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Children's understanding of how noise disrupts verbal communication

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Abstract

An abstract understanding of communication should support reasoning about both its success and failure: why it fails, what happens as a consequence, and how to fix it. Auditory noise frequently corrupts verbal communication, but little is known about how humans come to reason about it. The current work explored American 3- to 5-year-olds' third-party reasoning (Experiment 1, $N = 168$, 95 female) and communicative behaviors (Experiment 2, $N = 48$, 23 female) in noisy environments between 2021 and 2024. Children understood that auditory noise impedes others' hearing and prevents knowledge transmission, and they modified their own communication by gesturing more when their partner could not hear. Thus, even young children understand how noise disrupts communication and can communicate effectively in its presence.

Keywords auditory perception, cognitive development, communication, noise, theory of mind

Lay summary

Humans understand not just how communication affects what people know, but also when communication can fail to do so. Auditory noise in particular often prevents people from sharing their knowledge with others, but it remains unclear how we reason about its impact or how such reasoning develops. Across two experiments, 3–5 year-old American children were able to predict how listeners and speakers would behave in noisy environments (Experiment 1) and adapt how they themselves communicate in noisy environments by utilizing more gestures (Experiment 2). These results evidence an early-emerging understanding of how communication can both succeed and fail to transmit knowledge, as well as a precocious ability to tailor how we communicate to others' auditory perception.

Humans are a communicative species: much of what we know and do is shaped by what others tell us. Yet, communication is an imperfect process. Many factors can prevent the successful transmission of information between a communicator and a listener. For instance, in the context of auditory communication, ambient noise affects many people in an environment, whereas hearing loss targets particular individuals. Thus, to navigate the complexities of everyday social interactions, we must be able to reason not only about successes but also about failures in communication: what can disrupt a communicative exchange, the specific consequences of such disruptions, and, importantly, how disrupted communication can be remedied or even prevented. The current studies examine children's reasoning about auditory noise, a particularly pervasive factor that affects the fidelity of verbal communication (Summers et al., 1988; e.g., Buxton et al., 2017).

By distorting listeners' auditory perception, noise prevents listeners from comprehending speakers' verbal messages (Calandruccio et al., 2020; Puglisi et al., 2021) and learning from them (see Mealings, 2022). As adults, we understand how auditory noise disrupts communication and how its effects can be remedied or circumvented. For example, an observer might expect people in a noisy environment to be unable to hear or understand speech, and that a speaker may need to repeat what they said or find other means to communicate. As communicators, we can even anticipate the consequences of noise and proactively choose a means of communication that is not disrupted by noise, such as gestures instead of speech (Clark, 1991; Clark, 2016; Sekine & Özyürek, 2024; Trujillo et al., 2021). What are the cognitive processes that underlie our ability to anticipate and respond to the consequences of auditory noise, and how does this ability develop?

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At a minimum, intentional communication involves producing communicative signals in ways that are sensitive to the presence of its recipients or their attentional states as indicated by their observable behaviors (e.g., eye gaze; Townsend et al., 2017). From this perspective, even some nonhuman species such as chimpanzees engage in intentional communication (Schel et al., 2013). Communication in humans, however, often involves more than tracking others' presence or their behaviors; humans can tailor their communicative signals based on the recipient's unobservable mental states (Clark, 1996; Goodman & Frank, 2016; Grice, 1975; Gweon, 2021; Shafto et al., 2014; Sperber & Wilson, 1986). For instance, in pedagogical contexts or other forms of cooperative communication, a communicator generates a message based on what the recipient knows or wants to know, and can anticipate how the message might change the recipient's epistemic state. Drawing on these theoretical perspectives, we can entertain at least two different ways in which humans might learn about the role of auditory noise in communication.

One possibility is that humans start with a rudimentary understanding of communication (e.g., signal production contingent on others' overt behaviors) that cannot support inferences about the epistemic consequences of noise. Instead, children might simply predict that a communicator will repeat a message in noisy environments if the recipient does not react or respond. With experience, children might also acquire a series of heuristics about how people react to noise by watching others communicate or by being told what to do in noisy environments. For example, by observing their parents repeat themselves in noisy environments, children might come to expect that speakers always repeat information that was masked by noise, or that listeners always desire such information.

Another possibility is that humans, even early in life, understand communication as a process by which a communicator's message influences the recipient's mental states (see Chuey & Gweon, 2025). This abstract, theory-like understanding of communication can, in principle, explain not only how communication works but also how it might break down: By obstructing a listener's auditory perception, noise can prevent a speaker's message from influencing a listener's beliefs, and consequently, their behavior. Understanding the epistemic consequences of noise can support further inferences about what the listener wants (e.g., hear the same information again) or what the speaker should do (e.g., repeat the same information).

Although these two accounts make similar predictions about how people will typically respond to noise, they differ in the underlying cognitive mechanisms and their developmental origins. The current studies aim to disambiguate these accounts by examining how young children reason about the epistemic consequences of auditory noise. Going beyond whether children simply expect noise to prevent effective transmission of information, the current work focuses on whether children have expectations about how communicators and recipients ought to remedy (or even proactively minimize) the impact of noise in communication.

Notably, some prior work lends support for the latter possibility. First, even infants distinguish between communicative signals (e.g., speech) and non-communicative vocalizations (e.g., coughing), and expect communicative signals to influence listeners' behaviors (Martin et al., 2012; Tauzin & Gergely, 2018; Vouloumanos et al., 2012, 2014). Second, toddlers readily modify their communicative behaviors based on their partner's perceptual access (e.g., by modifying their pointing or naming instead of pointing to avoid referential ambiguity; see Liszkowski et al., 2008; O'Neill, 1996; O'Neill & Topolovec, 2001; Tauzin et al., 2024), providing suggestive evidence that they understand the epistemic consequences of communicative gestures. Third, by around age 4, children can even tailor the amount of information information depending on the recipient's goals or epistemic state (Gweon et al., 2018; Gweon & Schulz, 2019). Yet, much remains unknown about how children come to understand communicative failures. An abstract, mentalistic understanding of communication should not only support accurate inferences about the epistemic consequences of noise but also help children generate appropriate measures to mitigate its impact.

Understanding how children reason about the consequences of noise may also provide insight into how we reason about others' perception, especially people whose perceptual capabilities differ substantially from our own. In particular, sensory disorders, such as hearing and vision loss, can radically alter people's ability to perceive certain communicative acts. There is some evidence that children are sensitive to such impairments; for instance, hearing children of deaf parents utilize more gestures when communicating with their parents compared to people who are able to hear (see Singleton & Tittle, 2000). Yet, it remains unclear whether such communicative behaviors are driven by an abstract understanding of others' perceptual access or context-specific expectations about the communicative acts preferred by particular recipients (e.g., one's own parents).

Studying children's reasoning about auditory noise can also complement a broader literature on early social cognition. More specifically, prior research on children's mental-state reasoning has focused primarily on their understanding of others' vision. Many experiments have used occlusion, such as blocking the view of an object using an opaque screen, to show that children use what someone can and cannot see to reason about their beliefs (e.g., Flavell et al., 1978; Kim & Song, 2015; Lempers et al., 1977; Luo & Baillargeon, 2007; Luo & Johnson, 2009; Surian et al., 2007). Yet, far fewer experiments have explicitly examined children's understanding of auditory perception. In the same way that occluded objects have been used to study children's visual perspective taking, auditory noise, which occludes people's ability to comprehend speech, can be used to examine children's auditory perspective taking.

While both modalities—visual and auditory perception—are important for learning, auditory perception is particularly important for learning from other humans. Even infants understand that auditory signals can be used to transmit information from one agent to another (Tauzin & Gergely, 2018) and that speech in particular (as opposed to noncommunicative vocalizations, such as coughing) systematically influences agents' behaviors (Martin et al., 2012; Vouloumanos et al., 2012, 2014). By around 2–3 years, children acquire an understanding of how people perceive (Melis et al., 2010; Williamson et al., 2015; Yaniv & Shatz, 1988) and remember (Moll et al., 2014) auditory information more broadly. However, it is unclear when children acquire a more comprehensive understanding of how people influence, or fail to influence, each other's minds, as well as how auditory perception mediates this relationship.

The current work aims to fill these gaps by studying how children reason about the impact of noise on communication and how it can be remedied. In doing so, we took the following empirical approaches. First, we take a data-driven, descriptive approach to characterize at what age children might begin to detect, respond to, and even remedy the impact of noise in everyday communicative contexts. To this end, we first conducted an exploratory study (Parental Survey) by asking parents of 2- to 10-year-old children to recall whether and how their children communicate differently in noisy settings. Second, based on these findings, we conducted a series of preregistered experiments to better understand how children reason about noise, both as third-party observers (Experiments 1a–1c) and as communicators themselves (Experiment 2). Collectively, these studies suggest that by around age four, children can infer the effects of auditory noise on others' minds and actions, and even tailor their own communication when they communicate with people whose auditory perception is compromised due to noise. Preregistration and materials for experiments can be found at the OSF repository.

Confirmatory/exploratory statement

Experiments 1a, 1b, and 2 were conducted as confirmatory studies, and the hypotheses, outcome measures, and analytic plan for both experiments were preregistered on the Open Science Framework (https://osf.io/kufh5). All confirmatory analyses follow this preregistered plan.

In contrast, the parental survey was designed as a purely exploratory component intended to better characterize how and at what age children react to and adapt to noise in their everyday environments. Experiment 1c was designed as an extension of findings from Experiments 1a and 1b. Analyses of the survey data and of Experiment 1c were therefore not preregistered.

Parental survey: children's communicative behaviors in everyday noisy environments

The goal of this study was to get a sense of how children might be reacting and adapting to auditory noise in their everyday lives, and at what age they might begin to do so. Using parental surveys, we asked (1) whether participants' children acknowledged the presence of loud auditory noise or modified how they communicate in noisy settings, (2) at what age they first observed such behaviors, and (3) whether children received explicit instruction on what to do in noisy environments. Importantly, this study was exploratory in nature, with no a priori predictions about children's behaviors or their onset. Instead, the goal was to use the data to better calibrate the experimental design and the age range of participants in subsequent studies.

Method

Participants

Ninety-eight parents (mean age = 38.66 years; 72.4% Caucasian/White, 6.1% Asian, 1.0% Hispanic/Latino, 6.1% African/Black, 12.2% Biracial/Multiracial, 1.0% Other; 53 female) of 153 2- to 10-year-old children from the United States were recruited using Cloud Research (Litman et al., 2017) and participated via Qualtrics for $2 payment. An additional 3 parents participated but were excluded for not reporting any children within the requested age range.

Procedure

To better understand how children communicate in everyday noisy environments, we surveyed parents about their children's (age 2–10 years) communicative behaviors in noisy environments. They first listed the number of children they had between ages 2 and 10 years, and then provided each child's age, gender, race, as well as any language or hearing disorders, delays, or disabilities. In the next set of questions, caregivers were asked: "When it is noisy around your child, have you ever observed them spontaneously do any of the following without being asked when they are trying to communicate with someone?": (1) request listeners to pay closer attention, (2) ask someone if they have any questions about what was communicated, (3) talk louder or yells, (4) repeat themselves, (5) stop talking or wait until noise has stopped or abated, (6) use more gestures (e.g., pointing) or physical demonstrations, or use gestures or physical demonstrations instead of speech. Next, a similar question probed their child's behaviors when someone is trying to communicate with them (e.g., my child has asked someone to talk louder).

The next three questions explored children's acknowledgment of noise ("Have you ever observed your child explicitly acknowledge or refer to auditory noise?"), communicative behaviors in noisy situations ("Have you ever observed your child communicate differently when it is noisy?"), and the extent to which caregivers talked about noise with them ("Have you ever explicitly talked to your child about noise, or how they should act or communicate when it is noisy?"). If they answered "Yes" to any of these questions, parents were asked to provide their best estimate of how old their child was when such events first occurred, and to briefly describe a memorable instance of the behavior if possible. For each story caregivers provided, we coded children's behavior as demonstrating any of the six behaviors described above. Caregivers then completed a demographic questionnaire, including their age, gender, education level, and native language. See OSF repository for a full list of survey questions and answer choices.

Results

A majority of parents (72.5%) said their children communicated differently in noisy environments, and reported first observing these behaviors when their children were 3 years old on average ($M = 3.24$, $SD = 1.45$). Importantly, relatively fewer parents (45.8%) reported explicitly coaching their children how to behave in noisy environments, suggesting these communicative behaviors may emerge without explicit instruction. When asked to indicate what their children do to communicate in noisy environments, most parents reported speaking louder (79.3%) and repeating themselves (62.2%), followed by waiting until the noise abated to continue speaking (35.1%) and using gestures instead of speech (34.2%).

These results provide some preliminary evidence that children alter their communicative behaviors in environments where their partner's auditory access is masked by noise. However, it is unclear whether these responses are guided by simple heuristics that associate noisy environments with behaviors like speaking louder and gesture use, or a more inferential, mentalistic understanding of communication. If children do rely on mental-state reasoning to communicate in noisy environments, they should be able to (1) infer how one might remedy the impact of noise, either as a listener or as a speaker, and (2), as communicators themselves, use an alternative means of communication to circumvent these effects. In subsequent studies, we took an experimental approach to test these hypotheses by examining children's ability to reason about noise as third-party observers (Experiment 1) and as communicators (Experiment 2).

Experiment 1: children's inferences as observers of noisy communicative exchanges

The first set of experiments examines whether and how 3- to 5-year-old children reason about how an agent might try to remedy the effect of noise in communicative contexts, either as a listener (Experiment 1a) or a speaker (Experiment 1b). Children viewed videos where a speaker described two novel toys to a listener, but one of the descriptions was masked by loud auditory noise. Afterwards, children were asked which toy the listener would like to hear about again (1a) or which toy the speaker would describe again (1b). To examine whether these choices are informed by a mentalistic understanding of communication—more specifically, the consequence of noise on the listener's epistemic state—we also manipulated the listener's prior knowledge about these toys, such that one listener possessed no prior knowledge about either toy (no-knowledge condition) while the other listener possessed extensive prior knowledge about the noise-masked toy (partial-knowledge condition). Critically, children had already learned about both toys to ensure that any difference across conditions would reflect children's reasoning about the listener's prior knowledge of the toys, rather than their own prior knowledge.

If children have an inferential understanding of how noise affects the minds of others, then they should predict its consequences based on the epistemic state of the listener. In the no-knowledge condition, the listener was able to learn about one of the toys from the speaker, but remained ignorant about the noise-masked toy due to the noise.

Thus, children should expect the listener to desire—and the speaker to repeat—the description of the noise-masked toy. But in the partial-knowledge condition, the listener is ultimately knowledgeable about both toys; they possessed prior knowledge about the noise-masked toy and learned about the other toy from the speaker. Thus, children should be less likely to expect the listener to desire and the speaker to repeat the description of the noise-masked toy compared to the no-knowledge condition. However, if children simply possess a heuristic that people prefer noise-masked information, they should expect listeners to desire noise-masked information and speakers to repeat noise-masked information regardless of the listeners' prior knowledge.

Experiment 1a methods

Participants

Seventy-two 3- to 5-year-old children (mean age = 4.56 years; 44.4% Caucasian/White, 29.1% Asian, 2.8% Hispanic/Latino, 1.3% African/Black, 20.8% Biracial/Multiracial, 1.3% Other; 40 female) from the United States were recruited through online advertisements. Children had no visual, cognitive, or neurological concerns and heard English at least 75% of the time. Based on preregistered exclusion criteria, an additional three children were ultimately excluded from analysis due to caregiver intervention ($n = 1$), experimenter error ($n = 1$), or technical difficulties ($n = 1$).

Materials

Visual stimuli were designed using Vyond Animation Software in video format. Auditory stimuli were recorded by the first authors and edited in Praat and Audacity. All target speech, including silences and pauses, was equalized to an average sound pressure level of 65 dB. The background noise, recorded in a local preschool classroom of 4- and 5-year-old children and adult teachers, was equalized to a default average sound pressure level of 40 dB and increased to 85 dB during the critical period when the target object label was completely masked by noise. See the OSF repository for study stimuli, videos, and PowerPoint presentations.

Procedure

Children completed the study with a trained experimenter synchronously via Zoom on either a desktop, laptop, or tablet computer. Before the session, caregivers were shown an unrelated video and asked to adjust their device's volume to confirm their child could hear the audio clearly. The experimenter then guided children through a slideshow that included both still images and videos.

The experimenter first introduced children to Teacher June, a female adult character, in her classroom. Children then completed two trials (order counterbalanced): the no-knowledge condition and the partial-knowledge condition. In the no-knowledge condition, children saw two novel toys on a table, one on each side of Teacher June; the toy labels were selected from the NOUN Database and matched on complexity (Horst & Hout, 2016). The experimenter then labeled each object (e.g., "a kern") and described their functions (e.g., "when you squeeze it, it spins around"), and asked to repeat this information for both toys. This was to ensure that all children learned the toys' names and functions before the main procedure, such that their responses to the test question would not be affected by their own desire to learn about the toys. If they were unable to do so, the experimenter reminded them of the correct answers before repeating the question. All children could correctly identify and provide the function of each novel object on the first or second try.

The experimenter then explained that Tim 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 Tim about the toys in her classroom! But the classroom is noisy today, and it may be hard for Tim to hear what teacher June is saying sometimes." Children then viewed a video that proceeded as follows: Teacher June stood behind a desk that had each of the novel toys on top. Tim then entered from the right side of the screen, stopped in front of the desk, and said "Teacher June, can you tell me about the toys in your classroom?"

Light background noise (40 dB) played while Teacher June said both the name and function of each toy. Teacher June pointed to each toy during explanation to indicate which toy she is talking about. However, while she described one of the toys (henceforth the noise-masked toy), the volume of the background noise increased substantially (85 dB) such that the toy's description was impossible for participants to hear (and presumably for Tim as well). The other toy (henceforth the unmasked toy) was described with the light background noise, such that the description was audible to participants. Afterwards, Teacher June asked Tim whether he had any questions, and he replied: "I'd like to hear about one of these toys again," and the video stopped. The experimenter then asked children, "which toy do you think Tim wants to hear about again? The [left color] toy or the [right color] toy?" The toy presentation order was counterbalanced across conditions.

The partial-knowledge condition introduced a different pair of novel toys and student, Charles. It was similar to the no-knowledge condition with one key difference: Charles already knew about one of the toys (the noise-masked toy) but was ignorant about the other toy. The experimenter told children that Charles "had the [noise-masked] toy in his old classroom; he played with it a lot and knows everything about it already. But Charles has never seen the [other] toy before and knows nothing about it." The experimenter repeated this to children to ensure they understood. Critically, noise masked Teacher June's description of the toy that Charles already knew about, but did not mask the description of the other toy.

Coding and analysis plan

Preregistered analysis plans and scripts can be found in the OSF repository. In each condition, we coded whether children selected the noise-masked or unmasked toy as the toy that Tim or Charles wanted to hear about again. Acceptable responses included verbalizing the toy's name or color, or pointing to the toy on the screen. If it was unclear where the child was pointing, the caregiver could clarify to the experimenter which toy the child was pointing to. Children who did not provide a response for both trials after two verbal prompts from the experimenter were excluded from analysis.

We hypothesized that if children can reason about the epistemic consequence of noise while also incorporating the listener's prior knowledge, they should be more likely to choose the noise-masked toy in the no-knowledge condition than in the partial knowledge condition. To test this, we ran a Bayesian mixed effects model with age and condition (partial knowledge vs. no knowledge) as fixed effects and random intercepts and slopes by participant using the "rstanarm" package in R. The model centered the age on the overall mean (4.56 years) and included an interaction term with condition. The number of iterations was set to 10,000. From this logistic regression, we extracted the beta coefficients and 95% credible intervals (at 2.5% at the lower bound and 97.5% at the upper bound).

Beta coefficients represent the estimated change in log-odds of the outcome variable (choosing the noise-masked toy) based on the predictor (condition or age) while holding the other predictors constant. Thus, positive values mean that the predictor increases the log-odds of choosing the noise-masked toy, negative values indicate the predictor decreases the likelihood that children choose the noise-masked toy, and values near zero indicate a weak relationship between the two variables. Credible intervals are the Bayesian analog to confidence intervals in frequentist statistics and represent the range within which the true value (in this case, of the toy explanation that will be repeated) lies. Note that, unlike in frequentist statistics, credible intervals correspond to the probability of observing the true value within a given range rather than the range in which the true value may lie in future samples. For our exploratory analyses, we calculated a posterior predictive distribution based on the previous model using the "brms" R package. We used the default number of chains and draws with 100 iterations.

Experiment 1a results

The results were consistent with our hypothesis. In the no-knowledge condition, where the student was still ignorant about the noise-masked toy, children preferentially chose the noise-masked toy ($\beta = 1.58$, 95% CrI = [0.57–3.43]); in the partial-knowledge condition, children preferentially chose the toy that was not masked by noise ($\beta = -1.999$ [−4.45 to −0.58]). Across both conditions, the tendency to choose the noise-masked toy increased with age ($\beta = 0.09$ [0.01–0.22]), but there was no interaction of age and condition ($\beta = 0.00$ [−0.13 to 0.16]). Taken together, these results suggest that children, as a group, thought the student would be more likely to desire information about the noise-masked toy when they possessed no prior knowledge about it; interestingly, while this pattern held across age, the tendency to choose the noise-masked toy increased with age in both conditions.

Experiment 1b method

Participants

Seventy-two 3- to 5-year-old children (mean age = 4.47 years; 43.0% Caucasian/White, 29.1% Asian, 2.8% African/Black, 1.3% Hispanic/Latino, 20.8% Biracial/Multiracial, 2.8% Other; 43 female) from the United States were recruited through online advertisements.[1] An additional five children were excluded from analysis due to caregiver intervention ($n = 3$), inattention ($n = 1$), or not finishing the task ($n = 1$).

Materials

The materials were identical to those in Experiment 1a.

Procedure

Experiment 1b was similar to Experiment 1a with a few minor modifications. First, when children were introduced to two novel toys along with their functions, the toys were simply referred to using their primary color (e.g., "blue toy", "green toy") instead of novel object labels (e.g., "kern"). This was to minimize memory demands by leveraging a salient perceptual cue, and using colors in binary choice paradigms has become standard practice for online studies (see Chuey et al., 2021).

Second, in addition to having the experimenter explain the student's prior knowledge, in the video, the students also stated their knowledge about the toys. Right before asking Teacher June to describe the toys, the student in the no-knowledge condition said: "I've never seen this yellow toy before and I've never seen this purple toy before." In the partial knowledge-condition, the student said: "I've seen this blue toy before. I had one in my old classroom and I know all about it. But I've never seen this green toy before. Third, after describing both toys (and a loud noise

[1] Because we tested similar age groups of children across the reported studies, our recruitment strategy precluded children from participating in more than one of the reported studies.

masked one of the descriptions), Teacher June said: "I'm going to tell you about one of these toys again," and the experimenter said: "Teacher June is going to tell [Tim/Charles] about one of these toys again; which toy do you think Teacher June is going to tell [Tim/Charles] about again—the [left color] toy or the [right color] toy?" This procedure was repeated for the other condition.

Analysis plan

The coding and analysis plan was identical to Experiment 1a. See the OSF repository for preregistration and analysis scripts.

Experiment 1b results

Experiment 1b results largely mirrored Experiment 1a results (see Figure 1). Consistent with our predictions, children were more likely to choose the noise-masked toy in the no-knowledge condition ($\beta = 1.13$, 95% CrI = [0.24–2.48]) and the unmasked toy in the partial knowledge condition ($\beta = 0.37$ [0.03–0.89]). This effect became more pronounced with age ($\beta = 0.11$ [0.02–0.25]), and again there was no interaction of age and condition ($\beta = -0.09$ [−0.24 to 0.04]). These results suggest that children were more likely to think the teacher would repeat information about the noise-masked toy when the student did not already know about it. Additionally, as children aged, they were generally more likely to think the teacher would repeat information about the noise-masked toy to the student.

Taking the results from Experiments 1a and 1b together, these findings are not easily explained by inflexible heuristics about how people respond to noise in communicative contexts; instead, the results are consistent with the possibility that young children in these experiments used listeners" epistemic states to infer the consequences of noise and predict what the listener or the speaker would do to remedy its effect. When the student possessed no prior knowledge about the noise-masked toy, they inferred both that the student would want to hear about it again, and that the teacher would repeat information about it. However, when the student already possessed prior knowledge about the noise-masked toy, children were less likely to think that the student would want to hear about it again or that the teacher would repeat information about it.

In our samples, children's ability to reason about the consequences of both successful and unsuccessful communication appeared to develop with age. While older children overwhelmingly thought the student who did not have prior knowledge about the noise-masked toy would want to hear about it again, younger children were more uncertain. Interestingly, even though there is no strong reason to choose either toy in the partial knowledge condition (by the end of the teacher's instruction, the student presumably knew about both toys), younger children (3-year-olds) in our sample seemed to think that the student who already knew about the noise-masked toy would want to hear about the unmasked toy again. While this is consistent with the possibility that children expect people to seek information based only on their prior knowledge, the pattern was weak and not observed in Experiment 1b.

Together with a lack of clear preference in the no-knowledge condition, these results raise questions about whether 3-year-olds understand the impact of noise on the listener at all. To follow up on this possibility, Experiment 1c was designed to assess whether 3-year-olds hold any expectations that auditory noise impacts listeners' auditory perception and their subsequent information seeking. We used a simplified procedure with a single video in order to limit cognitive demands that might have obscured younger children's competence.

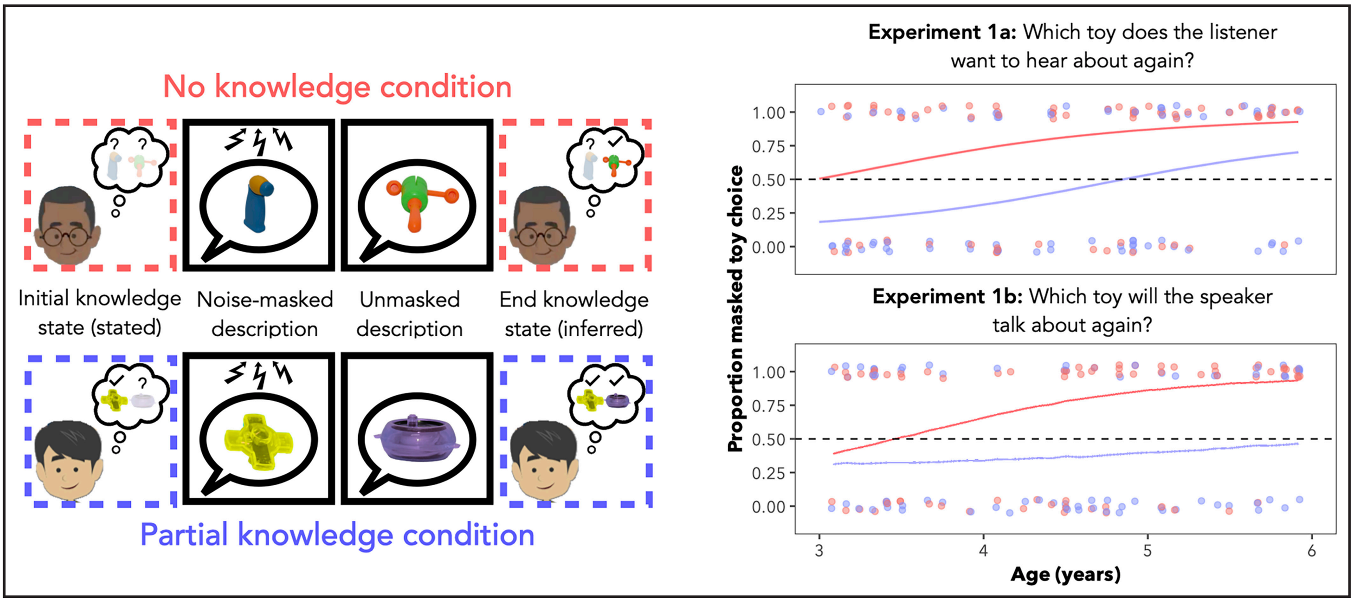

Figure 1 Experiments 1a and 1b procedure and results. Children watched two videos where a teacher describes two toys to two students; during one of the descriptions (noise-masked toy), loud auditory noise masks the teacher's speech. Afterwards, the student expressed a desire to hear about one of the toys again, and children were asked which toy the student would want to hear about again (Experiment 1a) or which toy the teacher would talk about again (Experiment 1b). Crucially, we manipulated the student's prior knowledge: one student (no-knowledge) had no prior knowledge about either toy, while the other student (partial-knowledge) had extensive prior knowledge about the noise-masked toy only. Thus, by the end of the video, the no-knowledge student was still ignorant about the noise-masked toy while the partial-knowledge student was knowledgeable about both toys. Graphs depict Bayesian logistic curves fitted to the data for Experiment 1a (top) and Experiment 1b (bottom), depicting masked-toy choice by participant age and student knowledge.

Experiment 1c methods

Participants

Twenty-four 3-year-old children (mean age = 3.58 years, race = 58.3% Caucasian/White, 20.8% Asian, 4.1% African/Black, 16.7% Biracial/Multiracial; 12 female) from the United States were recruited through online advertisements. An additional eight children were excluded from analysis due to not answering or incorrectly answering the inclusion question ($n=4$), not responding despite prompting ($n=2$), or technical difficulties ($n=2$). Unlike Experiments 1a and 1b, this study was not preregistered.

Materials

The materials were identical to those in Experiments 1a and 2b.

Procedure

Experiment 1c was similar to Experiment 1a with several modifications. First, children completed an inclusion check at the beginning of the study to ensure they understood the word "hear." After viewing a short, unrelated video with sound, children were asked if they could hear the video; if they failed to give an affirmative response, they were asked once more. Then, the experimenter muted the video and asked if children could "hear the video now." Children who gave an affirmative response were asked once more. If children failed either question after being corrected (e.g., reported hearing the muted video), they were excluded from the final analysis.

Children were first introduced to the two novel toys and their functions, labeled by their primary colors (green and blue). They were then introduced to Tim, "a new student in Teacher June's class who wants to learn about these cool toys too." Importantly, there were no explicit statements about Tim's knowledge of the toys. Children then watched a video of Teacher June describing the green toy to Tim, with light background noise (identical to the videos from Experiment 1a). Then, the video paused, and children were asked: "could Tim hear what Teacher June said about the green toy, or could he not hear what Teacher June said?" After providing a response, children viewed the second half of the video where Teacher June described the blue toy but the instruction was masked by noise, and answered the same question. Finally, children were told: "Tim wants to hear about one of the toys again," and the experimenter then asked: "which toy do you think Tim wants to hear about again—the green toy or the blue toy?" Toy colors were counterbalanced across participants.

Analysis plan

We ran two Bayesian mixed effects models with random intercepts for each participant using "rstanarm." We evaluated whether noise that masked the toy description would affect whether children reported that the student could or could not hear (model 1) and which toy description should be repeated (model 2). In both models, we ran 10,000 iterations and used the default values for the remaining parameters.

Experiment 1c results

While 3-year-olds were uncertain whether the student could hear the noise-masked utterance ($\beta=-0.193$, 95% CrI = [−2.394 to 1.799]), they reliably responded that the student could hear the unmasked utterance ($\beta=2.337$ [0.220–5.297]). In line with these judgments, when asked which toy the student wanted to hear about again, 3-year-olds were more likely to choose the noise-masked toy over the other toy ($\beta=2.794$ [0.352–5.801]).

To summarize: using a simplified procedure, we found that 3-year-olds were more likely to think that an ignorant student would want noise-masked information repeated, and they were also less likely to say that the student could hear a noise-masked description compared to one that was not masked by loud noise. This finding provides some evidence that 3-year-olds understand that auditory noise makes it more difficult for people to hear speech and causes them to desire that information, at least when the presence of noise and listeners' auditory access are made sufficiently salient.

Experiment 1 discussion

Together, the results of Experiment 1 suggest that by around age 4, children have an inferential understanding of the process by which auditory noise affects people's minds and behaviors. In Experiment 1a, 3–5-year-olds were more likely to think a listener would like to hear information that was masked by noise when they did not already possess prior knowledge about it. Thus, children seem to use a listener's epistemic state following a communicative exchange to infer what they want to know, rather than a heuristic that listeners always desire noise-masked information. In Experiment 1b, we found a similar pattern of results when children were prompted to predict what information a speaker would repeat to a listener.

Interestingly, we also found that across age, children were more likely to think that listeners would like to hear noise-masked information again, regardless of their prior knowledge. This is consistent with the possibility that (1) even very young children understand people typically seek information they do not already possess, but that (2) an understanding that auditory noise prevents speakers from transmitting information to listeners develops more slowly. Because 3-year-olds did not reliably expect ignorant listeners to desire noise-masked information or speakers to repeat it for them, we wondered whether the complexity of the task might be obscuring their underlying competence.

Therefore, Experiment 1c used a simplified task to assess whether 3-year-olds (1) understand that auditory noise makes it harder for listeners to hear speech, and (2) expect listeners to desire noise-masked information. Indeed, we found evidence that when explicitly asked about a listener's auditory perception, even 3-year-olds understand that noise makes it harder for them to hear a speaker's utterance. They also inferred that the listener desired the noise-masked information. However, because we no longer specified the listener's epistemic state to reduce task demands, it is ambiguous whether or not 3-year-olds relied on a heuristic to arrive at these judgments.

Experiment 2: children's adaptive communication

By around age 4, children in Experiment 1 reliably understood that auditory noise prevents listeners from understanding, and ultimately learning from, speakers' utterances. They could apply that understanding to infer what listeners wanted to know and predict

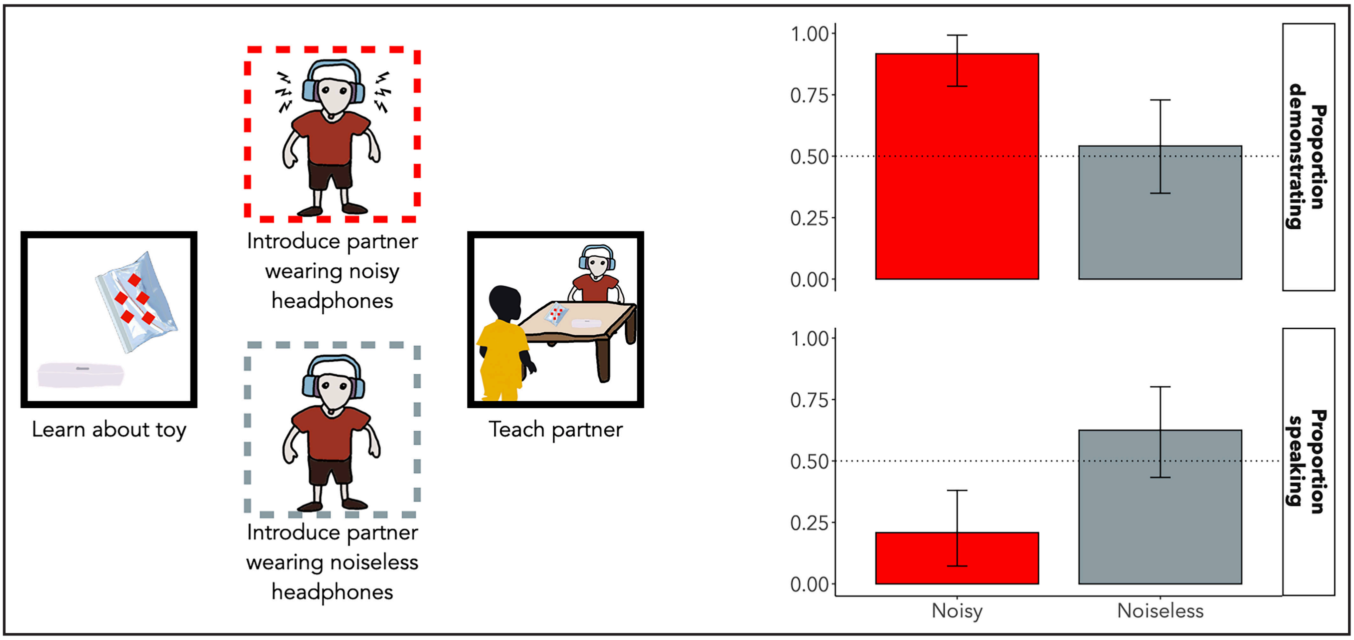

Figure 2 Experiment 2 procedure and results. The experimenter verbally described a novel toy to the child, explaining that stacking five red blocks on a platform causes it to light up. The experimenter then introduced a puppet, Gus, who was wearing headphones that either played loud music or were silent. Finally, the experimenter invited the child to teach Gus how the toy works. We measured whether children (1) physically demonstrated the toy to Gus and (2) verbally instructed Gus. Graphs depict the proportion of children who physically demonstrated (top) and verbally instructed (bottom) by condition. Error bars indicate 95% bootstrapped CIs.

what a speaker would say next. However, an abstract understanding of communication may not only support children's inferences about third parties, but also their own communicative behaviors. In the Parental Survey, for instance, parents reported that their children adapted how they communicate in noisy environments by talking louder, repeating themselves, and even modifying the modality of their communication (e.g., employing gestures instead of speech). While children may simply associate these kinds of behaviors with louder environments, they could be the product of a comprehensive understanding of others' perceptual access and the kinds of strategies that can mitigate the corruptive effect of auditory noise.

In Experiment 2, we experimentally tested whether 4-year-old children can circumvent the effect of noise on communication by using gestures instead of speech. To create a strong test of children's auditory perspective-taking, we used noisy headphones instead of ambient noise, which makes someone else's auditory experience substantially different from children's own: Children's own auditory access was preserved, but the listener's auditory access was either preserved or corrupted by noise, depending on the condition. In this context, given a chance to explain a novel toy to a naïve learner, we predicted that children would be (1) more likely to demonstrate the toy and (2) less likely to explain it verbally when the listener's auditory access was corrupted than when it was preserved (see Figure 2).

Method

Participants

Forty-eight 4-year-old children (mean age = 4.41 years; 45.8% White, 25.0% Asian American/Pacific Islander, 8.3% Black, 6.2% Hispanic/Latino, 14.6% Mixed-race; 23 female) from a San Francisco Bay Area preschool participated in the study in a separate room. An additional 12 children were excluded for providing incomplete responses ($n = 6$), technical difficulties ($n = 1$), or failing an auditory check question ($n = 5$).

We recruited 4-year-old children for two reasons. First, while parents in the Parental Survey study reported that children began displaying adaptive behaviors as early as age 3, these behaviors may not necessarily reflect their understanding of others' auditory access, which differs from their own, which may be more challenging and later emerging.

Second, pilot testing suggested that a majority of children under age 4 had difficulty understanding and verbally describing how the toy worked. We had preregistered a sample of 96 children, including 48 4-year-olds and 48 5-year-olds. However, we encountered difficulty in recruiting a sufficient number of 5-year-old children and only report results with the full sample of four-year-olds here. The results of Experiment 2 do not qualitatively differ whether or not 5-year-olds are included.

Materials

A flat platform with a light in the middle (10 × 6 cm), along with five red blocks in a clear plastic bag, was introduced to participants as a toy. It was described as being out of batteries (in fact, the light was inert) in order to minimize children's desire to activate the toy for themselves. An anthropomorphic mouse puppet (approximately 64 cm in height) who wore a pair of over-the-ear Bluetooth headphones was introduced as Gus. The headphones either played loud guitar music ("Eruption" by Van Halen, 1978) or nothing.

Procedure

Children were seated at a table with the toy and bag of red blocks.

The experimenter sat beside the child and said: "I have a really cool toy to show you! It's out of batteries right now, but I'm going to tell you about it anyways." The experimenter explained that the toy normally lights up when five red blocks are stacked on top of each other in the center of the toy. Importantly, the experimenter only provided a verbal description and pointed to the bag of red blocks, but did not use the blocks to demonstrate the stacking. The experimenter then asked children to verbally explain how the toy worked, and provided the explanation again if children answered incorrectly.

Next, the experimenter retrieved Gus from under the table and introduced him as her friend. Prior work suggests that children readily treat a puppet as an agent, especially when others also treat it as an agent, such as referring to it as their friend (Asaba et al., 2022). In our study, using a puppet instead of a human confederate helped constrain children's communicative behaviors (i.e., verbally describing or demonstrating the toy, rather than asking the puppet to turn the volume down or take off his headphones).

Children were assigned to one of two conditions. In the noisy condition, Gus' headphones were playing loud music that was audible from several feet away but did not significantly disrupt the participant's own auditory access. In the noiseless condition, Gus' headphones were silent. The experimenter first asked children what Gus was wearing on their head. If children said "headphones" or something similar (e.g., earphones), the experimenter agreed; if children were not sure or gave an incorrect answer, the experimenter explained that Gus was wearing headphones that can play music.

The experimenter then asked children if they could hear anything coming from Gus' headphones. In the noisy condition, the experimenter remarked that Gus was listening to loud music. In the noiseless condition, the experimenter said that the headphones were not playing anything and that Gus liked to wear them because they "look cool." The experimenter asked children if they thought Gus could hear them talking. If they answered correctly (i.e., could not hear in the noisy condition and could hear in the noiseless condition), the experimenter agreed. If they answered incorrectly, the experimenter corrected them (i.e., "Actually, I think Gus can/can't hear us right now") and repeated the question. If they again answered incorrectly, they were excluded from subsequent analyses.

The experimenter then informed children: "Gus really wants to learn how the toy works; can you teach Gus how the toy works? You can teach Gus however you like, just let me know when you are finished." To minimize the possibility of children directing their explanation to the experimenter instead of Gus, the experimenter then moved to a chair approximately 1.2 m from the table and appeared to be reading something on a clipboard. Once children indicated they completed their explanation, the experimenter praised their teaching efforts and concluded the session.

Analysis plan

Children's communicative behaviors were divided into two primary categories: demonstration and instruction. Children's actions were considered demonstrations if they took the blocks out of the bag and stacked them onto the toy or approximated this behavior; partial stacking (e.g., stacking some, but not all, of the blocks) was counted as demonstrative. However, merely touching or pointing at the bag alone did not count as a demonstration. Children's actions were considered instructions when they verbalized how to use the toy with the puppet. To be classified as instruction, children must have mentioned stacking the blocks, but it was unnecessary that they described each step. Children who demonstrated and instructed were coded as having completed both.[2]

Children who directed their explanation to the experimenter or did not produce either behavior were coded as incomplete responses, which were excluded from subsequent analyses.

Given there were two possible distinct but overlapping communicative behaviors, we ran a Bayesian multivariate logistic regression in "brms" to calculate whether children adjusted both their demonstration and instruction behavior given Gus' auditory access. We used a Bernoulli distribution but retained default values for all other parameters. The beta coefficients and 95% credible intervals (at 2.5% at the lower bound and 97.5% at the upper bound) estimated these effects. Preregistration can be found at the OSF repository.

Results

Children were significantly more likely to demonstrate in the noisy condition (92%), $\beta = 2.58$, 95% CrI = [1.24–4.40], than in the noiseless condition (54%), $\beta = -2.42$ [−4.42 to −0.81]. Conversely, children were significantly more likely to verbally instruct in the noiseless condition (62%), $\beta = 1.93$ [0.70–3.25], relative to the noisy condition (21%), $\beta = -1.40$ [−2.49 to −0.42]. Thus, children produced more visual demonstrations and less verbal instruction when Gus' auditory perception was inhibited by loud noise. These results demonstrate that young children can tailor how they communicate based on whether their communicative partner can see and hear, even when their own auditory access remains intact and differs from their partner's.

General discussion

Successfully reasoning about communication requires not just an understanding of when it succeeds, but also when it fails. Building on parental reports suggesting that children begin to communicate differently in noisy environments in early childhood, our experiments examined whether young children can predict the effects of auditory noise on communication (Experiment 1) and even adapt their own communicative modalities depending on others' perceptual access (Experiment 2). These studies reveal how children between 3 and 5 years of age develop a mentalistic understanding of auditory noise. In aggregate, children understood that noise prevents listeners from learning from speakers' verbal utterances, causing ignorant listeners to desire the corrupted information (Experiment 1a), and cooperative speakers (i.e., a teacher) to repeat the corrupted information (Experiment 1b). While even 3-year-olds appeared to understand that auditory noise makes it more difficult for people to hear (Experiment 1c), these inferences became increasingly robust with age. As communicators themselves, 4-year-old children readily altered the modality of their communicative acts based on their partner's visual and auditory access. When their partner's auditory access was corrupted by loud music, children used demonstrations

[2] Performing both actions was somewhat rare; 3/24 did so in the noisy condition and 4/24 did so in the noiseless condition.

instead of verbal instruction to leverage the visual modality (Experiment 2).

Just as physical occlusion has been used in prior work to study children's understanding of others' visual perception, the current work used acoustic noise that occluded speech to study children's understanding of others' auditory perception in communicative contexts. The current results demonstrate that by around 3–4 years, children understand how sound, such as ambient noise or loud music, can render someone unable to hear and learn from speech. While the loud noise used in Experiment 1 affected children's own ability to hear speech, the headphones in Experiment 2 left children's hearing intact. Thus, young children appear capable of representing auditory perspectives that differ substantially from their own.

More broadly, the current results suggest an early understanding of communication that is integrated with children's ability to reason about others' mental states. To predict the outcomes of noisy exchanges, children in Experiment 1 needed to (1) represent the listeners' initial knowledge, (2) update it based on the speaker's testimony while accounting for the impact of noise, and (3) use the listeners' knowledge to predict what information they would desire (1a) or what information the speaker would repeat (1b). As communicators themselves, children in Experiment 2 needed to (1) represent what their partner could see and hear, (2) account for the selective impact of noise on their partner's auditory (but not visual) perception, and (3) choose a communicative act that would effectively transmit information given their partner's perceptual access.

Overall, successful performance in our studies requires the ability to reason about how others update their beliefs based on information from different perceptual modalities, while accounting for the selective impact of noise on one of these modalities (i.e., audition). Such an ability may be particularly consequential for understanding and communicating with those with sensory disorders. While even toddlers seem to understand the consequences of visual occlusion (e.g., opaque glasses) once they have experienced it themselves (Meltzoff & Brooks, 2008), children without any sensory disorders might initially assume that everyone can see or hear. Our work suggests that in the domain of auditory perception, by age 4, children are at least capable of understanding that certain individuals may have different auditory access. Future research should investigate how children's communicative adaptations manifest in diverse social contexts with individuals who possess different sensory capabilities.

Although the current results demonstrate that children can reason about and adapt to auditory noise from a young age, there are also several limitations to consider. First, the current studies used noise that completely prevented someone from hearing other sounds. However, noise often has a more subtle, graded effect on people's hearing, attention, and cognitive resources. As listeners, young children can disambiguate the meaning of degraded speech by relying on their top-down expectations about speakers, suggesting they understand how noise can interfere with (but not entirely block) communication (Yurovsky et al., 2017). Nonetheless, it remains unclear whether children—as third-party observers—can infer how noise might alter others' speech comprehension in a similarly nuanced way.

Second, the current studies involved simplified exchanges where a speaker transmitted information to a listener without feedback. Yet, most conversations are more dynamic; for example, listeners can express that they are having difficulty hearing, change their physical position, or ask questions about what they could not hear. In Experiment 1, the students in the videos did not immediately respond to the loud noise, which may have signaled that they could still hear what the teacher said. Future work could examine how children anticipate, interpret, and engage in such strategies.

Third, it is unclear how much children's own experience with noise necessitated or mediated the current results. Acoustic noise exposure varies systematically across environments by socioeconomic status (SES) and population density (Casey et al., 2017), which can lead to systemic differences in speech processing (Fernald et al., 2013), memory (St. John & Tarullo, 2020; Waters et al., 2021), reading ability (Cohen et al., 1973), and word learning (McMillan & Saffran, 2016). In turn, these differences have been shown to drive both language (Dailey & Bergelson, 2022; Hart et al., 1997) and achievement (Hanushek et al., 2022) gaps across childhood and adolescence. Nonetheless, the degree to which early noise exposure affects children's ability to reason about the effects of noise on others remains unknown. Thus, future work should examine the role that experience plays in shaping children's understanding of noise and communication more broadly.

The current studies provide initial evidence about how children think about auditory noise and the conditions under which communication can fail as a whole. Instead of relying on experience-dependent heuristics to predict and adapt to the consequences of auditory noise, children appear to possess a sophisticated understanding of how people acquire information via fallible sensory channels. Such an understanding is crucial for navigating imperfect auditory environments, allowing children to understand when and how communication fails, what happens when it fails, and what they can do to communicate successfully.

Data availability

Experiments 1a, 1b, and 2 were preregistered. All data, analysis code, and preregistrations are publicly available at https://osf.io/kufh5.

Author contributions

Conceptualization (all authors), data curation (AC, RMW, CQ), formal analysis (AC, RMW), funding acquisition (HG), investigation (all authors), methodology (all authors), project administration (AC), supervision (MCF, HG), visualization (AC, RMW), writing-original draft (AC, RMW, MCF, HG), writing-review & editing (all authors).

Aaron Chuey (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Investigation [lead], Methodology [equal], Project administration [lead], Visualization [equal], Writing—original draft [lead], Writing—review & editing [equal]), Rondeline Williams (Conceptualization [equal], Data curation [equal], Formal analysis [lead], Investigation [lead], Methodology [equal], Project administration [supporting], Visualization [equal], Writing—original draft [lead], Writing—review & editing [equal]), Catherine Qing (Conceptualization [supporting], Data curation [equal], Investigation [supporting], Methodology [supporting], Project administration [supporting], Writing—review & editing [supporting]), Michael Frank (Conceptualization [equal], Formal analysis [equal], Investigation [equal], Methodology [equal], Supervision [equal], Writing—original draft [equal], Writing—review & editing [equal]), and Hyowon Gweon (Conceptualization [equal], Funding acquisition [lead], Investigation [equal], Methodology [equal], Supervision [equal], Writing—original draft [equal], Writing—review & editing [equal])

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Conflicts of interest

The authors declare no conflicts of interest.

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