¹ The role of salience in young children's processing of ad-hoc implicatures

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Abstract

Language comprehension often requires making *implicatures.* For example, inferring that "I ate some of the cookies" implicates the speaker ate some *but not all* (scalar implicatures); and "I ate the chocolate-chip cookies" where there are both chocolate chip cookies and raisin cookies in the context implicates that the speaker ate the chocolate chip, but *not both the chocolate chip and raisin cookies* (ad-hoc implicatures). Children's ability to make scalar implicatures develops around age five, with ad-hoc implicatures emerging somewhat earlier. In the current work, using a time-sensitive tablet paradigm, we examined developmental gains in children's ad-hoc implicature processing, and found evidence for successful implicature computation by children as young as 3 years in a supportive context and substantial developmental gains in implicature computation from 2 to 5 years. We also tested whether one cause of younger children (2-year-olds)'s consistent failure to make implicatures is their difficulty in inhibiting an alternative interpretation that is more salient than the target meaning (the *salience hypothesis*). Our findings supported this hypothesis: Younger children's failures with implicatures were related to effects of the salience mismatch between possible interpretations.

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33   The role of salience in young children's processing of ad-hoc implicatures

34   Language comprehension in context often requires inferring an intended meaning that

35 goes beyond the literal semantics of what a speaker says. Consider a speaker who asserts

36 that:

37   (1) I ate some of the cookies.

38 A reasonable listener could assume from this sentence that the speaker ate some *but not all*

39 *of the cookies.* Inferences like this one, known as *implicatures*, are commonplace in

40 conversation and provide one important tool for speakers to use language flexibly. They also

41 are related to a broader set of pragmatic phenomena like underspecification (Levinson, 2000)

42 and politeness (P. Brown & Levinson, 1987).

43   How does the ability to make pragmatic inferences develop in childhood? A general

44 finding is that implicature follows a relatively delayed trajectory, with even school-aged

45 children sometimes struggling with implicature tasks (Noveck, 2001). A rich literature has

46 explored both these developmental changes and possible hypotheses about the sources of

47 difficulty for children (Barner, Brooks, & Bale, 2011; e.g., Papafragou & Musolino, 2003;

48 Stiller, Goodman, & Frank, 2015). These investigations are important because they shed

49 light on developmental changes in children's ability to comprehend language in context more

50 broadly, as well as the processing challenges posed by pragmatic language comprehension.

51   In the current paper, we investigate the developmental trajectory of the processing of

52 one specific type of implicatures, *ad-hoc implicatures*, which tend to be easier for young

53 children than other implicatures that rely on more sophisticated linguistic knowledge

54 (Horowitz, Schneider, & Frank, 2018; Papafragou & Musolino, 2003; Stiller et al., 2015). In

55 addition, we test a specific proposal for why young children might find even these inferences

56 challenging, namely that the inferential target is typically less salient than the distractor. In

57 the remainder of the Introduction, before describing our own work we first introduce

58 pragmatic implicature in more depth, then review developmental evidence on implicature.

Pragmatic Implicature

In Grice (1975)'s classic account of pragmatic inference, conversation is a cooperative act. Speakers choose utterances such that the listener can understand the intended message, and listeners in turn interpret these utterances with the assumption of the speaker's cooperativeness in mind. The listener then expects a cooperative speaker to have produced an utterance that is truthful, informative, relevant, and concise, relative to the the present conversational needs. Based on these expectations, the listener can make inferences that go beyond the literal meanings of the speaker's words. The non-literal interpretations computed through these inferential processes are called pragmatic implicatures.

A concrete example of such an implicature follows from sentence (1), which implicates that the speaker ate some *but not all of the cookies.* This kind of inference is often referred to as a *scalar implicature* because it relies on the fact that "all of the cookies" entails "some of the cookies" as part of a lexical scale (Horn, 1972). In contrast, another kind of implicature, *ad-hoc implicature*, is context-based. Uttering:

(2) I ate the chocolate chip cookies.

in a context where two kinds of cookies – chocolate chip and raisin – are available, implicates that the speaker ate the chocolate chip *but not both the chocolate chip cookies and raisin cookies.*[1] In this case, the context sets up a contrast between the proposition offered ("ate the chocolate chip cookies") and a stronger set of alternatives ("ate [all/both the chocolate chip and the raisin] the cookies") that is determined by the context (and hence is "ad hoc" in the sense of being constructed in this particular situation).

Implicatures like these have been an important case study for pragmatics more broadly. Notably, different accounts of pragmatic reasoning analyze even the simple examples above in different ways. In the classic Gricean analysis (as elaborated by Levinson, 1983), the speaker

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[1] Grice (1975) calls these implicatures generalized (scalar) vs. particularized (ad-hoc), but we use a theory-neutral designation here.

utters p ("some of the cookies"), which implicates q ("not all of the cookies") in the following way. (A) The speaker is presumed to be cooperative and observing Grice's maxims. (B) To maintain this assumption, the listener must assume that q is true; otherwise a maxim will be violated. (In this case the maxim is informativeness, since saying "some of the cookies" if "all of the cookies" were true would be underinformative). (C) The speaker is presumed to believe that it is mutually known by both parties that the listener can work out q.

This analysis – though influential – is in fact just one proposal among many, and likely does not map onto either the mental computations carried out by listeners or the specific issues that lead to developmental differences in implicature ability. Both classic theories of communication (e.g., Sperber & Wilson, 1995) and more recent probabilistic models of pragmatic inference (e.g., Frank & Goodman, 2012; see Goodman & Frank, 2016 for review) describe the processes that language users use to compute such implicatures in different ways. For example, Chierchia, Fox, and Spector (2012) give an account of implicature as a specific, grammaticalized operation that involves enriching the meaning of p with the negation of all stronger alternatives within a specified alternative set. In contrast, on the probabilistic view, implicatures arise naturally as part of the process of cooperative reasoning by rational agents.

Our goal here is not to distinguish between these different formalisms; instead, we are interested in understanding the processing of implicature in childhood. Despite that, it is useful to review the probabilistic view as it helps guide some of our predictions below. We consider sentence (2), following the analysis given in Goodman and Frank (2016). Under the rational speech act (RSA) model, there is a space of meanings (e.g., ATE(chocolate chip & raisin), ATE(chocolate chip), etc.), each of which may have some prior probability of being correct. There is also a space of utterances (e.g., "I ate the chocolate chip cookies," "I ate the cookies"), each of which is either literally consistent or inconsistent with each meaning. Given a particular utterance, a listener can reason probabilistically about the speaker's intended meaning in making this utterance. He can do this by considering that the speaker is a Bayesian agent who chose the appropriate utterance for her intended meaning. He

reasons about the speaker making her own choice by considering a listener who is also a Bayesian agent reasoning in this same way. This definition is endlessly recursive, however. In practice, the recursion can be grounded by a speaker considering a "literal listener," who interprets utterances according to their literal truth value (for further formal details, see Goodman & Frank, 2016).

In the specific case of (2), the listener's reasoning can be glossed as "if the speaker had wanted to say she ate 'all of the cookies', she could have said just 'cookies'; but she didn't, she said something more specific: 'chocolate chip'; thus she probably intended me to recover the meaning ATE(chocolate chip)." Notice that this reasoning, when explained verbally, actually approximates the standard Gricean logic (though with some differences). Of course, one benefit of the RSA formalism is that probabilities can be put to each of these inferences and so the strength of the interpretive judgment can be predicted (Frank & Goodman, 2012).

The Development of Pragmatic Implicature

A rich psycholinguistic literature has measured adults' processing of implicatures relative to literal interpretations and has found that adults robustly compute implicatures in a range of contexts, though their processing time can vary depending on the context (Bott, Bailey, & Grodner, 2012; Breheny, Ferguson, & Katsos, 2013; Grodner, Klein, Carbary, & Tanenhaus, 2010; Huang & Snedeker, 2018). How does the ability to make implicatures develop? Since implicature computation is an important indicator of broader pragmatic understanding, many studies have tested children's abilities on a variety of implicatures.

Children tend to have the most difficulty with scalar implicatures relying on quantifiers, modals, and other functional elements. For example, in Papafragou and Musolino (2003)'s study, a puppet saw three out of three horses jump over a fence, and described the scene infelicitously by saying "Some of the horses jumped over the fence." Adults tend to reject this infelicitous statement, whereas 5-year-old children mostly accept it, suggesting that children failed to compute the relevant scalar implicature (though see Katsos & Bishop, 2011,

for an alternative explanation). Besides struggling with *some* vs. *all* (Huang & Snedeker,

2009; Hurewitz, Papafragou, Gleitman, & Gelman, 2006; Noveck, 2001), children in the same

age range have consistently failed to compute implicatures involving scalar contrasts,

including *a* vs. *some* (Barner, Chow, & Yang, 2009), *might* vs. *must* (Noveck, 2001), and *or*

vs. *and* (Chierchia, Crain, Guasti, Gualmini, & Meroni, 2001).

While children struggle on many scalar implicature tasks, they tend to be more

successful at computing ad-hoc implicatures (which depend on context, rather than lexical

scales). One potential difficulty in a typical scalar implicature task is the need to generate

relevant alternatives to a given scalar term. For children to hear "some of the horses jumped

over the fence" and derive the implicature "some *but not all*," they must first realize that

"all" is the relevant alternative to "some." Barner et al. (2011) argued that children's failures

in scalar implicature tasks are due to their lack of ability to generate the alternative to

negate spontaneously upon hearing the term offered. Barner et al. (2011)'s claim predicts

that children's implicature computation should improve when they can access the relevant

alternatives. Consistent with this claim, children can be primed with relevant scalar

alternatives, leading to enhanced implicature performance (Skordos & Papafragou, 2016).

Furthermore, children show substantially improved implicature computation in ad-hoc

implicature tasks – which provided access to relevant alternatives in context – compared to

scalar implicature tasks (Horowitz et al., 2018; Katsos & Bishop, 2011; Papafragou &

Tantalou, 2004; Stiller et al., 2015).

For example, Stiller et al. (2015) showed 2.5- to 5-year-old children three different

faces: a face with no item; a face with only glasses; and a face with glasses and a top-hat,

and asked children to choose one of the three faces as the referent in a puppet's statement,

"My friend has glasses." In this task, the alternative referent (face with glasses and hat) was

visible in the context, and thus access to the alternative terms ("glasses and hat") was made

easier. In general, we assume that the standard route for referring to these visual properties

of the context will be by naming them. The design intention in this study for using simple

nouns like "hat" was therefore to make it obvious what the linguistic alternatives would be by virtue of the highly accessible names for stimuli. Children as young as 3.5 years chose the face with only glasses as the referent, suggesting that they successfully computed the implicature that the puppet's friend has "glasses but not both glasses and hat." Similarly, in one study that tested both scalar and ad-hoc implicature computation, 4-year-olds successfully made ad-hoc implicatures, but performed poorly on scalar implicatures using the same stimuli (Horowitz et al., 2018).

Despite older children's success, children below 3 years of age appear to struggle with even simple ad-hoc implicatures. Even in the ad-hoc paradigm described above (Stiller et al., 2015), 2.5- and 3-year-olds still did not make the implicature-consistent choice at above-chance levels. Does this finding imply that young toddlers lack pragmatic understanding, specifically an awareness of the need for informativeness in cooperative communication? On the contrary, children are sensitive to informativeness in communication: From age two onward, when they are asked to produce referring expressions, children appear to recognize the level of referential ambiguity of their own expressions and attempt to provide more information through speech and gestures in more ambiguous situations (e.g., instead of "the boy," saying "the boy with the dog"; or naming an object while pointing in cases where the point alone is not precise enough; Matthews, Butcher, Lieven, & Tomasello, 2012; O'Neill & Topolovec, 2001). Hence, a lack of sensitivity to the need for communicative informativeness does not seem to be the problem for toddlers' implicature processing. So what causes toddlers' failures in these easier ad-hoc implicature tasks specifically?

The Current Study

One potential explanation for younger children's struggle with ad-hoc implicatures is the mismatch in salience between potential interpretations. This explanation is inspired by the RSA framework described above, in the sense that this salience mismatch would be manifest in the pragmatic computation as a higher prior probability of a particular referent.

189 For example, in Stiller et al. (2015)'s study, a target referent (e.g., face with glasses only)

190 had fewer features than its alternative distractor to be rejected (e.g., face with glasses and

191 hat). The distractor, which had a greater number of nameable features, was more salient

192 both perceptually and conceptually, likely drawing children's attention more strongly than

193 the target. Under the RSA framework – and very likely under other pragmatic theories,

194 though perhaps with a less clearly specified prediction – such a mismatch in prior

195 probabilities would lead to a weaker pragmatic inference.

196   The mismatch between stimulus salience (prior probability) and the target of the

197 pragmatic inference may be particularly difficult developmentally. From a mechanistic

198 perspective, a task with this kind of competition between targets may be especially

199 challenging to children because their executive function is not yet fully developed (Davidson,

200 Amso, Anderson, & Diamond, 2006; Diamond & Taylor, 1996), and specifically their ability

201 to inhibit responses to salient targets (but see Discussion for further consideration of whether

202 children's failures should be attributed to their inhibitory control abilities per se).

203   Such an issue might be important outside of the specific case of ad-hoc implicature and

204 referent-selection tasks. For example, referent selection tasks may be representative of

205 analogous problems in naturalistic language comprehension for children, in which the goal is

206 often to figure out what referent a speaker is talking about or how to connect a new word to

207 a new referent (in the case of word learning; Frank & Goodman, 2014). And in such

208 situations, there is a body of evidence suggesting that referent salience does in fact influence

209 children's attention (Hollich et al., 2000; Yurovsky & Frank, 2017).

210   Further, under RSA analysis given above there is no fundamental difference between

211 referent selection tasks and other implicature comprehension tasks. Thus, the asymmetry

212 between correct but weaker target meaning and incorrect but more salient or higher prior

213 probability distractor meaning is present in other types of implicatures too, though less

214 obviously so. For example, scalar implicature is typically described as rejecting the term that

215 yields the "stronger" propositional meaning (e.g., ate "all" of the cookies) and adding its

216 negation to the "weaker" proposition (e.g., "some but not all" of the cookies). Computing a

217 forced-choice scalar implicature thus also requires avoiding the stronger meaning, which

218 typically describes a larger set size. Although the referents in such tasks are not always

219 pictured visually side-by-side, they are in at least some paradigms (e.g., Huang & Snedeker,

220 2009). At least in these cases – and perhaps more generally – the stronger alternative could

221 reasonably be viewed as being more salient or higher prior probability. And, as above, when

222 prior probabilities (whether induced by perceptual factors like salience or emerging from

223 other sources) conflict with pragmatic inferences, the resulting comprehension situation may

224 be especially difficult for children.

225   For all of these reasons, in our current work, we were interested in exploring the issue

226 of distractor salience and how it played out in the development of implicature processing for

227 children. For our experiment, we adopted a referent selection method, in which participants

228 were asked to select a referent among a set of candidates. As mentioned earlier, referent

229 selection paradigms have shown evidence of successful implicature computation in youngest

230 children to date (Horowitz et al., 2018; Stiller et al., 2015), and are analogous to one

231 important aspect of of language comprehension in naturalistic language environments,

232 namely identifying a speaker's intended referent.

233   This setup allowed us to create a systematic manipulation of the stimuli in our referent

234 selection method. Under the RSA model, the more alternative utterances there are to refer

235 to a particular referent, the less likely any one of them is. Thus, adding more features to the

236 distractor referent in the referent selection task should make it even less likely as the referent

237 of any particular one. For example, in the faces case used by Stiller et al. (2015), if the

238 target is a face with glasses, then a face with a hat, glasses, and a mustache (three features)

239 should be a *worse* distractor referent for "glasses" than a face with just a hat and glasses

240 (two features). Frank and Goodman (2014) tested this prediction with adults in a

241 word-learning case and found quantitative support for the idea that the number of features

242 was related to the strength of pragmatic judgments.

243   The interesting thing about this manipulation, however, is that it might very well have

244 an *opposite* effect on young children because of the referent salience explanation given above.

245 While a distractor with more features should create a stronger pragmatic inference, it should

246 also be more salient to young children, leading to a higher prior probability and worse

247 performance. Thus, in our current experiment we predicted that young children would

248 struggle differentially in the case there were more features on the distractor, while older

249 children would find this case no more difficult and perhaps even easier.

250   We stress that, although our manipulation was inspired by the RSA model, it does not

251 depend on that model. As touched on above, there are a variety of different accounts that

252 try to explain exactly what pragmatic inference children are making in ad-hoc implicature

253 tasks. In the Stiller et al. (2015) example, "my friend has glasses" can implicate "my friend

254 has glasses *but no hat*" based on the immediate context. A slightly different interpretation

255 could be: "...glasses *but no other distinguishing features*," however (exhaustivity

256 implicature; Groenendijk & Stokhof, 1985). For the purposes of the current work, we cannot

257 differentiate between these proposals – as long as an account incorporated prior information

258 in some fashion, it would likely make a similar prediction. Thus, our goal is not to make a

259 test of a particular implicature account, but rather to test the idea that referent salience

260 (instantiated as prior probability in the RSA model) affects children's implicature behavior.

261   In our experiment, we implemented the referent selection task using a tablet paradigm.

262 This methodological change allowed us to examine children's reaction times for selecting the

263 target referent along with their specific selection (Frank, Sugarman, Horowitz, Lewis, &

264 Yurovsky, 2016). Compared to previous studies, we also reduced the number of potential

265 referents in context to further simplify the task. In Stiller et al. (2015)'s paradigm, there

266 were three potential referents in the context (face with no item, face with only glasses, face

267 with glasses and hat); in our current paradigm, we presented two instead of three potential

268 referents (e.g. plate with a carrot and plate with a carrot and a banana) to minimize

269 cognitive load for the younger children in our task.

270   We present data here from two independent samples: The first planned sample of

271 children across four age groups (2-, 3-, 4-, and 5-year-olds) initially showed a pattern

272 consistent with the salience hypothesis, where children were more accurate for trials with

273 lower salience contrasts than for trials with higher salience contrasts. This effect was

274 relatively small, however, and our analysis plan was not prespecified, leading us to worry

275 about the possibility that analytic flexibility might have led us to overestimate our effect

276 (e.g., Simmons, Nelson, & Simonsohn, 2011). We thus collected a second, fully preregistered

277 sample of children across the three youngest groups (2-, 3- and 4-year-olds) to replicate this

278 initial finding and make a stronger test of the hypothesis.

Methods

280   We report how we determined our sample size, all data exclusions (if any), all

281 manipulations, and all measures in the study.

Participants

283   In the original sample, either parents and their children visiting Children's Discovery

284 Museum (San Jose, CA), or children in a local nursery school were invited to participate in a

285 tablet study, and a total of 123 children were recruited. Participants were excluded from the

286 sample for the following reasons: age other than 2 to 5 years ($n = 3$); parent-reported

287 English exposure less than our prespecified criterion of 75% ($n = 5$); parental interference ($n

288 = 2$); and noncompliance or difficulty with the experimental procedure ($n = 9$). After

289 excluding participants who completed fewer than the prespecified number of 10 trials ($n =

290 2$), the final sample consisted of 102 children (see Table 1).

291   In the replication sample, a total of 116 children were recruited, all at Children's

292 Discovery Museum in San Jose. Reasons for exclusions were: age other than 2 to 4 years ($n

293 = 11$); parent-reported English exposure less than our prespecified criterion of 75% ($n = 15$);

294 parental interference ($n = 3$); noncompliance or difficulty with the experimental procedure

₂₉₅ ($n = 3$); and technical error ($n = 4$). The final sample consisted of 80 children (no

₂₉₆ participant was excluded for completing fewer than 10 trials).

Stimuli and Design

₂₉₈ On each trial, participants saw two images: a target and distractor, which could either

₂₉₉ be an item with a single feature (e.g. a lunchbox with only an apple or only an orange), or

₃₀₀ an item with double features (e.g., a lunchbox with an apple and an orange). In each trial, a

₃₀₁ pre-recorded voice said a sentence (e.g., "Look at these lunchboxes. Elmo's lunchbox has an

₃₀₂ apple."). After participants chose the object that was being referred to, a green box appeared

₃₀₃ around the chosen object to show that the choice had been made. For each trial, we recorded

₃₀₄ the participant's accuracy, or whether he or she selected the correct target referent, and

₃₀₅ reaction time, or time spent between naming of the referent ("... an *apple*") and the

₃₀₆ participant's referent selection.

₃₀₇ There were three types of test trials (shown at the top of each panel in Figure 1). In

₃₀₈ *implicature* trials, the target item had a single feature (e.g., an apple), and the distractor

₃₀₉ item had two or three features (see below for the manipulation of number of features) – one

₃₁₀ that was in common with the target (e.g., an apple) and the other feature(s) that was/were

₃₁₁ unique (e.g., an orange). The test sentence named the feature that was common to the

₃₁₂ target and distractor. Thus, if participants understood that "Elmo's lunchbox has an apple"

₃₁₃ implicates "Elmo's lunchbox has an apple *but not an orange*" in the given context, it was

₃₁₄ predicted that they would choose the target more often than the distractor; otherwise, if

₃₁₅ they did not make implicatures, they would choose the two at equal rates (or even choose

₃₁₆ the distractor more often depending on the degree of saliency contrast – see below).

₃₁₇ There were two additional trial types, with semantically unambiguous targets:

₃₁₈ *Control-double* trials looked identical to implicature trials, but the target and distractor were

₃₁₉ switched, such that the double-feature item was the target and the single-feature item was

₃₂₀ the distractor, and the test sentence named the unique feature on the target. *Control-single*

trials presented two items that each had a unique single feature, and either could be the target. Children saw 4 implicature, 4 control-double, and 8 control-single trials; adults saw 6 implicature, 6 control-double, and 12 control-single trials.

Each trial type was further divided by the number of features present on the target and distractor (shown on the right side of Figure 1): Within implicature trials, *fewer-feature* (2-vs-1) trials presented two features (an apple and an orange) on the distractor and one feature (an apple) on the target, whereas *more-feature* (3-vs-1) trials presented three features (an apple, an orange, and a cookie) on the distractor and one feature on the target; Within control-double trials, *fewer-feature* (2-vs-1) trials presented two features (an apple and an orange) on the target and one feature (an apple) on the distractor, whereas *more-feature* (3-vs-1) trials presented three features (an apple, an orange, and a cookie) on the distractor and one feature on the target; Lastly, within control-single trials, *fewer-feature* (1-vs-1) trials presented one feature each on the distractor and the target, whereas *more-feature* (2-vs-2) trials presented two features each on the distractor and on the target.

We hypothesized that older children would choose the target more often in the more-feature implicature trials than the fewer-feature implicature trials because implicatures are strengthened more in more-feature trials – "Elmo's lunchbox has an apple" is more likely to mean "apple only" given an orange AND cookie on the alternative referent, thus more things that could have been named but were not. On the contrary, younger children were predicted to choose the target less often in the more-feature trials than the fewer-feature trials because the distractor is more salient in the fewer-feature trials, while still being consistent with the literal meaning.

There were six sets of item and feature types, and the features were named with nouns found on the MacArthur-Bates Communicative Development Inventory word list (Fenson et al., 1994). Two orders of the test trials were created, such that trial types and item types were counterbalanced and trial order was pseudo-randomized across the two orders.

Procedure

An experimenter introduced children to the task as a game on a tablet. Then they completed two practice trials, where they were asked to select an obvious, unambiguous referent (e.g., "cow" as opposed to "rabbit"), followed by 16 test trials.

Data analysis

We used R (Version 3.5.0; R Core Team, 2017) and the R-packages *bindrcpp* (Version 0.2.2; Müller, 2017a), *brms* (Version 2.4.0; Bürkner, 2017), *dplyr* (Version 0.7.8; Wickham, Francois, Henry, & Müller, 2017), *forcats* (Version 0.3.0; Wickham, 2017a), *ggplot2* (Version 3.1.0; Wickham, 2009), *ggthemes* (Version 3.5.0; Arnold, 2017), *here* (Version 0.1; Müller, 2017b), *langcog* (Version 0.1.9001; Braginsky, Yurovsky, & Frank, n.d.), *lme4* (Version 1.1.13; D. Bates, Mächler, Bolker, & Walker, 2015), *Matrix* (Version 1.2.14; D. Bates & Maechler, 2017), *papaja* (Version 0.1.0.9709; Aust & Barth, 2017), *purrr* (Version 0.2.5; Henry & Wickham, 2017), *Rcpp* (Eddelbuettel & Balamuta, 2017; Version 1.0.0; Eddelbuettel & François, 2011), *readr* (Version 1.1.1; Wickham, Hester, & Francois, 2017), *stringr* (Version 1.3.1; Wickham, 2017b), *tibble* (Version 1.4.2; Müller & Wickham, 2017), *tidyr* (Version 0.8.1; Wickham & Henry, 2017), *tidyverse* (Version 1.2.1; Wickham, 2017c), and *xtable* (Version 1.8.3; Dahl, 2016) for all our analyses.

Results

We were interested in children's processing of implicatures in comparison to unambiguous utterances, and developmental gains across ages. We used two different measures: (1) accuracy and (2) reaction time for choosing the correct referent. For each measure, we asked: (a) do children show developmental gains in selection of the target referent? And (b) does children's performance vary depending on salience contrast? That is, when there are a relatively greater number of features on the distractor, do children have more difficulty and are they slower in choosing the correct referent?

372   As per our standard operating procedures, we removed trials in which the log of

373 reaction time was more than 3 standard deviations above or below the mean (upper bound:

374 14.04 seconds; lower bound: 0.47 second; percentage of data excluded: 1.67 %). Throughout

375 this section, we used Bayesian linear mixed-effects models (`brms` package in R; Bürkner,

376 2017) using crossed random effects of participant, item, and sample (original vs. replication)

377 with the maximal random effects structure supported by the design (Barr, Levy, Scheepers,

378 & Tily, 2013; A. Gelman & Hill, 2006). Age is plotted in year bins, but was analyzed as a

379 continuous variable, scaled and centered, in our statistical model.

380 **Accuracy**

381   The analysis of the accuracy rate (Figure 2) showed that children across all ages were

382 able to identify the target in control trials, indicating that, as expected, they can readily

383 compute unambiguous meanings. In implicature trials, 4- and 5-year-olds' performances were

384 nearly at ceiling, replicating the previous results (Horowitz et al., 2018; Stiller et al., 2015).

385 In our paradigm, even 3-year-olds chose the inferential target above chance[2] (original sample:

386 $t(58) = 6.82$, $p < 0.001$; replication sample: $t(57) = 5.33$, $p < 0.001$). On the other hand,

387 2-year-olds' performance in implicature trials did not differ from chance overall, but their

388 performance varied depending on the number of features present. In 3-vs-1 trials (i.e., with a

389 relatively greater number of features on the distractor), 2-year-olds did not choose the

390 correct target referent, and even tended to choose the distractor somewhat more often

391 numerically (original sample: $t(23) = -1.42$, $p = 0.17$; replication sample: $t(24) = -0.72$, $p =$

392 0.48). However, In 2-vs-1 trials (with fewer features on the distractor), 2-year-olds tended to

393 choose the target more often than the distractor. This difference was numerically present in

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[2] Because our task is a two-alternative forced choice, we define chance to be 50% across all trials. This baseline is a standard comparison that reflects the possibility that a child was completely inattentive to the task and chose completely at random. This baseline is more conservative than a salience-based baseline, which would likely suggest that the correct (inferentially-consistent) target would be chosen less than 50% of the time (e.g., the "mumble" condition in Stiller et al., 2015).

394   both samples and statistically significant in one (original sample: $t(26) = 0.46$, $p = 0.65$;

395   replication sample: $t(24) = 2.57$, $p = 0.02$). By 4 years, this difference in accuracy rate

396   between 2-vs-1 and 3-vs-1 trials was not present.

397   A Bayesian linear mixed-effects model predicting accuracy based on age, trial type and

398   number of features (salience contrast; more-feature vs. fewer-feature) showed a three-way

399   positive interaction of age, implicature trials, and number of features (Table 2). Unlike

400   control trials, in which children's performances did not differ by salience contrast,

401   implicature trials showed lower accuracy in 3-vs-1 than 2-vs-1 trials in younger children, but

402   not in older children. Thus, this result supports our hypothesis that the salience contrast

403   between conditions led to greater difficulty with the implicature task for for younger children.

Reaction time

405   With increasing age, children computed both implicatures and unambiguous meanings

406   and identified the target faster (Figure 3). A Bayesian linear mixed-effects model predicting

407   reaction time based on age, trial type and number of features present showed a positive

408   two-way interaction between age and implicature trial (Table 3), indicating that reaction

409   time on implicature trials did not improve with age as much as the speed of processing

410   unambiguous meanings. Together with the accuracy finding, this result suggests that though

411   children become proficient at determining the *correct* target referents for ad-hoc implicatures

412   by 5 years, implicature processing develops relatively more slowly.

413   We also observed a positive two-way interaction between control-double trials and

414   number of features, indicating that children took longer to identify the target in

415   control-double trials with more features than in control-single trials with more features.

416   There was no interaction between inference trials and number of features, or between

417   inference trial, age and number of features, however. Why would this be? We did not have a

418   pre-specified hypothesis regarding this pattern of data, but we speculate that once a feature

419   is named (e.g., Elmo's lunchbox has an apple), it is relatively easier to find the feature in an

inferential target image than in the distractor image. The target feature is by itself in the target referent, whereas it is grouped with with other features in the distractor. Thus, the inference trials may allow easy perceptual access to the target feature but also competition with the overall perceptual salience of the distractor. These factors might cancel one another out and lead to undifferentiated reaction times and hence the lack of reaction time interactions. The potential advantage of identifying a feature when it is by itself is only speculative, however, and should be examined further in future work.

Discussion

In our experiment, we confirmed 3- to 5-year-old children's successes on ad-hoc implicature computation, and saw substantial developmental gains in their accuracy and speed. 4- and 5-year-old children successfully computed ad-hoc implicatures and identified the inferential targets, consistent with previous findings. We found evidence of successful implicature computation even in 3-year-olds. Further, between 2 and 5 years, there was a clear improvement in processing skills with increasing age, such that correct referent identification was more accurate and faster across both control and implicature trials. Thus, these findings add to the existing literature to attest to children's growing proficiency in pragmatic processing.

We also investigated the salience hypothesis, namely that one cause of young children's struggle with implicatures stems from their difficulty to inhibit choosing the more salient distractor. In earlier work, there was some numerical suggestion of 2-year-olds' preference for the more salient but pragmatically incorrect distractor (Stiller et al., 2015). Inspired by this pattern and following the predictions of the RSA model of pragmatic inference, we predicted that increasing the salience of this distractor would result in decreased performance for younger children while increasing performance for older children. The first part of this prediction was clearly supported in our data, with younger children performing worse when the distractor was more salient, with more mixed support for the second part.

In particular, although we observed numerical hints of a gain in accuracy for older children in one sample, we did not see a consistent facilitation effect due to our manipulation. We suspect this finding is due to a ceiling effect: Referent selection via ad-hoc implicature is relatively trivial for four-year-olds (see also Horowitz et al., 2018). However, we saw a possible age-related advantage of pragmatic strengthening in the speed of computation: Whereas younger children tended to be slower in trials with a greater number of features for both unambiguous and inferential meanings, older children began to close the gap and become faster to compute implicatures given increased distractor saliency.

Our findings here support the idea that salience-related competition plays a role in young children's difficulties with ad-hoc implicature. Our salience account is most manifest in the kind of simple referent selection tasks we used here. Despite this, following the general mapping of perceptual salience to prior probabilities in the RSA framework more broadly, we speculate that the account may apply more broadly to implicature computation beyond the scope of these tasks. Any pragmatic implicature requires an asymmetry in the "strength" of the alternatives. In ad-hoc referent-selection contexts, the stronger (more salient) alternative is the item with more features. In scalar implicatures, the implicature that you ate *some but not all of the cookies* is only possible because there is a stronger alternative ("all"). It remains an open empirical question whether the a salience mismatch account – perhaps relabeled as a prior probability mismatch – might explain some aspects of children's difficulty with these other cases of implicatures as well.

The salience hypothesis we tested here relates to broader methodological issues in experiments for young children with both visual and verbal alternative responses. One example of such a bias is the tendency of 2-year-olds to show a bias toward "yes" compared to "no" in answering questions. This bias disappears with age (Fritzley & Lee, 2003), and there is some evidence that it is related to children's verbal ability and inhibitory control (Moriguchi, Okanda, & Itakura, 2008). In general, as work on pragmatic inference begins to examine younger children's abilities, it is important to take into consideration a range of

473 cognitive factors in task design.

474   Following this line of reasoning, one further potential application of our account is to

475 word learning contexts, where children's learning of a novel word is facilitated when the

476 target referent is more (not less) salient than its alternative. For example, Frank and

477 Goodman (2014) used an analogous pragmatic inference paradigm in a word learning

478 context: Participants heard a novel label (e.g., "a dinosaur with a *dax*") used to describe an

479 object with two features (a dinosaur with a hat and a bandanna) in the presence of another

480 dinosaur that had one but not the other of the features (a dinosaur with a hat only). 3- and

481 4-year-olds performed quite well in mapping the novel label to the unique feature, even

482 though in many respects this task should be more, not less, difficult than ad-hoc implicature.

483 One reason for this success might be that the novel label was being mapped to the more,

484 rather than less, salient object.

485   Similarly, in classic "mutual exclusivity" paradigms (Markman & Wachtel, 1988), by

486 around 18 months, participants succeed in mapping a novel label to a novel object (Halberda,

487 2003). While the mechanisms underlying this empirical phenomenon are complex, it is

488 well-established that the salience of the novel target is an important factor in children's

489 success (see Markman, Wasow, & Hansen, 2003 for discussion). Overall, evidence for

490 children's pragmatic word learning emerges earlier than implicature computation: Children

491 succeed in these tasks substantially at earlier ages than even in our simplified implicature

492 paradigm. We might speculate that one reason for this asymmetry is because implicature

493 tasks require selecting the *less* salient alternative while word learning tasks typically ask

494 participants to select a *more* salient alternative.

495   Our findings help in the construction of a comprehensive developmental account of

496 processing of implicatures, and pragmatic inferences in general. In the samples that have

497 been studied in this literature, by 2 years of age, children begin to be aware that

498 informativeness is important to communication. By 3 to 4 years, the ability to inhibit these

499 salient targets is more developed, and they start to compute ad-hoc implicatures when

relevant alternatives to the speaker's words are provided in context. Scalar implicature

performance develops more slowly, however, as children's ability to access the relevant

inferential alternatives is only beginning to emerge in the period from 4 top 6 (Barner et al.,

2011; Horowitz et al., 2018; Skordos & Papafragou, 2016); their performance during these

ages is highly variable and dependent on the nature of the context and its pragmatic

demands (Papafragou & Tantalou, 2004).

      As illlustrated by this timeline, the salience hypothesis we tested is not mutually

exclusive with other accounts of children's difficulties in implicature. For example, the

"alternatives hypothesis" (Barner et al., 2011) is independently supported by a variety of

experiments (Horowitz et al., 2018; Skordos & Papafragou, 2016). Indeed, both the salience

and alternatives hypotheses are likely true and likely contribute to children's difficulty with

implicatures to different degrees in different tasks and at different ages.

      One important challenge for this viewpoint is the nature of the ability that children use

to overcome the pull of the salient alternative. One possible naive mapping for the ability

would be to the broader construct of executive function, which undergoes substantial

developmental changes during this period (Davidson et al., 2006; Diamond & Taylor, 1996).

But executive function is a multi-faceted construct (Miyake et al., 2000), and the particular

components that would be expected to predict visual (and perhaps conceptual)

disengagement with a particular referent is unclear. Our own studies attempting to probe

individual difference correlations between executive function and implicature ability in

development have not been successful (e.g., Horowitz et al., 2018; Nordmeyer, Yoon, &

Frank, 2016). Thus, a target for future work is to better characterize the particular cognitive

changes that relate to the developmental effects we have observed here.

      There are several further limitations of our work here. First, our salience manipulation

involved manipulation of the number of features present on an item, which might have

caused a potential confound between salience and processing time. For example, children's

greater looking to the distractor (and thus greater processing time) might have been caused

by a real desire to acquire more information, rather than the mere perceptual salience of the distractors. Second, as noted in the Introduction, our study does not differentiate between different theoretical proposals about how pragmatic inference is being computed in the current task. However, we believe that we are addressing development of implicatures in general. Third, as with nearly all work in the literature on implicature processing, we address the performance of only relatively high socioeconomic status children in a Western context. In our ongoing work we address the generalizability of our task to other developmental contexts (Fortier, Kellier, Fernández Flecha, & Frank, in prep).

In sum, our work shows evidence that from at least 3 years, children are able to compute ad-hoc implicatures, and that younger children's failures with implicatures on an referent-choosing task are confounded by the salience mismatch between possible referents. This pattern is consistent with a broader generalization, namely that tasks that have typically been used to look at children's implicature processing have a variety of extraneous processing demands, which may explain why it has been difficult to see children's underlying pragmatic abilities in such paradigms. Thus, our work demonstrates the importance of using a range of methods to measure children's pragmatic processing.

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Table 1

Demographic information of participants in the original and replication samples.

Sample	Age bin	Number of participants	Mean (years)	SD (years)	% Girls
original	2	27	2.51	0.31	70.40
original	3	30	3.54	0.28	56.70
original	4	26	4.45	0.29	34.60
original	5	19	5.30	0.23	57.90
replication	2	25	2.66	0.27	56.00
replication	3	29	3.49	0.27	55.20
replication	4	25	4.39	0.29	40.00

Table 2

Predictor mean estimates with standard deviation and 95% credible interval information for a Bayesian linear mixed-effects model predicting accurate selection of target.

Predictor	Mean	SD	95% CI-Lower	95% CI-Upper
Intercept	4.60	3.86	-4.94	11.71
Age	2.30	3.80	-5.84	10.06
Control-double	-0.07	3.53	-7.86	7.71
Implicature	-3.33	4.41	-13.11	4.46
More features	-0.68	3.70	-9.83	5.81
Control-double * Age	-0.72	0.38	-1.46	0.03
Implicature * Age	-1.00	0.38	-1.77	-0.29
More features * Age	-0.59	0.35	-1.28	0.09
Control-double * More features	-0.06	0.56	-1.16	1.02
Implicature * More features	0.23	0.63	-1.00	1.46
Control-double * Age * More features	0.66	0.41	-0.13	1.49
Implicature * Age * More features	1.16	0.44	0.32	2.02

Table 3

Predictor mean estimates with standard deviation and 95% credible interval information for a Bayesian linear mixed-effects model predicting log reaction time to select the target.

| Predictor	Mean	SD	95% CI-Lower	95% CI-Upper
Intercept	7.80	2.24	3.19	12.79
Age	-0.22	2.83	-6.43	5.97
Control-double	0.02	3.16	-6.98	6.05
Implicature	-0.05	3.65	-8.44	6.01
More features	0.25	2.67	-4.92	6.56
Control-double * Age	-0.03	0.02	-0.07	0.02
Implicature * Age	0.09	0.03	0.04	0.14
More features * Age	0.02	0.02	-0.02	0.07
Control-double * More features	0.09	0.04	0.02	0.17
Implicature * More features	-0.04	0.06	-0.15	0.07
Control-double * Age * More features	0.01	0.03	-0.05	0.06
Implicature * Age * More features	-0.07	0.04	-0.13	0.00
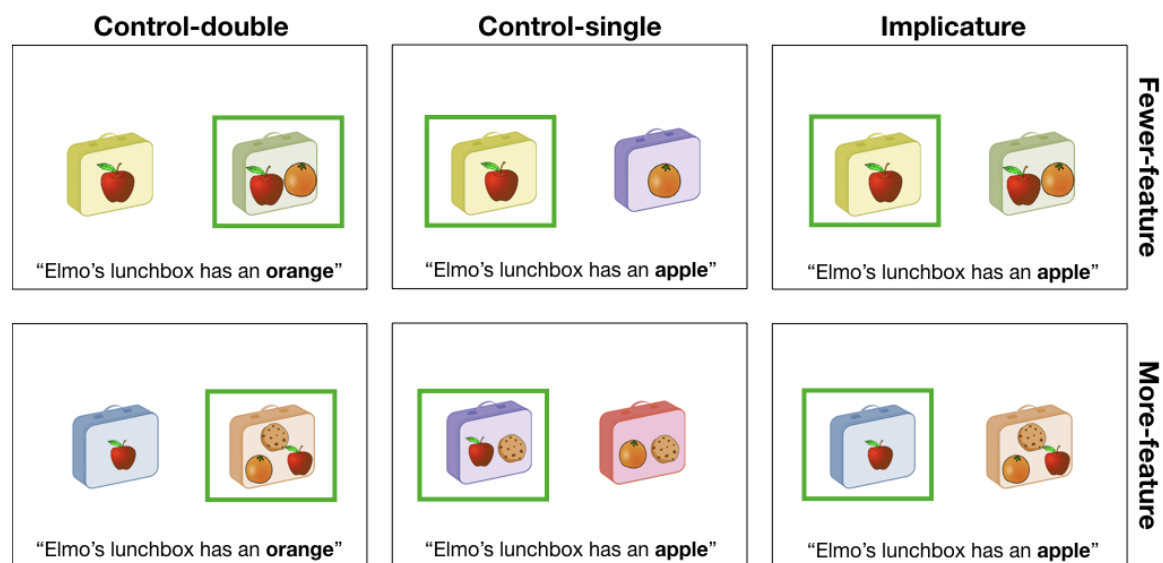
Figure 1. Trial types. Green box indicates the target referent for each trial given the utterance at the bottom.
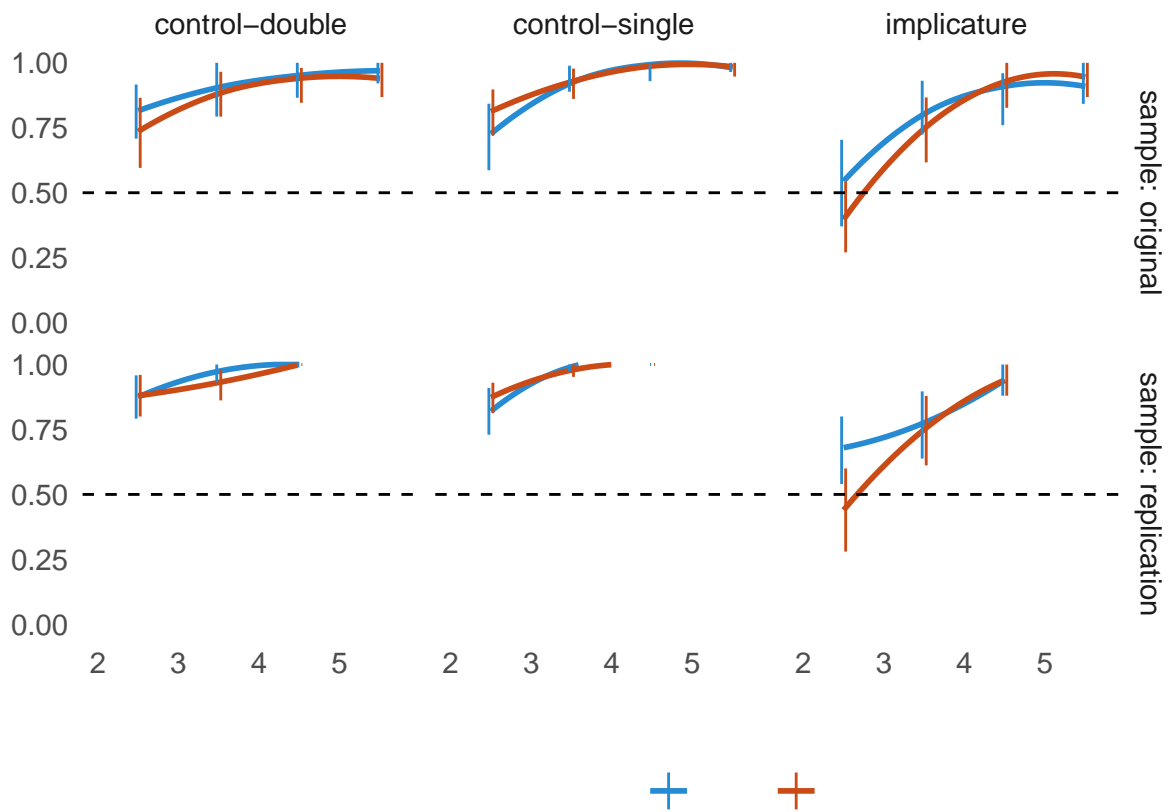
Figure 2. Proportion of 2- to 5-year-old children selecting the target in the original and replication samples (rows) in different trial types (columns). Data are binned into 6-month age groups for visualization purposes (all analyses are conducted on continuous data). Lines are loess smoothing functions. Blue lines represent trials in which there were fewer features present (2-vs-1 for control-double and implicature, 1-vs-1 for control-single) and red lines represent trials with more features (3-vs-1 for control-double and implicature, 2-vs-2 for control-single). Error bars are 95% confidence intervals, and are placed at the mean of the age bin and offset slightly to avoid overplotting. Dashed line represents a conservative chance level at 50%.
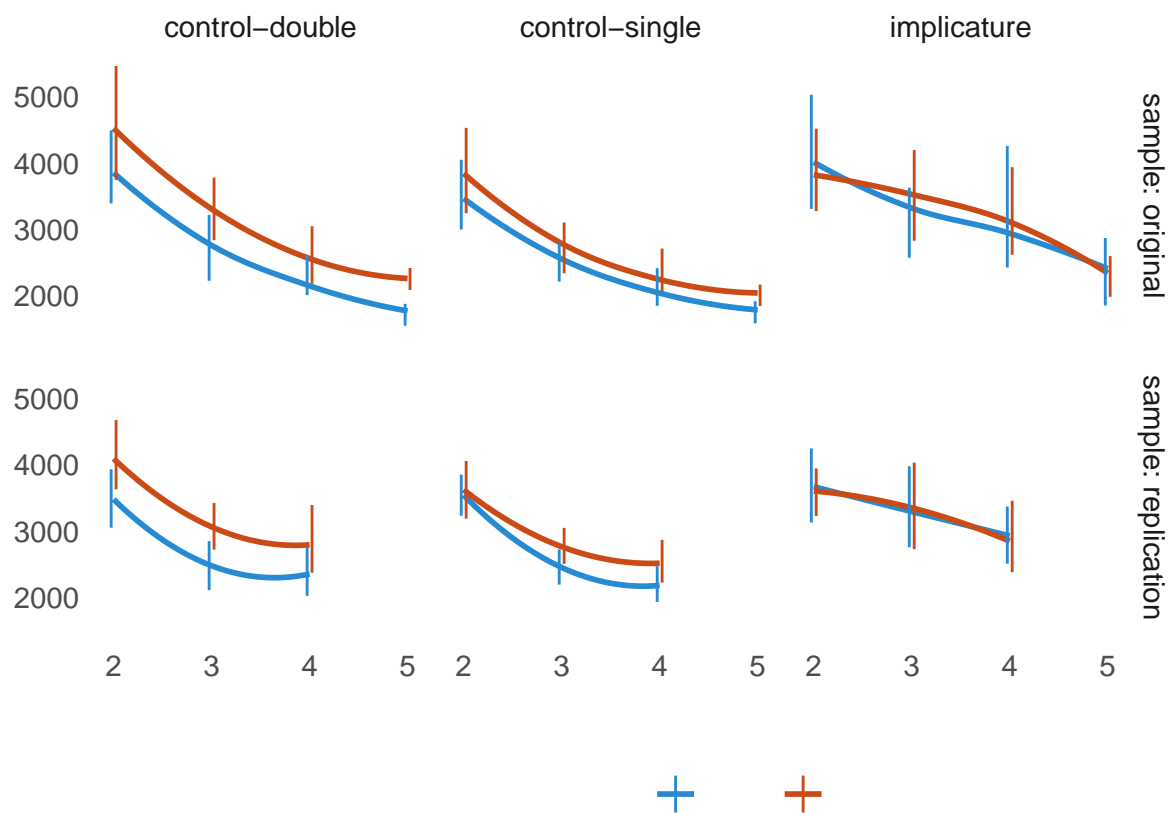
Figure 3. Reaction time to select the correct target referent. Conventions are identical to Figure 2.