190) = 8170$) ($\alpha = 0.2657$, $\gamma = 0.2214$,
24 $\beta = 0.0030$). Overall, the results show that participants are indeed able to infer
25 the feature preferences that lead to the choice of an object. Moreover, the higher
26 model flexibility of fullPSIRSA—controlled via parameter α —does not yield any
27 modeling improvement, implying that an approximation of the more shallow rea-
28 soning process modeled by simplePSIRSA typically unfolded in the minds of the
29 participants.

30 **Individually-fitted models**

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

38 The full model optimized at the individual level for the additional parame-
39 ter α does not improve the fit compared to the simplified model (simplePSIRSA:

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.

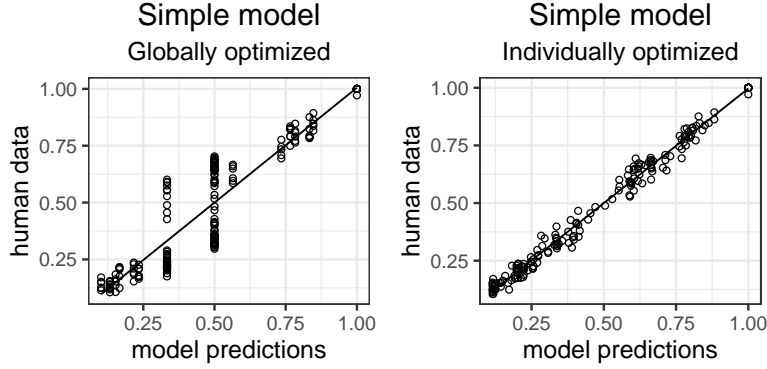


Figure 3: Human data from Experiment 1 plotted against the predictions of simplePSIRSA. Each data point indicates the slider values and model predicted feature preference posteriors for a particular ambiguity class. Left panel: γ optimized globally ($r^2 = 0.8614$); right panel: γ and β optimized individually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

1 $r^2 = 0.8631, F(1, 190) = 1205$; fullPSIRSA: $r^2 = 0.8627, F(1, 190) = 1201$). See-
2 ing that both models again fit the data nearly equally well (if anything, simpleP-
3 SIRSA performs slightly better), we only consider the predictions of simpleP-
4 SIRSA henceforth. Note further that the individually-fitted parameters do not im-
5 prove the correlation values much, if at all, when compared to the globally-fitted
6 model.

7 The model fit improves considerably when we additionally fit the obedience
8 parameter β at the individual level. Here the model explains a large proportion of
9 variance in the human judgments ($r^2 = 0.9919, F(1, 190) = 23480$). The likelihood
10 ratio test (two-tailed) revealed that a γ - and β -optimized simplePSIRSA model pro-
11 vides a better fit compared to a model optimized only for γ ($G^2 = 237.36, df =$
12 $82, p < 0.01$). The more complex model contains one additional parameter β fitted
13 for each subject, giving us 82 degrees of freedom. We additionally checked the
14 generalizability of the model by performing leave-one-out cross-validation on the
15 individual level. Figure 3 shows that the resulting cross-validated model predic-
16 tions retain the strong fit ($r^2 = 0.99, F(1, 190) = 18910$).

17 To appreciate the gains obtained by fitting model parameters, Figure 4 shows
18 the average responses of the human participants and of the individually-, two-
19 parameter-optimized simplePSIRSA model and the non-optimized simplePSIRSA
20 model for the scene type of the sample trial from Figure 2. In that trial, partici-
21 pants saw that the middle object was chosen following the utterance “red”. There
22 are two potential referents for this description: the red striped cloud and the red
23 dotted circle. Since the cloud was chosen, we infer that the person who chose this
24 object has a preference for clouds over circles, and for striped objects over dotted
25 ones. Note that we cannot learn anything about the preference for solid things or
26 squares in this trial because these features are not present, thus we ignore the re-

spective slider values. Moreover, we can definitely not learn anything about color preferences because the color was 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.

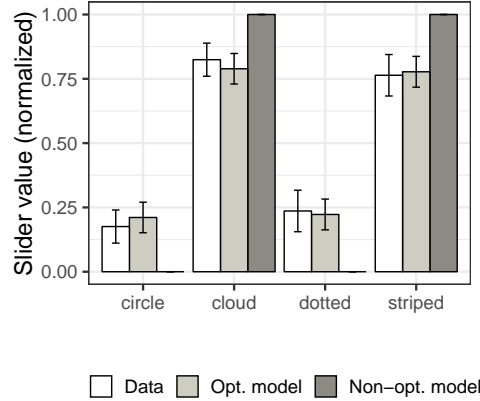


Figure 4: Human data and simplePSIRSA’s (individually-, two-parameter-optimized and non-optimized) feature preference posterior estimates for the scenario S shown in Figure 2. Error bars represent 95% confidence intervals.

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 aware that ambiguous language is potentially more informative and can thus use ambiguous language in a socially epistemic, strategic manner?


Experiment 2: Choosing utterances to learn about others

Our next task is to check the predictions of our strategic utterance selection model: given a set of potential referents S , are participants able to reason pragmatically about the anticipated potential epistemic utility of utterances $u \in U$ in inferring the listener’s preferences? Figure 5 shows a sample trial, in which the speaker (“Katie” in the example) is to choose an utterance in order to learn about the listener’s preferences (“Elizabeth” in the example). While the ambiguous utterances “cloud”, “green”, and “striped” may allow inferences about color & texture, shape & texture, and color & shape, respectively, the utterances “solid”, “blue”, and “circle” leave only one response option to the listener, such that the speaker cannot learn

- 1 about the listener’s preferences when observing the listener’s response (assuming
- 2 the listener obeys the speaker’s order).

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"	<div style="width: 100%; height: 10px; background-color: #ccc; position: relative;"><div style="position: absolute; left: 50%; transform: translate(-50%, 0); width: 0; height: 0; border-left: 5px solid #ccc; border-right: 5px solid #ccc; border-bottom: 10px solid #fff;"></div></div>	
"solid"	<div style="width: 100%; height: 10px; background-color: #ccc; position: relative;"><div style="position: absolute; left: 50%; transform: translate(-50%, 0); width: 0; height: 0; border-left: 5px solid #ccc; border-right: 5px solid #ccc; border-bottom: 10px solid #fff;"></div></div>	
"green"	<div style="width: 100%; height: 10px; background-color: #ccc; position: relative;"><div style="position: absolute; left: 50%; transform: translate(-50%, 0); width: 0; height: 0; border-left: 5px solid #ccc; border-right: 5px solid #ccc; border-bottom: 10px solid #fff;"></div></div>	
"striped"	<div style="width: 100%; height: 10px; background-color: #ccc; position: relative;"><div style="position: absolute; left: 50%; transform: translate(-50%, 0); width: 0; height: 0; border-left: 5px solid #ccc; border-right: 5px solid #ccc; border-bottom: 10px solid #fff;"></div></div>	
"blue"	<div style="width: 100%; height: 10px; background-color: #ccc; position: relative;"><div style="position: absolute; left: 50%; transform: translate(-50%, 0); width: 0; height: 0; border-left: 5px solid #ccc; border-right: 5px solid #ccc; border-bottom: 10px solid #fff;"></div></div>	
"circle"	<div style="width: 100%; height: 10px; background-color: #ccc; position: relative;"><div style="position: absolute; left: 50%; transform: translate(-50%, 0); width: 0; height: 0; border-left: 5px solid #ccc; border-right: 5px solid #ccc; border-bottom: 10px solid #fff;"></div></div>	

[Continue](#)

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

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

7 To generate predictions from $P_{S_1\text{-simp}}(u)$, three free parameters can be identi-
8 fied: the preference softness γ , the obedience β , and a λ parameter, which factors
9 the importance of choosing the expected most informative utterance with respect
10 to the expected KL divergence between preference priors and expected preference
11 posteriors.

12 We compare simplePSIRSA with non-optimized parameters and with several
13 parameter optimizations with the performance of a uniform base model, which
14 simply chooses one of the available utterances at random. Seeing that in particu-
15 lar ambiguity cases with particular constellations S three up to nine utterances are
16 possible, the base model yields different model predictions for the available utter-
17 ances in the respective ambiguity classes. As a result, the uniform base model is
18 much better in capturing variance in the data than one would expect without this
19 insight ($r^2 = 0.7466$, $F(1, 82) = 245.6$, $p < 0.001$). Figure 6 compares this perfor-
20 mance to the non-optimized simplePSIRSA, where we set the parameters to hard
21 preference and obedience ($\gamma = 0$, $\beta = 0$) and the information gain factor to $\lambda = 1$,
22 thus preferring to choose those utterances that are expected to yield high informa-
23 tion gain. Surprisingly, this model captures very little variance in the human data
24 ($r^2 = 0.0595$, $F(1, 82) = 6.253$, $p < 0.05$)

25 To examine the reasons for this failure, we first performed additional global pa-

parameter optimization runs. When optimizing all the model parameters, the model accounts for more variance than the uniform base model ($r^2 = 0.7991$, $F(1, 82) = 331.2$, $p < 0.001$; optimized model parameters: $\gamma = 0.0006$, $\beta = 0.2758$, $\lambda = 0.3663$). Moreover, the nested model comparison test with three free parameters yields a G^2 value of 13.6912, which indicates a more accurate model with $p < 0.05$. Figure 7 shows the correlation plot. The parameters indicate that the preference strength is rather high, obedience is not as strong, while the information gain intention is present. We now turn to individual parameter optimization, suspecting that there may be fundamental differences between the individual workers.

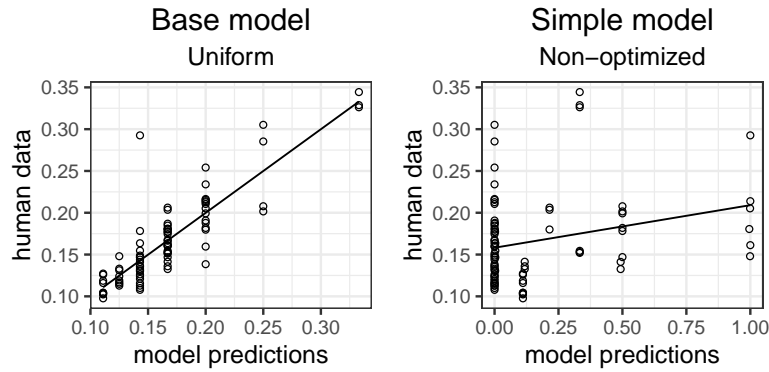


Figure 6: Average human data from Experiment 2 plotted against the predictions of the uniform baseline model and the simplePSIRSA model. Left panel: *uniform model* ($r^2 = 0.7466$); right panel: *non-optimized simplePSIRSA* ($r^2 = 0.0595$).

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

Unlike for Experiment 1 where even the non-optimized models provided a good linear fit to the data, optimization produces a large effect on the model predictions in Experiment 2. Figure 8 compares individually-optimized vs. non-optimized model predictions against the human behavior for the sample trial in Figure 5. We see that the non-optimized model strongly favors ambiguous utterances: in a situation with a striped green circle, a blue striped cloud, and a solid green cloud, uttering things like *cloud*, *striped*, or *green* (i.e., the utterances that point to more

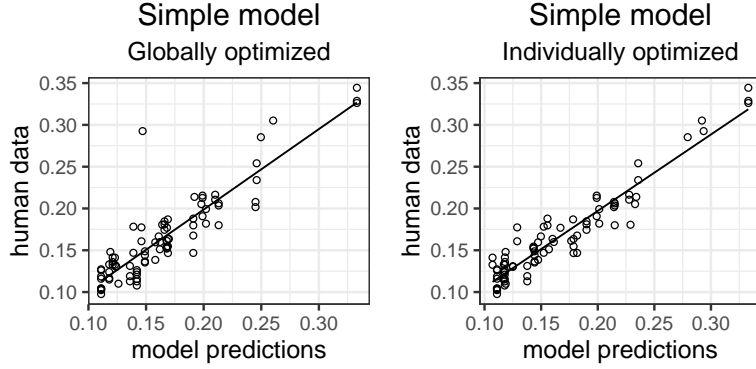


Figure 7: Average human data from Experiment 2 plotted against the predictions of optimized simplePSIRSA models. Left panel: *globally optimized 3 parameter model* ($r^2 = 0.7466$; right panel: *individual KL-factor λ -optimized model* ($r^2 = 0.9059$).

- 1 than one object in the scene) and could let the speaker learn something about the
- 2 listener’s preferences. However, Figure 8 shows that human behavior deviates quite
- 3 strongly from the non-optimized, ambiguity-selecting baseline; once we optimize
- 4 λ , we are able to capture human behavior in the task.

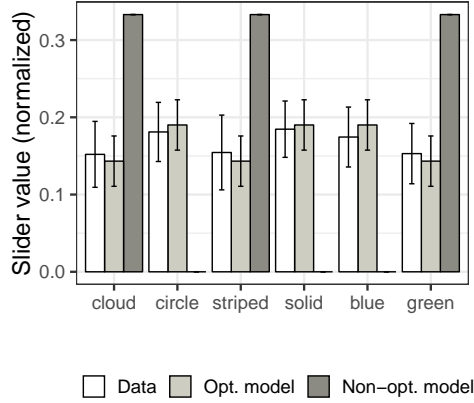


Figure 8: Simple Social Inference model predictions and human data for one of the classes of stimuli *Experiment 2: Picking utterances*. The optimized version of the model is optimized for the KL-factor λ . Error bars represent 95% confidence intervals.

- 5 When examining the individually optimized parameter values λ , we noticed
- 6 that three groups of participants could be distinguished. The first one is a “lazy
- 7 worker” group of 18 participants whose fitted λ values were close to zero (i.e.,
- 8 $-.02 < \lambda < .02$), indicating that they were randomly selecting utterances. The
- 9 second group of 32 participants yielded more negative values (i.e., $-7.13 < \lambda <$

1 —.02), indicating that a significant number of participants preferred to systemat-
2 ically choose unambiguous utterances. The third group of again 32 participants
3 yielded more positive values (i.e., $.02 < \lambda < .54$), indicating that these participants
4 indeed chose the most ambiguous utterance in a strategic manner.

5 Discussion

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

30 Nonetheless, taken together, the results of our experiments and the success of
31 PSIRSA in modeling these results indicate that humans are aware of the fact that by
32 observing responses to ambiguous utterances, information about the listener’s prior
33 preferences can be inferred—that is, they are able to learn about the hidden model
34 states of others, including preferences but probably also other aspects of beliefs. It
35 should also be noted that ambiguous utterances used in this way are closely related
36 to questions, which may ask directly about considered preferences. Ambiguous
37 utterances provide a ready but more subtle, indirect alternative to asking directly.
38 In normal conversations, a speaker might favor the indirect route, given consider-
39 ations of politeness and possibly also in an effort to keep the conversation open.
40 With ambiguous language, the conversation partner can choose to disambiguate the
41 ambiguous utterance or, alternatively, choose to continue in a different direction or

1 even change topic.

2 We note that the analyzed preference prior, viewed from a broader perspective,
3 can be closely related to a part of the event-predictive mind of the listener and the
4 speaker (Butz, 2016; Butz & Kutter, 2017). When interpreting an utterance—in
5 our case, opening up a set of referent choices—the listener’s mind infers the cur-
6 rent choices and integrates them with her preference priors, implicitly anticipating
7 possible choice consequences. Moreover, the expected information gain term—
8 computing the utterance choice of the speaker—can be equated with the compu-
9 tation of socially-motivated active inference (Butz, 2017; Friston et al., 2015). It
10 causes the model to strive for an anticipated epistemic value that quantifies the ex-
11 pected information gain about the preferences of the listener—that is, expecting a
12 form of social information gain.

13 More generally, predictive states of mind about others do not only include con-
14 siderations of the preferences of others, but may also concern all imaginable knowl-
15 edge, opinions, beliefs, current trains of thought, and preferences of the listener.
16 Moreover, during a conversation, the involved “social” priors will dynamically de-
17 velop depending on the internal predictive models and the generated utterances,
18 actions, and responses of the speaker and listener. The priors dynamically depend
19 on the privileged grounds of the conversational partners, and also on the common
20 ground in which the conversation unfolds. In that sense, ambiguous utterances and
21 resolutions thereof are one device for projecting parts of each other’s privileged
22 grounds into the common ground.

23 **Methods**

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

25 **Participants**

26 We recruited 90 participants with US IP addresses through Amazon.com’s Me-
27 chanical Turk crowdsourcing service. Participants were compensated for their par-
28 ticipation. On the basis of a post-test demographics questionnaire, we identified 82
29 participants as native speakers of English; their data were included in the analyses
30 reported below. We obtained a confirmation from all the subjects that they agree to
31 participate in the study.

32 **Design and methods**

33 We presented participants with a series of reference game scenarios modeled after
34 Figure 1 from Frank and Goodman (2012). Each scenario featured two people and
35 three objects. One of the people served as the speaker, and the other served as the
36 listener. The speaker asks the listener to choose one of the objects, but in doing
37 so she is allowed to mention only one of the features of the target object. Partici-
38 pants were told that the listener might have a preference for certain object features,

1 and participants were tasked with inferring those preferences after observing the
2 speaker’s utterance and listener’s object choice.

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

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

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

27 **Ambiguity classes**

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

1 Experiment 2

2 Participants

3 We recruited 90 participants with US IP addresses through Amazon.com’s Me-
4 chanical Turk crowdsourcing service; participants in Experiment 1 were not eligi-
5 ble to participate in Experiment 2. Participants were compensated for their partici-
6 pation. On the basis of a post-test demographics questionnaire, we again identified
7 82 participants as native speakers of English; their data were included in the analy-
8 ses. We obtained a confirmation from all the subjects that they agree to participate
9 in the study.

10 Design and methods

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

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

40 Participants completed a series of fifteen trials. As with Experiment 1, objects
41 were chosen at random, with the constraint that ten trials were potentially informa-

1 tive with respect to the listener’s preferences (as in Figure 5) and five trials were
 2 uninformative with respect to the listener’s preferences (e.g., observing a set of
 3 three identical objects).

4 **Ambiguity classes**

5 As for Experiment 1, to determine model correlations with the gathered data,
 6 we partitioned the data into ambiguity classes. For Experiment 2, the ambigu-
 7 ity classes distinguish how the three objects in the respective scenario S differ from
 8 each other. As a result, the two most extreme classes contain identical objects –
 9 in which case exactly three features are present in the scenario – and three objects
 10 with all unique features, in which case all nine possible features are present. As
 11 for Experiment 1, each ambiguity class yields exact model prediction values for
 12 the individual features (with respect to their ambiguity role in the respective am-
 13 biguity class) present in the respective scenarios S , effectively distinguishing all
 14 model-relevant cases. Please see Supplementary materials for examples of differ-
 15 ent classes.

16 **Original RSA Formalization**

17 RSA (cf. Frank & Goodman, 2012; Franke & Jäger, 2016; Goodman & Frank,
 18 2016) formalizes a state space, or scenario, S in the form of a particular set of ob-
 19 jects (cf. the example in Figure 1). Moreover, RSA unfolds computations over the
 20 corresponding utterance space U , which consists of the set of possible utterances,
 21 which in turn contains all object features that are present in a particular scenario
 22 S . At the base of the reasoning process, there is a hypothetical, naïve literal lis-
 23 tener L_0 , who hears an utterance $u \in U$ and attempts to infer the object $s \in S$ that
 24 u is meant to reference. L_0 performs this inference by conditioning on the literal
 25 semantics of u , $\llbracket u \rrbracket(s)$, which returns *true* (i.e., 1) for those objects that contain the
 26 uttered feature and *false* (i.e., 0), otherwise. As a result, object choice probabilities
 27 for the literal listener can be computed by:

$$28 \quad P_{L_0}(s \mid u) \propto \llbracket u \rrbracket(s), \quad (7)$$

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

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

$$35 \quad U_{S_1}(u; s) = \log(P_{L_0}(s \mid u)). \quad (8)$$

³Note that the context S is typically not made explicit, but rather treated implicitly in the speci-
 fication 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.

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).

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 fullP-SIRSA 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 calculate the the G^2 -statistic and perform the likelihood ratio test for nested models, since G^2

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 softmax 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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3 man Research Foundation)–Project number 198647426.

4 **Data availability**

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

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