# Young children's reasoning about the epistemic consequences of auditory noise

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## Abstract

Prior work suggests children understand how speech conveys information and influences others' minds. Although these studies have focused on communication under ideal conditions, auditory noise plagues the real world, often corrupting the transmission of information. The current study examines how children reason about the impact of auditory noise on communication. Children (N=72, Age:3;0-5;11) watched scenarios where a teacher tells a learner about two toys, but loud auditory noise masks one of the explanations. When asked which toy the learner wants to hear about again, children were more likely to select the noise-masked toy when the learner knew about neither toy (No Knowledge) than when he already knew about the masked toy (Partial Knowledge). However, their preference for the masked toy also increased with age in both conditions. Overall, these results demonstrate children's developing understanding of when and how communication affects listeners' knowledge and information-seeking behaviors.

**Keywords:** Cognitive Development; Language Development; Theory of Mind; Communication; Auditory Noise

## Introduction

Throughout our daily lives, we experience various kinds of auditory signals, ranging from useful, pleasant, or captivating to irrelevant, distracting, or even painful. Although the human brain is well equipped to process auditory input in the presence of background noise (Kell & McDermott, 2019), at sufficiently high levels, even familiar sounds—people talking in a busy restaurant or loud music at a party—can cause serious disruptions in our thinking, learning, and communication. Indeed, research suggests exposure to high levels of noise can have lasting negative consequences for speech processing (Klatte, Bergström, & Lachmann, 2013; Dockrell & Shield, 2006), memory (Klatte, Meis, Sukowski, Schick, et al., 2007; Sullivan, Osman, & Schafer, 2015), reading abilities (Hygge, Evans, & Bullinger, 2002), and language development more broadly (Evans & Maxwell, 1997).

Although the long-term effects of auditory noise may not be immediately apparent, its negative impact is readily noticeable in communicative contexts. As adults, we intuitively understand how auditory noise can disrupt verbal communication, and seek to rectify its effects as speakers (e.g., by repeating information) and as listeners (e.g., by asking questions, Clark & Brennan, 1991). Auditory noise, however, is just as, if not more, common in young children's lives. In classrooms, playgrounds, and at home, children frequently spend time in noisy environments and are often the sources of it themselves. Although much prior work has investigated young children's understanding of how learning occurs in communicative contexts (e.g., Csibra & Gergely, 2009; Tomasello, 2010; Harris, Koenig, Corriveau, & Jaswal, 2018; Gweon, 2021), less attention has been paid to the factors that hinder learning from others, such as auditory noise, and whether children can reason about their consequences on other minds.

Imagine a teacher introducing a novel toy to one of her students. Once the teacher explains how it works ("when you open the top, it plays music!"), one might reasonably assume the student now knows. But what if, just as the teacher starts talking, the school bell rings loudly and the room becomes filled with bustling sounds of students talking, laughing, and packing their bags? What would the student hear, and what would he know about the new toy now? While answering these questions might seem easy to adults, surprisingly little is known about children's understanding of how noise can influence the outcome of a communicative exchange. Thus, we begin by reviewing existing literature that probes children's understanding of communication as a means for acquiring and sharing knowledge in ideal, noise-free contexts. We then introduce a paradigm that explores these questions in noisy environments where the presence of auditory noise can further modulate the impact of communication on other minds.

Prior work suggests that an abstract understanding of communication emerges early in life. For instance, when a speaker produces speech (i.e., a nonsense word), 12- and even 6-month-olds expect the listener to retrieve an object that was previously preferred by the speaker (Vouloumanos, Onishi, & Pogue, 2012; Vouloumanos, Martin, & Onishi, 2014). Intriguingly, these inferences are constrained to speech-like signals and do not extend to non-speech vocalization (e.g., coughing). These findings provide evidence that infants in their first year of life readily understand that speech (but not non-communicative vocalizations) can convey information from one agent to another. Furthermore, rather than simply associating a particular kind of auditory cue (speech) and its impact on the listener's behavior, infants seem to appreciate communication as a coordinated, cooperative interaction between two agents. Indeed, ten-month-old infants expect agents to look at, rather than away from, each other when they engage in verbal communication (Beier & Spelke, 2012); meanwhile, 13-month-olds interpret variable, but not identical, sequences of tones from one agent to another as carrying information about the location of a desired object (Tauzin & Gergely, 2018). Taken together, these studies suggest even infants understand that agents can convey information to one another by communicating, and that such an understanding does not require the ability to comprehend the meaning of speech signals themselves.

As children's own linguistic competence and ability to reason about others' mental states develops with age, so does their understanding of the epistemic consequences of communication. For instance, 18-month-olds expect a previously ignorant listener to reach for the accurate location of a hidden object after a speaker tells the listener where it is (e.g. "the ball is under the cup"), but not when the speaker's utterances are uninformative (e.g. "I like the cup" or "ball and cup") (Song, Onishi, Baillargeon, & Fisher, 2008; Jin et al., 2019, but see also Powell, Hobbs, Bardis, Carey, & Saxe, 2018). As listeners, 17-month-olds interpret the referent of a novel word differently depending on whether the speaker has a true or false belief about a desired object's location (Southgate, Chevallier, & Csibra, 2010). As speakers, toddlers actively communicate information to remedy others' ignorance by both pointing (Liszkowski, Carpenter, & Tomasello, 2008; Liszkowski, Schäfer, Carpenter, & Tomasello, 2009) and speaking (O'Neill, 1996). Collectively, these studies demonstrate children's developing understanding of how mental states give rise to observable behaviors, and how such behaviors can, in turn, change observers' mental states in communicative contexts (Gweon, 2021).

Yet, an adult-like understanding of communication entails an abstract, theory-like representation of how agents acquire and revise their knowledge, as well as what factors can disrupt this process. Prior work suggests such an understanding remains elusive throughout the preschool years. When asked to teach a learner, five- and six-year-olds can use the learner's prior knowledge to tailor the amount of evidence they provide, but four-year-olds struggle to do so (Gweon, Shafto, & Schulz, 2018). Such difficulties are also reflected in children's understanding of their own knowledge. Although toddlers can express their knowledge or ignorance by using epistemic verbs (e.g., "I know", "I don't know") or asking questions (Chouinard, Harris, & Maratsos, 2007; Harris, Bartz, & Rowe, 2017; Harris, Yang, & Cui, 2017), it is not until later that children can clearly express *how* they know what they know. Children under five years of age have difficulty reporting whether they learned about what is inside a box by seeing it (vision), hearing about it from someone else (speech), or figuring it out from a clue (inference; Gopnik & Graf, 1988). Furthermore, children's ability to reason about how learners update their knowledge given new information continues to develop between 4 to 7 years of age (Sodian, 1988; Magid, Yan, Siegel, Tenenbaum, & Schulz, 2018). Although children's "failures" in these tasks do not necessarily entail a true lack of competence, these findings do suggest an adult-like understanding of how communication affects other minds is a hard-won feat.

Despite abundant work on children's understanding of communication, the flexibility of children's epistemic inferences in communicative contexts is still unclear. Language comprehension is an error-prone process due to errors in production as well as children's limited cognitive resources (Gibson, Bergen, & Piantadosi, 2013); the presence of auditory noise, especially at high levels, can significantly increase the uncertainty in the relationship between what a speaker says, what a listener hears, and ultimately, what a listener knows. An abstract, theory-like understanding of how communication affects others' mental states therefore also involves understanding how compromising the fidelity of communicative channels—such as adding auditory noise to speech signals—can result in communication failure. Children understand how visual evidence gives rise to others' mental states (e.g., Baron-Cohen, Leslie, & Frith, 1985; Hogrefe, Wimmer, & Perner, 1986; Aboody, Zhou, & Jara-Ettinger, 2021) and adjust their own interpretation of others' speech in noisy channels (Yurovsky, Case, & Frank, 2017). However, little prior work has examined children's understanding of how the fidelity of auditory sources of information affects other minds.

Here we explore how children reason about the way auditory noise can disrupt the communication of information: do children understand that noise can disrupt learning from speech signals, and do they expect listeners to selectively seek information that was previously compromised by noise? To this end, we designed a novel study that presented children with a communicative interaction between a teacher and a student; after the teacher's communication was partially compromised by high levels of background noise, children were asked what information the student wanted to hear again.

## Experiment

### Methods

**Participants** Seventy-two 3- to 5-year-olds (N=24/age group, mean age = 4.56 years, 44.44% Caucasian/White) were recruited through online advertisements. We collected both informed consent from the caregivers and assent from participants before data collection. Participants had no visual, cognitive, or neurological concerns and heard English at least 75% of the time. An additional three participants were ultimately excluded from analysis for caregiver intervention, experimenter error, or technical difficulties. 100 adults (mean age = 30, 67% Caucasian/White) were also recruited from Prolific and participated in the study for payment. A total of 11 adults were excluded for failing an attention check, yielding 89 in the final sample.

**Materials** Visual stimuli were designed using Vyond Animation Software in a video format. Auditory stimuli were recorded by the first authors and edited in Praat. All target speech, including any silences and pauses, was equalized to an average sound pressure level of 65dB. The background noise, taken from a preschool classroom of 4- and 5-year-old children and adult teachers, was equalized to a default aver-


Figure 1: Study setup and schematics of procedure. Left, top: Classroom setup in the video, showing a teacher and a student. Left, bottom: frame from the video showing a teacher explaining a blue toy to a student. Right: (1) Participants learned about two novel toys in the teacher's class, including their names and functions. (2) A new student is introduced who either knows everything about one toy and nothing about the other (Partial Knowledge) or nothing about either toy (No Knowledge). (3) Afterwards, the teacher tells the student the names and functions of both toys, but loud auditory noise masks one of the explanations. (4) The student expresses that they want to hear about one of the toys again and participants are asked which toy.

age sound pressure level of 40dB and increased to 85dB during the critical period when the target object was completely masked by noise.

**Procedure** Children completed the experiment via Zoom on either a desktop, laptop, tablet, or smartphone, communicating with a trained experimenter in real time. Before beginning the experimental session, caregivers were shown an unrelated video and asked to adjust their device's volume so their child could clearly hear the audio. The experimenter then guided participants through a slideshow which included both still images and videos. Adults completed the same experiment, except asynchronously via a Qualtrics survey. (Figure 1).

The experimenter first introduced participants to an adult female character named Teacher June in her classroom. Participants then completed two trials (order counterbalanced): the No Knowledge condition and the Partial Knowledge condition. In the No Knowledge condition, participants saw two novel toys from Teacher June's class; these toys were selected from the NOUN Database and matched on complexity (Horst & Hout, 2016). The experimenter labeled each object (e.g. "a kern") and then described their functions (e.g. "when you squeeze it, it spins around"). To ensure that all participants learned the toys' names and functions, the experimenter asked participants to repeat this information for both toys. If they were unable to do so, the experimenter reminded participants of the correct answers before repeating the question. All participants could correctly identify and provide the function of each novel object by the second try.

The experimenter then showed participants a still image of a male child character (Charles) and explained he was a new student in Teacher June's class who "had never seen either [of the novel toys] before and knew nothing about them". The experimenter then explained: "Teacher June is going to tell Charles about the toys in her classroom! But the classroom is noisy today and it may be hard for Charles to hear what teacher June is saying sometimes". Participants were asked if they wanted to see what happened next, and the experimenter played a video.

During the video, while light classroom background noise (40dB) played, Teacher June said both the name and function of each toy. However, while talking about one of the toys (the noise-masked toy), the volume of the background noise increased substantially (85dB) such that the Teacher June's description of the toy's label and function were very difficult to hear. After teacher June finished describing both toys, she asked Charles if he had any questions. Charles responded by saying “hmmm, I want to hear about one of these toys again”.

After the video, the experimenter showed participants a still image of Charles shrugging in between the two toys and asked the test question: “Charles wants Teacher June to tell him about ONE of these toys again. Which toy do you think Charles wants to hear about again? The [left toy color] toy or the [right toy color] toy?”[1].

The Partial Knowledge condition featured a different pair of novel toys and a different student (Tim). It was very similar to the No Knowledge condition except for one key difference: unlike the student in the No Knowledge condition who knew about neither toy, the student in the Partial Knowledge condition knew about only one of the toys, and was ignorant about the other toy. The experimenter told participants that Tim “had a [toy name] in his old classroom that he played with a lot”, and that he “knows everything about it already”, but that Tim “has never seen a [other toy name] before and knows nothing about it”. The experimenter repeated this to participants to ensure they understood. All other details were identical, but critically, noise masked Teacher June’s description of the toy that Tim already knew about, but did not influence the description of the other toy.

### Results

Our analysis plan was preregistered at https://osf.io/kufh5/. Overall, as predicted, both child and adults chose the noise masked toy more in the no knowledge condition than the partial knowledge condition (Figure 2). In addition, choices of the masked toy increased with age.

Following our confirmatory analysis plan, we fit a Bayesian generalized linear mixed effects model predicting participants’ toy choice (masked or unmasked) as a function of the students’ knowledge states (partial or none), participants’ age (centered), and their interaction. We added a maximal random effect structure with random intercepts and condition slopes by participant (Barr, Levy, Scheepers, & Tily, 2013). We used default weakly-informative priors in the `rstanarm` package (normal distributions with an SD of 2.5, scaled to the predictor).

Children in the No Knowledge condition showed a preference for the masked toy ($\beta = 1.581$, 95% CrI = [0.566, 3.427]) whereas children in the Partial Knowledge condition showed an opposite preference ($\beta = -1.999$, CrI = [-4.447, -0.584]). Masked toy choice increased with age ($\beta = 0.090$, CrI = [0.006, 0.221]) with little evidence for an interaction between age and condition ($\beta = 0.001$, CrI = [-0.128, 0.159]).

Nearly every adult in the No Knowledge condition selected the masked toy to be repeated ($\beta = 4.452$, 95% CrI = [2.396, 7.722]). Adults also showed a weaker, though significant, preference for the masked toy in the Partial Knowledge condition ($\beta = -3.330$, 95% CrI = [-6.179, -1.380]).

## Discussion

The current study asked whether preschool-aged children understand that noise masks information transfer and, by extension, a listener’s epistemic state. Children in our study were more likely to expect a student to seek information about a toy when a teacher’s explanation about that toy was masked by noise, but only if the student did not know about the toy beforehand; this difference between conditions remained stable between three to five years of age. However, we also found that children’s overall preference for the masked toy increased with age, in both conditions. Thus, while we found a reliable difference between conditions across all age groups, only the older children showed a pattern that was consistent with adults: overwhelming preferring the masked toy when the student possessed no prior knowledge, and only weakly preferring it when the student possessed prior knowledge about it. What might these results mean?

One possibility is that by three years of age, children understand how auditory noise can hinder others’ learning from speech, indicated by the condition difference across all age groups. However, they may also have a general aversion to the masked toy or a preference for the unmasked toy, which declines with age. Another interpretation of the results, however, is that younger children do not understand how noise impacts knowledge. Instead, they are genuinely at chance in the No Knowledge condition, but do appropriately expect other agents to seek information that corrects their ignorance (Aboody et al., 2021). Although the current results do not provide conclusive support for either interpretation, they do provide clear evidence that by 4 to 5 years of age, children 1) expect listeners to seek information that was masked by noise, and 2) constrain this information seeking based on that listener’s prior knowledge.

Building on existing research on children’s understanding of communication as a source of knowledge in high-fidelity, noise-free contexts, the current work more broadly reveals how children’s reasoning extends to noisy environments where communication can fail. These findings suggest that even as early as the preschool years, children have an abstract, nuanced understanding of communication as a process of information transfer. Rather than assuming a deterministic relationship between the speaker’s communicative behaviors and the listener’s knowledge, children understand that the process by which speech influences knowledge involves uncertainty and can be compromised by auditory noise.

Although the current results show evidence for an early appreciation of the epistemic consequences of noise, the current study still has several limitations that constrain our conclusions. First, it treats noise in a binary way: loud noise is either present or absent, and either does or does not obscure speech. Additionally, noise either masked all or none of the teacher’s speech. However, auditory noise is graded in the real world

[1] We chose to refer to the toys using color for two main reasons. First, color is a salient, stable cue that is easy for children to respond to online and has become standard practice for choice paradigms conducted online (see Sheskin & Keil, 2018; Chuey et al., 2021). Second, referring to the color of the toys does not rely on children’s memory (unlike referring to the toys by name) or their ability to correctly identify left and right.

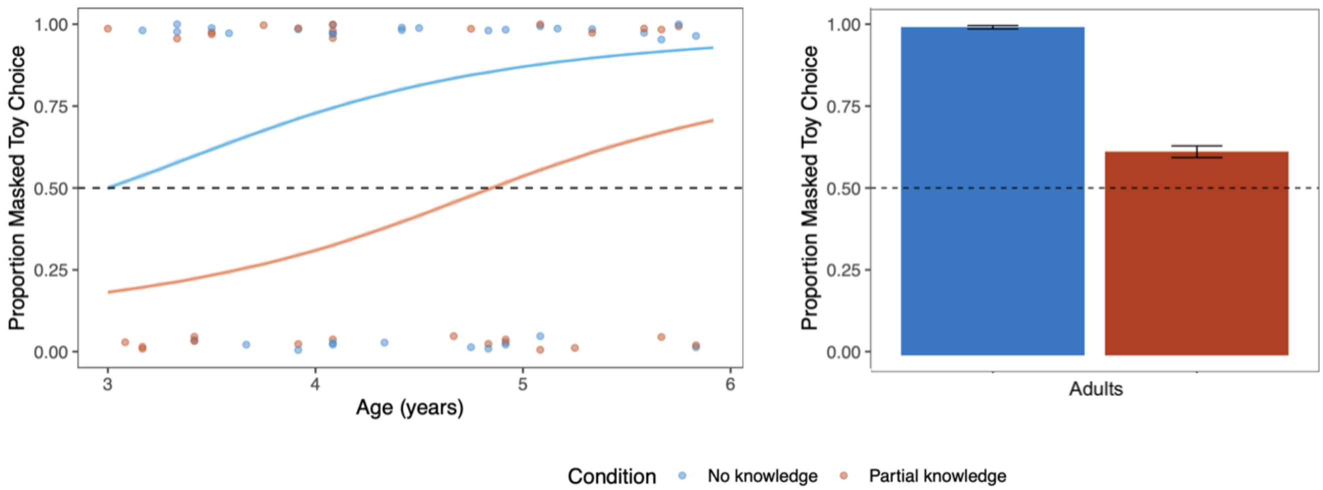


Figure 2: Left: Proportion of children who chose the masked toy, plotted by age and condition. Each dot represents individual participant (jittered slightly in the vertical axis). Lines show the parameters of the fitted Bayesian regression model. Right: Proportion of adults who chose the masked toy, plotted by condition. Error bars depict standard error.

and likely requires more subtle reasoning that may vary based on a number of factors including physical distance, the kind of noise, the importance of the signal being expressed, and whether other means of communication are possible. Therefore, future research should examine how these kinds of inferences unfold in real time under more graded noisy conditions.

Second, the communicative interactions depicted in the current study were mostly one-sided; one agent communicated to another without immediate feedback. However, in most communicative settings, listeners can take an active role in mitigating the impact of noise, such as by indicating they cannot hear, asking the speaker to repeat all or part of their utterance, or by altering the distance between them and the speaker (Clark & Brennan, 1991). Thus, it is important to consider not just how noise shapes speech, but how it shapes the dynamics of conversation. While the current study does not touch on this directly, it does suggest that young children may have the prerequisite ability to understand and shape these dynamics themselves. Therefore, one promising direction to generalize this work lies in examining children's actual language production in noisy environments. For example, when asked to communicate information to a listener in a noisy environment, how do children adjust their speech? Children's own language production under noisy conditions could reveal both how their understanding of noise pervades their language use as well as how they reason about what listeners know on the fly in more dynamic environments.

Third, the current study requires a fairly high level of language comprehension. This limits the age of participants and may underestimate children's competence. Prior work suggests even infants understand that speech communicates information (Vouloumanos et al., 2012, 2014), so it is possible infants also understand that noise may hinder a speaker's ability to communicate information. Future research could examine infants' understanding of noise using tasks that require fewer language demands, with a greater emphasis on the presence, rather than the content, of speech.

## Conclusion

Despite abundant research investigating children's understanding of the relationship between communication and knowledge as well as how noise influences children's own cognition and language use, little prior work has investigated the intersection of these questions. The current study fills this gap by examining how children reason about the way noise corrupts communication and ultimately its relationship to what others know. The results suggest that by around 4- or 5-years, children understand noise prevents listeners from acquiring knowledge via spoken communication, and they expect the learner to seek information that rectifies the epistemic consequences of noise. Although children are frequently the sources of auditory noise, our results reveal a sophisticated understanding of the process by which verbal communication gives rise to knowledge and how noise can compromise this process. The extent to which they choose to exercise this ability, however, depends on who you ask.

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