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Preschoolers Flexibly Adapt to Linguistic Input in a Noisy Channel

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Abstract

Because linguistic communication is inherently noisy and uncertain, adult language comprehenders integrate bottom-up cues from speech perception with top-down expectations about what speakers are likely to say. Further, in line with the predictions of ideal-observer models, past results have shown that adult comprehenders flexibly adapt how much they rely on these two kinds of cues in proportion to their changing reliability. Do children also show evidence of flexible, expectation-based language comprehension? We presented preschoolers with ambiguous utterances that could be interpreted in two different ways, depending on whether the children privileged perceptual input or top-down expectations. Across three experiments, we manipulated the reliability of both their perceptual input and their expectations about the speaker's intended meaning. As predicted by noisy-channel models of speech processing, results showed that 4- and 5-year-old—but perhaps not younger—children flexibly adjusted their interpretations as cues changed in reliability.

Keywords

language processing, noisy channel, cognitive development, open data, open materials

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Imagine that Bob hears Alice say "I had carrots and bees for dinner." Perhaps she visited an exotic restaurant, and he should ask how the bees tasted. Or perhaps he misheard her or she misspoke—she actually ate peas. To interpret Alice's utterance, Bob must integrate perceptual information from her speech with his expectations about what words usually go with "carrots" and "dinner" and what foods people usually eat. Modern statistical language-processing systems use a body of theory based on this idea—language is a noisy channel, and Bob can correct perceptual errors using linguistic expectations about what Alice was likely trying to say (Jelinek, 1976; Shannon, 1948).

Noisy-channel principles provide a powerful framework for explaining how people process language in complex and uncertain real-time communicative situations (Clayards, Tanenhaus, Aslin, & Jacobs, 2008; Jaeger, 2010; Levy, 2008). According to this view, comprehenders integrate prior expectations with perceptual data probabilistically, weighting each according to its reliability (Ernst & Banks, 2002; Jacobs, 1999). In one demonstration of such integration, Gibson, Bergen, and Piantadosi (2013) presented participants with semantically implausible sentences (e.g., "The mother gave the candle the daughter"), which could have been produced by small typographical errors in more plausible sentences ("The mother gave the candle to the daughter"). Adults corrected these errors, and critically did so more often when they thought the communicative channel was noisy (and hence the perceptual signal was unreliable). Conversely, adults corrected these errors less often when they thought they were in a silly context, in which many other sentences were similarly implausible.

Do children also process language in this flexible, expectation-based way? Toddlers use social and pragmatic cues to determine speakers' intended referent in otherwise ambiguous situations (Carpenter, Nagell,

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Tomasello, Butterworth, & Moore, 1998; E. V. Clark, 2009). They also use acoustic cues, such as speaker identity, and linguistic cues, such as grammatical gender (Creel, 2012; Lew-Williams & Fernald, 2007). However, these successes have been shown only when all cues point to the same meaning. When top-down and bottom-up cues conflict, preschoolers often overweigh, or even attend exclusively to, lower-level cues (Snedeker & Trueswell, 2004; Trueswell, Sekerina, Hill, & Logrip, 1999).

Outside of language processing, even older children sometimes fail to combine cues (Gori, Del Viva, Sandini, & Burr, 2008; Nardini, Bedford, & Mareschal, 2010; Nardini, Jones, Bedford, & Braddick, 2008). For example, while adults integrate visual and haptic cues to estimate both size and orientation, 8-year-olds rely exclusively on vision for orientation and haptic information for size. Thus, children's successful use of independent sources of information—for example, about high-level speaker expectations (Graham, Sedivy, & Khu, 2014; Matthews, Lieven, & Tomasello, 2010) or speaker reliability (Pasquini, Corriveau, Koenig, & Harris, 2007)—does not guarantee that children will be able to integrate these sources with perceptual uncertainty.

We created a paradigm to manipulate expectations about speaker plausibility and perceptual noise independently. We introduced preschoolers (and adults) to either a plausible or an implausible speaker, both of whom initially uttered unambiguously different sentences, such as "my cat has three little kittens" and "my cat has three little hammers," respectively (Fig. 1a). Participants were then asked to resolve the intended meaning of ambiguous sentences, such as the "bees/peas" example given earlier, which either could be produced by a perceptual error or could convey implausible content (Fig. 1b). If children integrate channel noise with expectations about what speakers are likely to say, their interpretations should be a product of both of these factors.

Experiment 1

Method

Participants. Children were recruited at the Bing Nursery School on Stanford University's campus. Children were asked if they would be willing to play a game with the experimenter and were informed that they could stop playing at any time. Children were randomly assigned to speaker conditions, and we collected data until there were at least 20 participants in each condition (similar to the sampling method in other psycholinguistic studies of children; e.g., Creel, 2012; Trueswell et al., 1999). Data from 43 children were collected; children were all between 4 and 6 years old, and approximately half were female. Neither age nor gender distribution varied significantly between the two conditions—plausible-speaker condition: 23 children (12 girls, 11 boys), mean age = 4.6 years, age range = 4.0–5.3 years; implausible-speaker condition: 20 children (10 girls, 10 boys), mean age = 4.7 years, age range = 4.1–5.4 years.

Adult participants were recruited through Amazon's Mechanical Turk. Only participants with U.S. Internet protocol (IP) addresses were included, and participants were paid 30¢ each. Participants were assigned randomly to speaker condition (plausible vs. implausible). A sample size of 50 was chosen on the basis of the effect size in the child data.

Stimuli, design, and procedure. Experiment 1 consisted of a series of trials on which participants saw two pictures and heard a sentence referring to one of them. Pictures were constructed from clip art freely available on the Internet, and audio was recorded by a female native speaker of English. To increase the ambiguity of the spoken utterances, and thus give us more power to detect error correction, we convolved all of the audio recordings with Brown noise of amplitude ~0.6 using the Audacity (2015) audio editor. We played the recordings back through computer speakers to produce additional distortion. The average signal-to-noise ratio in these recordings was 4.5 dB.

On each trial, participants saw one semantically plausible picture and one semantically implausible picture and had to click on the one that matched the speaker's description. On exposure trials, the referential expression for each picture was highly distinct, and therefore the speaker's reference was unambiguous (Fig. 1a). In contrast, on test trials, the referential expressions for the two pictures differed phonetically in a single consonant or vowel, and therefore the speaker's reference was ambiguous (Fig. 1b). Each participant saw one block of eight exposure trials, followed by a block of seven test trials. The order of trials within these two blocks was randomized across participants, as was the on-screen position (left vs. right) of the two pictures on each trial. For participants in the plausible-speaker condition, the speaker referred to the plausible referent on each of the eight exposure trials. In contrast, for participants in the implausible-speaker condition, the speaker referred to the implausible referent on each exposure trial. In both conditions, the speaker referred to the implausible referent on all seven test trials.

For all participants, the experiment began with a short introduction to Katie, the speaker who would be referring to pictures throughout the task. After seeing her picture and being introduced to her, participants completed the trials by selecting which of the two pictures corresponded to the speaker's description. They responded

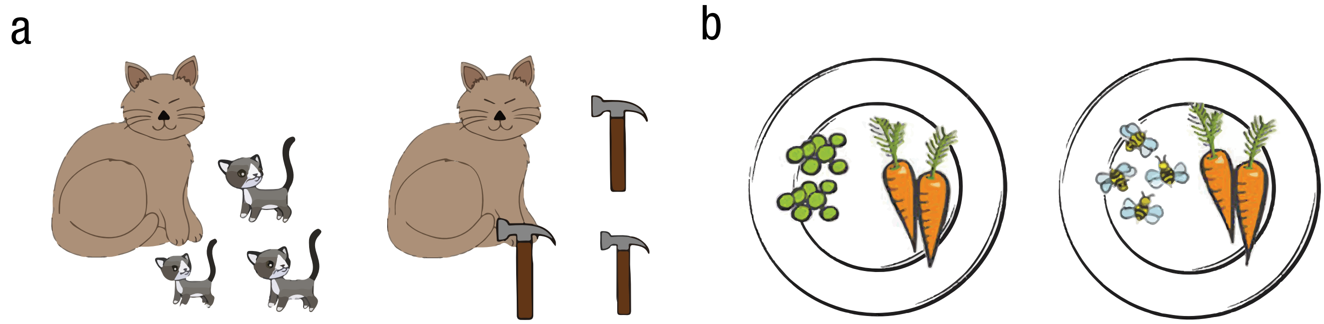

Fig. 1. Example pictures from (a) an exposure trial and (b) a test trial. On all trials, participants were shown two pictures that differed in a single way—one was plausible (left panels) and one was implausible (right panels)—and they heard an audio description of one of the pictures. On exposure trials, the referential expressions were phonologically distinct (e.g., "my cat has three little kittens" vs. "my cat has three little hammers"). In contrast, on test trials, the referential expressions differed phonologically in only a single consonant or vowel (e.g., "I had carrots and peas for dinner" vs. "I had carrots and bees for dinner"). For both trial types, participants had to select the picture described by the speaker. Stimuli adapted from images obtained from clipartbest.com.

either with the mouse (adults) or by touching one of the pictures on an iPad (children). Audio was presented to children through a set of external computer speakers approximately 2.5 ft away. Adults performed the experiment through Mechanical Turk, and thus their listening conditions were likely more variable. Adults were instructed by a series of written prompts; children were given instructions by a live experimenter. Three children's responses were coded from video because of a software error.

Results

To validate our manipulation, we first analyzed the effect of the speaker on exposure trials. If participants were attending to the speaker's descriptions during exposure trials, those in the plausible condition should have been more likely to choose the plausible referent (e.g., kittens), and those in the implausible condition should have been more likely to choose the implausible referent (e.g., hammers). We tested this prediction formally by fitting mixed-effects logistic regressions predicting choice on exposure trials, separately for children and adults. In this and all other models we report, conditions were dummy coded, and implausible was treated as the reference category. Random effects for all models were always maximal—random intercepts were included for subjects and items. As predicted, both children and adults selected the plausible referent more often in the plausible-speaker condition than in the implausible-speaker condition (children: $\beta = 4.54$, $z = 8.28$, $p < .001$, $d = 5.56$; adults: $\beta = 9.41$, $z = 5.83$, $p < .001$, $d = 24.3$). We then fitted a model to all of the data, asking whether adults and children were differentially affected by speaker condition; this model included main effects of condition and age group and an interaction between the two. We found significant effects of speaker condition ($\beta = 9.52$, $z = 7.87$, $p < .001$), age group ($\beta = 1.96$, $z = 3.33$, $p < .001$), and their interaction ($\beta = -5.01$, $z = -4.12$, $p < .001$). Thus, both children and adults were sensitive to the speaker manipulation during exposure trials, selecting the appropriate referent whether or not the request was implausible, although adults selected the correct referent more often in both conditions.

Did this exposure to a plausible versus an implausible speaker change participants' expectations on the ambiguous test trials? Figure 2 shows the proportion of both children and adults who selected the plausible referent at test in both conditions. As predicted, both groups were sensitive to the manipulation, selecting the plausible referent more often in the plausible-speaker condition than in the implausible-speaker condition (children: $\beta = 1.10$, $z = 3.53$, $p < .001$, $d = 1.10$; adults: $\beta = 3.11$, $z = 3.56$, $p < .001$, $d = 1.09$). While children were more likely than adults to pick the plausible referent in both conditions, the effect size of the difference between conditions was nearly identical in adults and children, which indicates equal adaptation to the plausible and the implausible speakers. To confirm these findings formally, we again fitted a mixed-effects regression predicting choice on test trials from age group (child vs. adult), speaker condition (plausible vs. implausible), and their interaction. Both of the main effects of age group ($\beta = 1.96$, $z = 3.33$, $p < .001$) and speaker condition ($\beta = 2.33$, $z = 4.40$, $p < .001$) were significant, but the interaction was not ($\beta = -1.01$, $z = -1.53$, $p = .13$). Thus, children and adults, to the same degree, were more likely to select the plausible referent on ambiguous test trials when the speaker had previously referred to a plausible referent on unambiguous exposure trials.

When children and adults were exposed to a speaker who was likely to produce semantically implausible

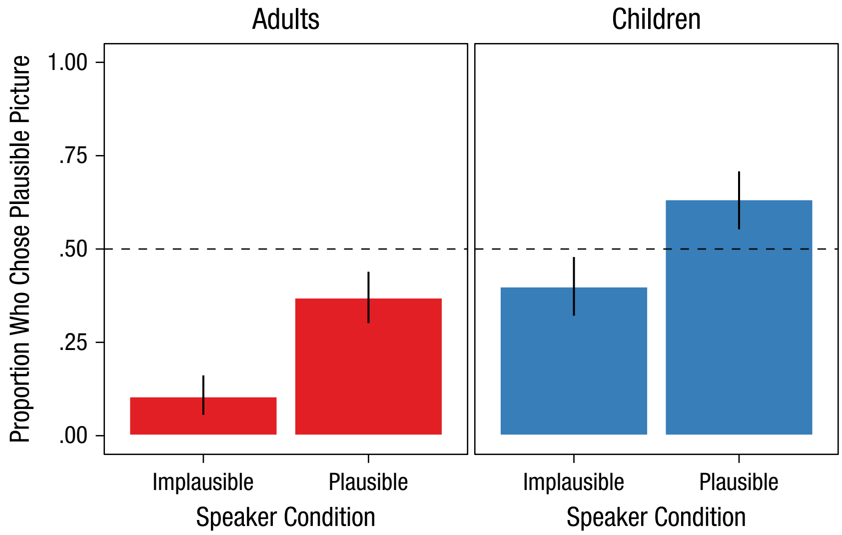

Fig. 2. Results from Experiment 1 test trials: group-averaged proportion of participants who chose the plausible picture as a function of the speaker's actual description, separately for adults and children. Error bars show 95% confidence intervals computed by nonparametric bootstrapping at the subject level using the multi_boot_standard function from the langcog package (Braginsky, Yurovsky, & Frank, 2015). The dashed line indicates chance performance.

utterances (e.g., "my cat has three little hammers"), they were more likely to interpret ambiguous utterances literally instead of error-correcting to a more semantically plausible alternative. Intriguingly, the size of this adaptation was nearly identical in both groups, which suggests that 4- and 5-year-olds were already adapting as rapidly as adults. Children were, however, more likely overall to pick the plausible referent during ambiguous test trials, which suggests that they generally rely more on their expectations than do adults. This finding is consonant with other evidence showing significantly more noise in children's perceptual systems (Neuman & Hochberg, 1983) but in contrast to cases in which children appear to overrely on bottom-up cues (Snedeker & Trueswell, 2004; Trueswell et al., 1999). These results suggest that children's relative reliance on bottom-up or top-down cues may not be fixed, but rather may be an adaptive function of the reliability of their processing of different kinds of cues. We explored this question further in Experiment 3 after we first replicated Experiment 1 in a larger sample of children.

Experiment 2

Experiment 2 was designed to replicate Experiment 1 in a larger and developmentally broader sample. We asked two related questions: (a) Does the use of expectations about what speakers are likely to say increase over development, and (b) if so, is this due to improving abilities to form these expectations or to use them in processing ambiguous utterances?

Method

For Experiment 2, children were recruited from the floor of the Children's Discovery Museum of San Jose, California. An experimenter approached the child and parent and obtained informed consent before inviting both to enter a separate room in which an iPad and camera were set up. Data were collected from a total of 146 children, 6 of whom were excluded because their parents indicated that they were exposed to English less than 50% of the time. As before, children were recruited until at least 20 had been run in each condition for each of three age groups: 3-, 4-, and 5-year-olds. Children's ages were comparable across conditions, although gender varied more because of the sampling procedure (Table 1). The stimuli, design, and procedure were exactly the same as in Experiment 1.

Results

Because genders were imbalanced across conditions, we performed all analyses with gender as a fixed effect. In no case did this gender effect reach significance, nor did it affect any of the other inferences. We thus do not report it here, but interested readers can see all of these models at our project page on GitHub: dyurovsky.github.io/noisy-kids/.

Table 1. Demographic Information for Participants in Experiment 2

Age group and speaker condition	Gender (*n*)		Age (years)	
	Boys	Girls	*M*	Range
Three-year-olds				
Plausible	11	16	3.50	3.00–3.93
Implausible	13	8	3.49	3.02–3.93
Four-year-olds				
Plausible	14	7	4.60	4.22–4.97
Implausible	5	23	4.51	4.00–4.94
Five-year-olds				
Plausible	4	19	5.49	5.01–5.95
Implausible	8	12	5.48	5.05–5.90

As in Experiment 1, we first established that children understood the task and responded appropriately to the plausible and implausible speakers on exposure trials. We began by fitting a mixed-effects logistic regression for each age group separately (exposure ~ speaker condition + (1 | subject) + (1 | item)). As in Experiment 1, conditions were dummy coded, and implausible was treated as the reference category. Random effects for all models were always maximal—random intercepts for participants and items. In all three age groups, children were more likely to select the plausible referent in the plausible-speaker condition (3-year-olds: $\beta = 1.43$, $z = 3.71$, $p < .001$, $d = 1.20$; 4-year-olds: $\beta = 3.10$, $z = 6.63$, $p < .001$, $d = 2.66$; 5-year-olds: $\beta = 5.55$, $z = 7.39$, $p < .001$, $d = 8.27$). We then asked whether children's behavior changed over development, including an interaction term for age and speaker condition in the model. A mixed-effects model fitted to all of the children's data showed main effects of both age ($\beta = -0.74$, $z = -4.18$, $p < .001$) and speaker condition ($\beta = -6.16$, $z = 1.81$, $p < .001$), and also an interaction between the two ($\beta = 2.12$, $z = 7.61$, $p < .001$). Thus, older children showed a greater sensitivity than younger children to the speaker on the unambiguous exposure trials.

We next turned to the test trials. When we examined each age group separately, we found that as in Experiment 1, both 4- and 5-year-olds leveraged their previous experience with the speaker when interpreting the ambiguous test utterances (Fig. 3). However, 3-year-olds did not (3-year-olds: $\beta = 0.06$, $z = 0.21$, $p = .83$, $d = 0.06$; 4-year-olds: $\beta = 1.01$, $z = 2.87$, $p < .01$, $d = 0.82$; 5-year-olds: $\beta = 1.35$, $z = 3.96$, $p < .001$, $d = 1.24$). A mixed-effects regression fitted to all of the data confirmed this developmental change in sensitivity, revealing a significant main effect of age group ($\beta = -0.43$, $z = -2.75$, $p < .01$), a marginal effect of speaker condition ($\beta = -1.71$, $z = -1.82$, $p = .07$), and a significant interaction between the two ($\beta = 0.54$, $z = 2.58$, $p = .01$). In line with previous work, these results show that 3-year-olds have trouble using top-down expectations about the speaker's intended meaning when processing ambiguous utterances (Kidd & Bavin, 2005). However, children appear to improve significantly over the next 2 years (Rabagliati, Pylkkänen, & Marcus, 2013).

Older children were thus more sensitive than younger children to the speaker's utterances on unambiguous exposure trials and relied more on their expectations of what the speaker was likely to say on ambiguous test trials. Did older children rely more on their expectations because they had built stronger expectations on exposure trials? If so, individual differences in children's performance on exposure trials should explain away the effect of age on test trials. In contrast, if the ability to leverage these expectations improves over development, age should predict additional variance in test-trial responses over and above children's responses on exposure trials.

To determine whether this was the case, we fitted an additional model including the proportion of exposure trials on which individual children had selected the plausible referent (test ~ age group + speaker condition × exposure + (1 | subject) + (1 | item)). We assumed that children who more frequently selected the plausible referent in the plausible-speaker condition or less frequently selected the plausible referent in the implausible-speaker condition were encoding more information about the speaker's plausibility.

This model showed a significant effect of speaker plausibility ($\beta = 1.92$, $z = 3.39$, $p = .001$), a significant effect of individual differences in selecting the plausible referent on exposure trials ($\beta = 2.84$, $z = 4.60$, $p < .001$), and a significant interaction between these two variables ($\beta = -3.32$, $z = -3.64$, $p < .001$), but no effect of age ($\beta = 0.06$, $z = 0.56$, $p = .57$). This was true both when all of the children were analyzed and when only the 4- and 5-year-olds were included in the model. Older children's increased use of expectations about the speaker's intended meaning on ambiguous test trials appears to be explained by their stronger encoding of speaker preferences on the unambiguous exposure trials.

It appears that older children relied more on their expectations about what the speaker was likely to say because they had formed stronger expectations rather than because they relied on expectations differently. Experiments 1 and 2 thus show that children's reliance on expectations about a speaker's intended meaning remains relatively constant across the 3- to 6-year age range, but that their ability to build these expectations improves gradually across development (Graham et al., 2014; Matthews et al., 2010).

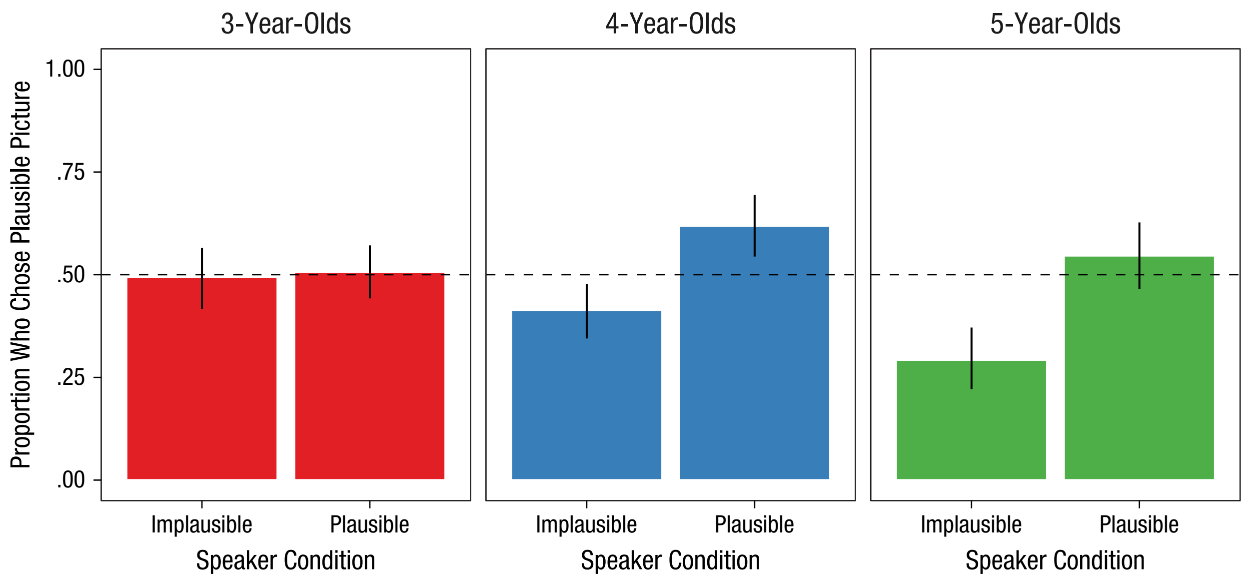

Fig. 3. Results from Experiment 2 test trials: group-averaged proportion of participants who chose the plausible picture as a function of speaker condition, separately for 3-, 4-, and 5-year-olds. Error bars show 95% confidence intervals computed by nonparametric bootstrapping at the subject level using the multi_boot_standard function from the langcog package (Braginsky, Yurovsky, & Frank, 2015). The dashed line indicates chance performance.

Experiment 3

Experiment 3 tested a second prediction of noisy-channel processing: As speech becomes noisier, and thus less reliable, children should rely more on their expectations.

Method

Participants. For Experiment 3, children were again recruited from the floor of the Children's Discovery Museum of San Jose, California. As 3-year-olds did not perform differently from chance in Experiment 2, we focused on 4- and 5-year-olds. Data were collected from 114 children, 1 of whom was excluded because he was exposed to English less than 50% of the time and 2 of whom were excluded for parent-reported developmental disabilities. As before, children were recruited until at least 20 had been run in each condition. Children's ages and genders were comparable across conditions (Table 2).

Stimuli, design, and procedure. The stimuli and procedure were the same as in Experiments 1 and 2 with a few small changes. First, one additional test trial was added to increase power. Second, two versions of each acoustic recording were made using Audacity (2015) software. One was recorded in a soundproof room by a female native-English speaker. The second was constructed by convolving each recording with randomly generated Brown noise with an amplitude of 0.7, which produced an average signal-to-noise ratio of −19.5 dB. The first version was used in the no-noise condition, and the second was used to replicate the two conditions from Experiment 1 as well as for the control condition.

In addition, because all of the test trials required the listener to select the semantically implausible referent, it is possible that exposure to an implausible speaker induced listeners to generally select the implausible referent at test, independently of the acoustic input. In Experiment 3, we also provided a control condition in which the implausible speaker from exposure trials referred to the semantically plausible referent at test. If children inferred from the unambiguous exposure trials that the goal of the game was to pick the silly referent, they should have continued to select the implausible referent on test trials. In contrast, if exposure trials caused them to adjust the relative weights on acoustic information and expectations about the speaker's intended meaning, they should instead have selected the plausible referent at test.

Results

As in the previous experiments, we first established that children understood the task and encoded the differences between plausible and implausible speakers on exposure trials. As in Experiment 1, conditions were dummy coded, and implausible was treated as the reference category. Random effects for all models were always maximal—random intercepts for participants and items. In each noise condition, children who heard the plausible speaker were more likely to select the plausible

Table 2. Demographic Information for Participants in Experiment 3

Speaker condition and noise condition	Gender (n)		Age (years)	
	Boys	Girls	M	Range
Plausible				
No noise	13	8	4.89	4.00–5.83
Noisy	14	12	4.89	4.02–5.94
Implausible				
No noise	8	12	4.98	4.00–5.83
Noisy	13	11	5.01	4.01–5.92
Noisy (control)	9	11	4.96	4.15–5.91

referent on exposure trials than those who heard the implausible speaker (no-noise condition: β = 6.92, z = 6.15, p < .001, d = 7.94; noisy condition: β = 4.91, z = 8.26, p < .001, d = 4.46). Further, children in the implausible-speaker control condition performed no differently from those in the implausible-speaker condition, which licenses comparison of their test trials (β = 0.35, z = 0.81, p = .42, d = 0.21).

Second, we again compared the conditions with each other, fitting a mixed-effects regression predicting choice on exposure trials from noise condition and speaker condition. Compared with children in the implausible-speaker condition, children in the plausible-speaker condition were more likely to pick the plausible referent on exposure trials (β = 6.62, z = 8.88, p < .001). Children exposed to the control speaker did not perform differently on exposure trials from those exposed to the implausible speaker, as predicted (β = 0.36, z = 0.83, p = .42). Further, the model showed a marginal effect of noise condition (β = 0.86, z = 1.74, p = .08) and a significant interaction between the noise and speaker conditions (β = −1.71, z = −2.15, p = .03), which indicates that the addition of noise moved children's performance in both conditions closer to chance.

Did children integrate the noise level of the acoustic stimuli with expectations about the speaker's intended meaning on ambiguous test trials? Figure 4 shows the proportion of trials on which children selected the plausible referent at test in both speaker and noise conditions. As predicted, children showed sensitivity to both speaker reliability and acoustic noise. Children selected the plausible referent at test, correcting the error in their acoustic input more often when the speaker had said plausible things on exposure trials (noisy condition: β = 1.17, z = 3.72, p < .001, d = 1.17; no-noise condition: β = 1.57, z = 4.14, p < .001, d = 1.17). In addition, regardless of speaker plausibility, children selected the plausible referent more frequently when the acoustic input was noisy than when it was not. To quantify this pattern, we again fitted a mixed-effects regression predicting choice on test trials from speaker condition and noise condition as well as their interaction. As predicted, main effects of both speaker condition (β = 1.96, z = 3.20, p < .001) and noise condition (β = 0.81, z = 2.21, p = .03) were significant, but their interaction was not (β = 0.33, z = 0.65, p = .51).

Finally, one alternative explanation for the difference between speaker conditions is that children simply followed their expectations at all times (e.g., that those exposed to the implausible speaker chose silly responses regardless of the question). To test this alternative, we asked whether children who responded to an implausible speaker on exposure trials always chose the implausible referent on test trials even when the speaker referred to the plausible referent (implausible-speaker control condition). A mixed-effects model estimating plausible referent selection on test trials showed that compared with children exposed to the plausible speaker, children exposed to the implausible speaker were less likely to pick the plausible referent at test (β = −1.57, z = −4.14, p < .001, d = 1.17), but children in the control condition were more likely to select the plausible referent (β = 1.06, z = 2.05, p = .04, d = 1.93). Thus, children who were asked for the plausible referent at test selected it, even when the speaker had previously always referred to the implausible referent. This control condition provided further evidence that children were attending to and responding to the acoustic input from the speaker on test trials, integrating it with their prior expectations.

General Discussion

When people use language to communicate, they do more than process the sounds they hear; they try to infer speakers' intended meaning (H. H. Clark, 1996). Because perception is inherently uncertain, expectations about what speakers are likely to say play an important role in resolving interpretive ambiguities (Frank & Goodman, 2012; Grice, 1975). Our experiments show that children are able to integrate expectations about what speakers are likely to say with perceptual uncertainty by the ages of 4 to 5 years, though perhaps not earlier. Children's reliance on expectations about speakers' intended meaning appears to track their developing ability to form these expectations, an ability that improves over the preschool years.

In our experiments, children adjusted their reliance on expectations as much as adults did, but they also generally relied more on top-down expectations. Because of the greater noise inherent in children's perceptual-processing systems, the same acoustic stimulus may effectively be less reliable for children than adults (Lyons & Ghetti, 2011; Neuman & Hochberg, 1983). Perhaps children with impaired acoustic processing rely relatively more on their expectations, whereas children with

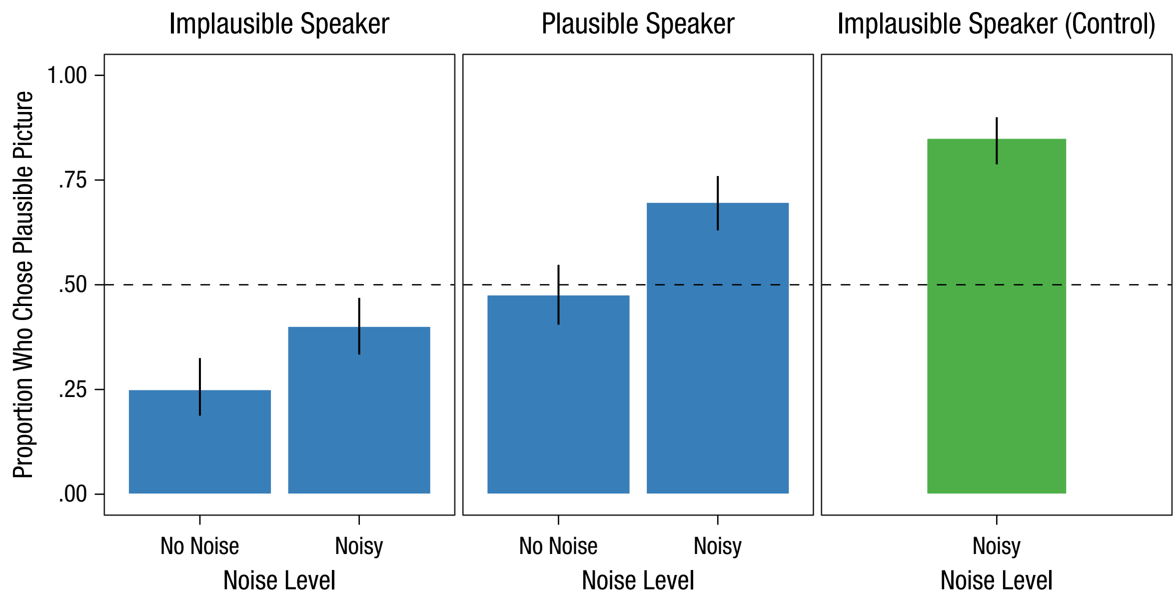

Fig. 4. Results from Experiment 3 test trials: group-averaged proportion of participants who chose the plausible picture as a function of whether or not the speaker's expression was accompanied by noise, separately for the three speaker conditions. Error bars show 95% confidence intervals computed by nonparametric bootstrapping at the subject level using the multi_boot_standard function from the langcog package (Braginsky, Yurovsky, & Frank, 2015). The dashed line indicates chance performance.

impaired higher-level linguistic expectations rely more on acoustics. Our paradigm could be used to test this prediction.

How much should listeners rely on acoustics, and how much should they rely on expectations? Ideal-observer models predict that cues should be weighted in proportion to their reliability (Ernst & Banks, 2002; Jacobs, 1999). This prediction holds for adults across levels in language processing from phonology to syntax (e.g., Gibson et al., 2013; McClelland, Mirman, & Holt, 2006). In our experiments, we cannot say that children's weighting was optimal, only that it was adaptive: Weighting changed with manipulations of reliability (as in Gibson et al., 2013). It is a challenge for future work to derive independent measures of reliability for high-level linguistic stimuli. Further, because our participants adapted to only one speaker, we cannot know whether their adaptation was speaker-specific or speaker-general. However, an attractive feature of the noisy-channel framework is that it can be applied hierarchically, with appropriate adaptation predicted at the level of speaker, community, and lexicon as evidence accumulates (Kleinschmidt & Jaeger, 2015).

Our experiments show that children, like adults, flexibly trade off between information sources in language comprehension in response to their reliability. Noisy-channel principles thus provide a framework for understanding language processing in both adults and children.

Action Editor

Matthew A. Goldrick served as action editor for this article.

Author Contributions

D. Yurovsky, S. Case, and M. C. Frank designed the study. D. Yurovsky and S. Case collected the data. D. Yurovsky, S. Case, and M. C. Frank analyzed the data. D. Yurovsky and M. C. Frank wrote the manuscript. All authors approved the final version of the manuscript for submission.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Open Practices

All data and materials have been made publicly available via the Open Science Framework and GitHub. The former can be accessed at https://osf.io/96cx7/, and the latter can be accessed at https://github.com/dyurovsky/noisy-kids and http://dyurovsky.github.io/noisy-kids/. The complete Open Practices Disclosure for this article can be found at http://pss.sagepub.com/content/

by/supplemental-data. This article has received the badges for Open Data and Open Materials. More information about the Open Practices badges can be found at https://osf.io/tvyxz/wiki/1.%20View%20the%20Badges/ and http://pss.sagepub.com/content/25/1/3.full.

References

Audacity Team. (2015). Audacity (Version 2.1.1) [Computer software]. Retrieved from http://www.audacityteam.org/

Braginsky, M., Yurovsky, D., & Frank, M. (2015). Langcog [R package]. Retrieved from https://github.com/langcog/langcog

Carpenter, M., Nagell, K., Tomasello, M., Butterworth, G., & Moore, C. (1998). Social cognition, joint attention, and communicative competence from 9 to 15 months of age. *Monographs of the Society for Research in Child Development*, *63*(4, Serial No. 255), i–143.

Clark, E. V. (2009). *First language acquisition* (2nd ed.). Cambridge, England: Cambridge University Press.

Clark, H. H. (1996). *Using language*. Cambridge, England: Cambridge University Press.

Clayards, M., Tanenhaus, M. K., Aslin, R. N., & Jacobs, R. A. (2008). Perception of speech reflects optimal use of probabilistic speech cues. *Cognition*, *108*, 804–809.

Creel, S. C. (2012). Preschoolers' use of talker information in on-line comprehension. *Child Development*, *83*, 2042–2056.

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, *415*, 429–433.

Frank, M. C., & Goodman, N. D. (2012). Predicting pragmatic reasoning in language games. *Science*, *336*, 998.

Gibson, E., Bergen, L., & Piantadosi, S. T. (2013). Rational integration of noisy evidence and prior semantic expectations in sentence interpretation. *Proceedings of the National Academy of Sciences, USA*, *110*, 8051–8056.

Gori, M., Del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not integrate visual and haptic form information. *Current Biology*, *18*, 694–698.

Graham, S. A., Sedivy, J., & Khu, M. (2014). That's not what you said earlier: Preschoolers expect partners to be referentially consistent. *Journal of Child Language*, *41*, 34–50.

Grice, H. P. (1975). Logic and conversation. In P. Cole & J. Morgan (Eds.), *Syntax and semantics: Speech acts* (Vol. 3, pp. 41–58). New York, NY: Academic Press.

Jacobs, R. A. (1999). Optimal integration of texture and motion cues to depth. *Vision Research*, *39*, 3621–3629.

Jaeger, F. T. (2010). Redundancy and reduction: Speakers manage density. *Cognitive Psychology*, *61*, 23–62.

Jelinek, F. (1976). Continuous speech recognition by statistical methods. *Proceedings of the IEEE*, *64*, 532–556.

Kidd, E., & Bavin, E. L. (2005). Lexical and referential cues to sentence interpretation: An investigation of children's interpretations of ambiguous sentences. *Journal of Child Language*, *32*, 855–876.

Kleinschmidt, D. F., & Jaeger, T. F. (2015). Robust speech perception: Recognize the familiar, generalize to the similar, and adapt to the novel. *Psychological Review*, *122*, 148–203.

Levy, R. (2008). Expectation-based syntactic comprehension. *Cognition*, *106*, 1126–1177.

Lew-Williams, C., & Fernald, A. (2007). Young children learning Spanish make rapid use of grammatical gender in spoken word recognition. *Psychological Science*, *18*, 193–198.

Lyons, K. E., & Ghetti, S. (2011). The development of uncertainty monitoring in early childhood. *Child Development*, *82*, 1778–1787.

Matthews, D., Lieven, E., & Tomasello, M. (2010). What's in a manner of speaking? Children's sensitivity to partner-specific referential precedents. *Developmental Psychology*, *46*, 749–760.

McClelland, J. L., Mirman, D., & Holt, L. L. (2006). Are there interactive processes in speech perception? *Trends in Cognitive Sciences*, *10*, 363–369.

Nardini, M., Bedford, R., & Mareschal, D. (2010). Fusion of visual cues is not mandatory in children. *Proceedings of the National Academy of Sciences, USA*, *107*, 17041–17046.

Nardini, M., Jones, P., Bedford, R., & Braddick, O. (2008). Development of cue integration in human navigation. *Current Biology*, *18*, 689–693.

Neuman, A. C., & Hochberg, I. (1983). Children's perception of speech in reverberation. *The Journal of the Acoustical Society of America*, *73*, 2145–2149.

Pasquini, E. S., Corriveau, K. H., Koenig, M., & Harris, P. L. (2007). Preschoolers monitor the relative accuracy of informants. *Developmental Psychology*, *43*, 1216–1226.

Rabagliati, H., Pylkkänen, L., & Marcus, G. F. (2013). Top-down influence in young children's linguistic ambiguity resolution. *Developmental Psychology*, *49*, 1076–1089.

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell Systems Technical Journal, XXVII*, 379–423.

Snedeker, J., & Trueswell, J. C. (2004). The developing constraints on parsing decisions: The role of lexical-biases and referential scenes in child and adult sentence processing. *Cognitive Psychology*, *49*, 238–299.

Trueswell, J. C., Sekerina, I., Hill, N. M., & Logrip, M. L. (1999). The kindergarten-path effect: Studying on-line sentence processing in young children. *Cognition*, *73*, 89–134.