"It kinda has like a mind": Children's and parents' beliefs concerning viral disease transmission for COVID-19 and the common cold

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Acknowledgements. We thank Hannah Meloche, Tania Dhaliwal, Sophie Martel, Kaylee Chan, Golzar Ejadi, Logan Smith, Lester Mejia Gomez, Valerie Umscheid, Ella Simmons, Solangel Troncoso, and the rest of the research team for their assistance. We thank David Menendez for input.

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Word count: 12,085 (excluding title page, abstract, and references)

Running head: COVID-19 AND COMMON COLD

Abstract

How people reason about disease transmission is central to their commonsense theories, scientific literacy, and adherence to public health guidelines. This study provided an in-depth assessment of U.S. children's (ages 5-12, *N*=180) and their parents' (*N*=125) understanding of viral transmission of COVID-19 and the common cold, during the first year of the COVID-19 pandemic. The primary aim was to discover children's causal models of viral transmission, by asking them to predict and explain counter-intuitive outcomes (e.g., asymptomatic disease, symptom delay, viral replication) and processes that cannot be directly observed (e.g., viral replication, how vaccines work). A secondary aim was to explore parental factors that might contribute to children's understanding. Although even the youngest children understood germs as disease-causing and were highly knowledgeable about certain behaviors that transmit or block viral disease (e.g., sneezing, mask-wearing), they generally failed to appreciate the processes that play out over time within the body. Overall, children appeared to rely on two competing mental models of viruses: one in which viruses operate strictly via mechanical processes (movement through space), and one in which viruses are small living creatures, able to grow in size and to move by themselves. These results suggest that distinct causal frameworks co-exist in children's understanding. A challenge for the future is how to teach children about illness as a biological process without also fostering inappropriate animism or anthropomorphism of viruses.

"It kinda has like a mind": Children's and parents' beliefs concerning viral disease transmission for COVID-19 and the common cold

Children's causal models of viral disease transmission are of central importance to developing knowledge systems, scientific literacy, and public health. Illness is central to children's naïve theories of biology (Carey, 1985; Keil et al., 1999; Shtulman & Walker, 2020; Wellman & Gelman, 1992), and understanding the role that viruses play in disease exemplifies the key cross-cutting concept of "cause and effect" that is a goal in U.S. education throughout grades K-12 (NGSS Lead States, 2013). Children's understanding of contagious disease is also central from a public health perspective. Children are more likely to engage in disease-preventive behaviors when they have a causal understanding of illness (Au & Romo, 1999; Blacker & LoBue, 2016; Weisman & Markman, 2017). Although much is known regarding children's beliefs and misconceptions regarding germs and illness, relatively little work has examined their understanding of the non-visible processes taking place within the body during viral transmission.

Prior research on children's understanding of viral transmission

Children begin thinking about biological entities and processes long before they receive formal instruction (Coley & Tanner, 2012; Hatano & Inagaki, 1994). They demonstrate a strong desire to understand why things happen in the natural world, and seek information from informal sources, including parents and museum exhibits (Callanan, 1999; Callanan et al., 2020; Frazier et al., 2016; Gopnik & Sobel, 2000; Keil, 1992; Legare et al., 2017; Menendez et al., 2021; Sobel & Jipson, 2015; Wellman, 2011). Children are deeply curious and motivated to learn about unexpected or surprising events—including contagious illness (Legare et al., 2010).

By age 5, children possess elements of a basic 'framework' understanding of contagious disease: that illness is contagious, that close and prolonged contact with someone who is sick increases the likelihood of contracting illness, that germs can make people sick, that germs are too small to be seen, and that certain behaviors transmit germs (Bares & Gelman, 2008; Blacker & LoBue, 2016; DeJesus et al., 2021; Kalish, 1996; Keil et al., 1999; Legare et al., 2009; Legare et al., 2010; Lockhart & Keil, 2018; Rosengren & Nguyen, 2004; Siegal & Peterson, 2005).

At the same time, however, young children may lack a coherent biological theory of disease transmission (Au et al., 2008; Keil et al., 1999; Shtulman & Walker, 2021; Solomon & Cassimatis, 1999). Elementary-school children do not seem to understand that germs operate via biological processes (germ reproduction, replication, or death), instead construing germs as operating via strictly mechanical processes (transfer from one person to another) (Au & Romo, 1999; Au et al., 2008; Neulight et al., 2007). These gaps limit children's ability to make appropriate inferences in novel contexts that haven't been covered in a memorized list of "do's and don't's". For example, even when children know to wash their hands and cover coughs with their elbow, they fail to understand that wiping off a fork with a paper napkin is less effective than placing the fork in a glass of steaming hot water (Au et al., 2008). Prior research indicates that what is required to bridge the gap between recommendations and action is understanding the underlying scientific process of what a germ is, and how it operates inside and outside the body (Au et al., 2008; Blacker & LoBue, 2016). Misconceptions about viral processes may persist even into middle school or beyond. For example, in one investigation, even 9th-grade students often reported that vaccines directly attack a virus rather than as stimulating the immune system, thus misunderstanding the benefits of vaccines and how they operate over time (Jee et al., 2015).

Currently there is still much we don’t know about children’s understanding of infectious disease (Sigelman & Glaser, 2019). Whereas much research has focused on children’s understanding of behaviors that can result in illness transmission (e.g., sneezing, coughing), less is known about children's understanding of the causal processes that take place within the body. We also know little about how children think about viruses specifically, as most prior research has examined micro-organisms or transmissible disease in an undifferentiated way (including viruses, bacteria, and fungi; e.g., Au et al., 2008; Byrne, 2011). Because viruses are not themselves organisms but are parasitic on their host, this has implications for their features, transmission, prevention, and treatment.

The present study

The present study has two primary aims: first, to uncover elementary-school-aged children's causal models of viral transmission, and second, to examine parental factors that might contribute to children's beliefs and understanding. We examined children's understanding across the elementary-school years, to chart developmental changes. Much of the available research on children's understanding of disease has examined children within a single age period (e.g., preschoolers, or 4^{th} graders). By including children 5-12 years of age, we can ask at what ages key concepts are emerging, and whether different concepts show different developmental trajectories.

Causal models of viral transmission. To determine children's causal models, we assessed their predictions and explanations regarding viruses, viral transmission, and protective behaviors. We posed open-ended questions to elicit explanations as well as close-ended questions to probe understanding of counterintuitive aspects of viral transmission that are "diagnostic" of the underlying biological processes, such as asymptomatic carriers, transmission from seemingly innocuous activities (e.g., singing), delays in symptom onset, and increases in viral load over time. These phenomena extend beyond the typical scenarios that have been the focus of much prior work, in which children are asked about a person who is overtly ill engaging in a classic disease symptom – for example, someone who has a runny nose and coughs or sneezes into another person's face.

A central component of a naïve theory is its ontology (Carey, 1985), and we examined what sort of ontological framework(s) children used to characterize viruses (e.g., biological, mechanical, intentional). A virus is an intriguing edge entity—neither wholly alive nor wholly not-alive (Villarreal, 2004). That viruses "reproduce" and can be "killed" by soap and antimicrobial pesticides are crucial similarities to living organisms (Au et al., 2008). Yet viruses differ from living organisms, because they are not independent organisms and do not have their own metabolism; when outside the host's body they cannot function and ultimately will not survive. As noted earlier, prior research suggests that children *under*-apply a biological framework, by treating germs as operating via strictly mechanical forces (e.g., transfer of germs from one location to another, without consideration of whether germs are 'alive' or 'dead'). At the same time, there is reason to predict that children may *over*-apply a biological framework, by construing viruses as animate agents that are capable of eating, growing bigger, and moving intentionally and independently. In English, the language used to talk about infectious agents with children blurs the distinction between living organisms and non- or quasi-living entities ("bug" refers to both insects and germs, and "germ" broadly encompasses viruses, bacteria, and fungi). Additionally, children readily engage in anthropomorphism and personification (Beran et al., 2011; Byrne et al., 2009; Ganea et al., 2014; Geerdts, 2016; Gelman et al., 2022; Hatano & Inagaki, 1994; Inagaki & Hatano, 1987), and anthropomorphism is common in children's literature regarding the natural world (Ganea et al., 2014; Geerdtz et al., 2016; Waxman et al., 2014), including viruses (e.g., Brown, 2021; Jackson, 2021; Sisteré, 2021). One study found that

British children ages 7-14 had a tendency to categorize micro-organisms as animals or animal-like (Byrne, 2011), though it is not yet known whether this pattern holds for viruses specifically.

To determine the generality of children's causal theories, we compared children's reasoning about a pandemic that had massively disrupted participants' daily lives (COVID-19) with an exceedingly "ordinary" and innocuous illness (the common cold). Although the biological mechanisms for these viral illnesses are in broad strokes quite similar, the behavioral consequences are dramatically different. By directly comparing the two, we can determine whether children invoked different causal mechanisms for illness as a function of its familiarity and/or consequences. Although the common cold is a more familiar illness, we hypothesized that COVID-19 may be better understood, given children's heightened interest in causal mechanisms when encountering unexpected phenomena (Legare et al., 2010; Stahl & Feigenson, 2015), as well as the enormous amount of attention COVID-19 had received by the time of the present study. Consistent with this possibility, adults tested early in the pandemic showed higher rates of accuracy regarding COVID-19 than the common cold (Labotka & Gelman, 2022), and children tested during the COVID-19 pandemic were found to have more in-depth knowledge and causal understanding of contagious illness than children tested prior to the pandemic (Leotti et al., 2021).

Parental factors. A secondary goal of this project was to explore how children's responses compared with those of their parents, as well as how children's understanding correlated with parental attitudes, behaviors, and demographic variables. Parents completed a written version of the COVID-19 interview that children received (see below) and provided information regarding their attitudes toward COVID-19, their engagement with protective behaviors, how much they discussed COVID-19 with their children, and demographics.

Additionally, both children and parents indicated their interest in being vaccinated (at a time when COVID vaccines were not yet widely available). We were interested in examining whether any of the parental measures would correspond to children's causal understanding and/or their interest in being vaccinated.

Study overview. Children participated in two extensive face-to-face interviews with a trained researcher: one focused on COVID-19, the other focused on the common cold. The interviews included both close-ended and open-ended questions designed to assess children's understanding of the causal mechanisms involved in viral illness, transmission, and prevention, as well as what kinds of entities viruses are. Based on prior work in this area, sample sizes of 40 per cell were determined to provide adequate power to detect differences at an $\alpha = 0.05$ Type I error level, using a predicted effect size of partial $\eta 2 = .06$ and power (1- β err prob) = .80. Parents completed a survey regarding COVID-19 only (not the common cold), as this was of greater theoretical and practical interest.

The study was approved by the University of Michigan Institutional Review Board: "Children's Biological Beliefs Concerning COVID-19 Disease Transmission (HOW)" (HUM00184556).The research questions, coding, analyses, and participant exclusion criteria were pre-registered in AsPredicted, and can be viewed at the following anonymized links: "Children's & Parents' Biological Beliefs Concerning COVID-19 Transmission" (https://aspredicted.org/S8N_6H8) and "Coding and Analysis Amendment to AsPredicted #44594" (https://aspredicted.org/DFL_PL2).

Method

Participants

Child participants were 180 children ranging from 5-12 years of age at the first testing session (*M* age = 9.04, SD = 2.23): 5-6 years (*n* = 40, *M* = 6.03, *SD* = 0.62; 18 girls, 22 boys), 7-8 years (*n* = 49, *M* = 7.95, *SD* = 0.55; 27 girls, 22 boys), 9-10 years (*n* = 46, *M* = 9.98, *SD* = 0.52; 26 girls, 19 boys, 1 other), and 11-12 years (*n* = 45, *M* = 11.93, *SD* = 0.61; 27 girls, 18 boys). We had preregistered a goal of including 160 child participants (40 per age group) but noted that if more participants signed up to participate prior to reaching our goal, we would continue testing until all those who had signed up had been tested. Altogether, the parent-reported race/ethnicity of the child sample included 145 white, 9 Black or African-American, 3 Asian or Asian American, 10 Latine, 14 multi-racial/ethnic, and 1 preferred not to answer. Children were tested from July 2020 to February 2021. Thirteen additional children were tested but dropped, due to non-responsiveness (*n*=9), technical issues (*n*=2), completing their second session fewer than 10 days after their first session (*n*=1), and falling outside the pre-determined age range (*n*=1). Two of the participants who were retained had only partial data: one had a usable COVID-19 session but not cold, and the other did not have open-ended responses for the COVID-19 session due to data loss.

125 parents or caregivers participated (representing 87% of the families and 94% of the children, due to the inclusion of siblings in the child sample). They were 24-54 years of age (*M* age 39.08); 110 were women, 12 were men, and 3 did not report their gender. Self-reported race/ethnicity was white (*n*=105), Black or African-American (*n*=7), Asian or Asian American (*n*=2), South Asian (*n*=1), Latine (*n*=3), multi-racial (*n*=3), and unreported (*n*=4). Education levels ranged from high school or equivalent through to professional degree, with median level of education being a Bachelor's degree. Annual household income was reported in ranges, and included the full range, from less than $15,000 (the lowest option provided) to over $85,000 (the highest option provided), with median level being above $85,000. (The median household

income in the U.S. is about $65,000.) Participants' self-reported zip codes indicated they resided in 13 different states (2 not reported), with the vast majority in Michigan (87%). Three additional caregivers started but completed less than 50% of the survey and thus were not included. An additional parent completed the survey twice, so their second set of responses was dropped. Parents completed their surveys from August 2020 to March of 2021.

Materials

Children and their parents were queried about their knowledge and beliefs regarding viral transmission. Parents additionally answered questions regarding COVID-19 attitudes, protective behaviors, conversations with their children about illness, and demographics. The survey was based on a previously conducted survey with MTurkers (Labotka & Gelman, 2022, which provides additional details).

Viral transmission. This survey included a series of 41 closed-ended and 22 open-ended questions assessing a range of concepts regarding viruses and viral transmission, including: features of viruses (e.g., size, biological features), nonvisible processes (e.g., viral replication, asymptomatic disease, why protective behaviors are effective), incubation periods (lag between infection and disease onset), asymptomatic hosts, viral death when outside the host for a prolonged period, the ontological status of viruses (alive or not), and how viruses gain access to the body. Table 1 provides the full list of items. Several questions were adapted from prior research (Au et al., 2008; Au & Romo, 1996, 1999; Raman & Gelman, 2007; Solomon & Cassimatis, 1999). Children and parents received comparable questions, but the wording differed slightly as appropriate for each age group. For children but not parents, pictures accompanied each question to keep children engaged and help communicate the vignettes and response choices.

Table 1. Viral transmission survey (COVID-19 version), with concepts and items in order of presentation. For children, wording in parentheses was added if needed. Note: The Coding column indicates whether responses were: close-ended items included in the Accuracy Composite (AC; with correct response indicated), close-ended items analyzed individually (IN), open-ended questions coded for content (OE), or not coded (X).

Concept	**Item**	**Parent Wording**	**Child Wording**	**Coding**
General knowledge	Effects	Please briefly explain how COVID-19 has affected your life.	You may have noticed that people are doing things differently because of COVID. Has COVID changed things for you? How has it changed things? What's different? (How about school - did you do school from home? How about seeing your friends? How about going out shopping or going swimming?)	X
	Symptoms	What are the symptoms of COVID-19?	[older:] What symptoms does someone have when they get COVID? [younger:] What happens when someone gets COVID? (How do they feel?)	X
	Contract	How do people contract COVID-19?	How do people get COVID? (How do people catch COVID? Can they catch it from other people?)	OE
	Protect	What can you do to protect yourself and other people from getting COVID-19?	What can you do to protect yourself and other people from getting COVID? (Should you stay away from people who are sick?)	OE
	Get better	If someone contracted COVID-19, how would they get better?	If someone did get COVID, how would they get better? (Is there any medicine that makes COVID go away?)	OE
Introduction to virus	(N/A)	This is a picture of the virus that causes COVID-19. Some of our questions will refer to this virus. Sometimes we refer to this as "the COVID-19 virus", or "COVID-19 germs", for short.	You may have seen this picture before when people talk about COVID. It's a picture of what the germ that gives people COVID looks like. I am going to ask you some questions about COVID germs.	
Invisibility	Size	In real life, how big is a COVID-19 virus? [Too tiny to see with just your eyes, the size of a speck of dust, the size of a pea, the size of an orange]	In real life, how big is a COVID germ? [Too tiny to see with just your eyes, the size of a speck of dust, the size of a pea, the size of an orange]	AC: Too tiny to see
Biological features	Grow	Imagine a single COVID-19 virus. Can a COVID-19 virus grow bigger?	Remember, here's a COVID germ. I have some more questions about it. Can it grow bigger?	AC: No
	Move by itself	Can a COVID-19 virus move by itself?	Can it move by itself?	AC: No
	Need food	Does a COVID-19 virus need food?	Does it need food?	AC: No
Alive/dead	Can die	Can a COVID-19 virus die?	Will it die someday?	IN
	Alive	Please indicate whether each of the following is alive or not alive. [6 items including: an animal, a plant, a non-living natural kind, a moving artifact, a simple artifact, and "a COVID-19 virus"]	I'm going to show you some pictures, and for each one, you tell me: is it alive, or not alive? [6 items including: an animal, a plant, a non-living natural kind, a self-moving artifact, a simple artifact, and "the germ that	IN

			gives people COVID"]	
		You said that a COVID-19 virus is [is not] alive. Why? [Why not?]	You said that a COVID germ is [isn't] alive. Why? [Why not?]	OE
	Dead sick	If a COVID-19 virus is dead, can it still make people sick?	If a COVID germ is dead, can it still make people sick?	AC: No
	How kill	How can you kill a COVID-19 virus?	If a COVID germ isn't dead, how can you kill it?	OE
	Kill shoes	Can you kill COVID germs by stepping on them with your shoes?	Can you kill COVID germs by stepping on them with your shoes?	AC: No
	Kill freezer	Can you kill COVID-19 germs by putting them in the freezer?	Can you kill COVID germs by putting them in the freezer?	AC: No
	Wash out	If COVID-19 germs get in your mouth, can you wash them out by drinking a big glass of water?	If COVID germs get in your mouth, can you wash them out by drinking a big glass of water?	AC: No
Delayed onset	Symptom delay	Imagine a woman who was coughed on by someone who had COVID-19. How long would it take before she would start to feel sick? (Right away, later that same day, the next day, a few days later, one to two weeks later)	This woman was coughed on by someone who had COVID and got some COVID germs in her body. How long did it take before she started to feel sick? [Right away, later that same day, the next day, a few days later, one to two weeks later]	AC: A few days later or 1-2 weeks later
Viral replication	Time lag	Some COVID-19 germs got inside a man's body. He felt okay for a few days. But then later he started to feel sick, all over his whole body. His head ached and his throat hurt and he had trouble breathing -- all at the same time. Why did it take a few days for him to feel sick after the COVID-19 germs got inside his body?	Some COVID germs got inside a man's body. He felt okay for a few days. But then later he started to feel sick, all over his whole body. His head ached and his throat hurt and he had trouble breathing -- all at the same time. Why did it take a few days for him to feel sick after the COVID germs got inside his body?	OE
	Sick all over	How did the COVID-19 germs make him feel sick in so many parts of his body at the same time?	How did the COVID germs make him feel sick in so many parts of his body at the same time? (What happened -- what was different from when he was feeling okay?)	OE
	More germs	One day, a man was feeling very sick, so he went to the hospital. He stayed in a room that was very, very clean. Over the next few days, there were more and more COVID germs in his body. How did that happen? Why were there more COVID germs in his body?	See this man? One day, he was feeling very sick, so he went to the hospital. He stayed in a room that was very, very clean. Over the next few days, there were more and more COVID germs in his body. How did that happen? Why were there more COVID germs in his body?	OE
	Inside-outside	Did the additional COVID-19 germs come from inside his body or from outside his body?	Did the extra germs come from inside his body or from outside his body?	AC: Inside

Fomites	Package	Suppose someone who was sick with COVID-19 coughed on a package, and their germs got all over the package. Do you think someone else could get COVID-19 by picking up the package?	Someone who was sick with COVID coughed on this package, and their germs got all over the package. Do you think someone else could get COVID by picking up the package?	AC: Yes
		Why or why not?	Why? / Why not?	OE
	Package Delay	What if the package stayed on a shelf for a whole week, and then someone picked it up -- could they get COVID-19 by picking up the package?	What if the package stayed on a shelf for a whole week, and then someone picked it up -- could they get COVID by picking up the package?	AC: No
		Why or why not?	Why? / Why not?	OE
Asymptomatic disease	Asymptomatic	Imagine a woman who feels great. She's not coughing or sneezing. She doesn't have a fever or headache. Could she have COVID-19?	This lady feels great. She's not coughing or sneezing. She doesn't have a fever or headache. Could she have COVID?	AC: Yes
		Why or why not?	Why? / Why not?	OE
	Asymptomatic Transmit	Could she give someone else COVID-19?	Could she give someone else COVID?	AC: Yes
		How or why not?	How? / Why not?	OE
Points of entry	Foot	What if someone got COVID-19 germs on the bottom of their foot but not inside their body. Could that make them sick?	What if someone got COVID germs on the bottom of their foot. Could that make them sick?	AC: No
	Nose	What if someone got COVID-19 germs in their nose. Could that make them sick?	What if someone got COVID germs in their nose. Could that make them sick?	AC: Yes
	Eyes	What if someone got COVID-19 germs in their eyes. Could that make them sick?	What if someone got COVID germs in their eyes. Could that make them sick?	AC: Yes
Transmission risks	(N/A)	Consider a person who has COVID-19. For each of these activities, what is the likelihood that it would transmit COVID-19 to someone else?	What if someone has COVID? Could they give someone else COVID by…	
	Sneeze	Sneezing	… sneezing on them?	AC: Yes
	Cough	Coughing	… coughing on them?	AC: Yes
	Candles	Blowing out birthday candles	… blowing out birthday candles?	AC: Yes
	High-Five	Giving someone a high-five	… giving them a high-five?	AC: Yes
	Sing	Singing together	… singing together?	AC: Yes
	Cards	Playing cards	… playing cards?	AC: Yes
	Phone	Talking to someone on the phone	… talking to them on the phone?	AC: No
	Door	Standing on opposite sides of a glass door	… standing on opposite sides of a glass door?	AC: No
	Park	Sitting in different areas in a big park	… sitting in different areas in a big park?	AC: No
Reinfection	Get Again	If someone gets COVID-19 once and then gets better, can they get it again or not?	If someone gets COVID once and then gets better, can they get it again or not?	AC: Yes
		Why or why not?	Why? / Why not?	X
Folk beliefs	Foods_prevent	Are there any foods that can stop you from	Are there any foods that can stop you from getting	AC: No

		getting COVID?	COVID?	
		Why or why not?	Why? / Why not?	OE
	Summer	Does COVID-19 go away in the summertime, when the weather gets hot?	Does COVID go away in the summertime, when the weather gets hot?	AC: No
		Why or why not?	Why? / Why not?	OE
Vaccines	Vaccine Knowledge	As you may know, scientists are working on developing a vaccine for COVID-19. How do vaccines work? How would a COVID-19 vaccine protect people?	Scientists and doctors are working on developing a vaccine for COVID. How do vaccines work? How would a COVID vaccine protect people?	OE
	Vaccine Want	If a COVID-19 vaccine is developed, would you like to get the vaccine? [7-point scale]	If they create a COVID vaccine, would you want to get it?	IN
Protective behaviors	(N/A)	Here are some behaviors that are good ways to protect yourself from COVID-19. For each one, please briefly explain why you think it helps.	I'm going to tell you some things you can do, that are good ways to protect yourself from COVID. For each one, can you tell me why you think it helps.	
	Proximity	Don't stand too close to someone who is sick.	Don't stand too close to someone who is sick.	OE
	Shake Hands	Don't shake hands with someone who is sick.	Don't shake hands with someone who is sick.	OE
	Mask	Wear a mask.	Wear a mask.	OE
	Wash Hands	Wash your hands.	Wash your hands.	OE
	Wash Hands Soap	If you washed your hands with water but not soap, would that protect you from COVID-19? If so, how? If not, why not?	What if you wash your hands with water but not soap? Does that protect you from COVID? How? / Why not?	OE
	Touch Face	Don't touch your face.	Don't touch your face.	OE
	Clean Surface	Clean the countertop.	Clean the countertop.	OE
Mask wearing (COVID-19 condition only)	(N/A)	Is this person wearing their mask correctly?	Now I'm going to show you some people wearing a mask. Tell me if they're wearing their mask right or not.	
	Mask: Chin	[mask below chin]	[mask below chin]	IN
	Mask: Nose	[mask under nose]	[mask under nose]	IN
	Mask: Gap	[gaps on sides]	[gaps on sides]	IN
	Mask: Correct	[correct]	[correct]	IN

Knowledge self-appraisal. Participants were asked to indicate how much they knew about COVID-19 or colds. This question was asked twice (beginning and end of the viral transmission survey), to determine if the in-depth questioning of the survey would lower their self-perceived knowledge, in line with prior studies of the illusion of explanatory depth (Rozenblit & Keil, 2002). Children received a 1-4 scale ranging from 1 (Nothing at all) to 4 (A lot). Parents received a 1-5 scale ranging from 1 (Not at all knowledgeable) to 5 (Extremely knowledgeable). A simplified scale was employed for children to be comprehensible to the youngest participants.

COVID-19 attitudes and protective behaviors. Parents received 3 questions regarding their attitudes about COVID-19, adapted from the Pew Research Center, assessing how much they viewed COVID as a threat, much they thought social distancing measures helped slow the spread of COVID, and how much confidence they had in medical scientists. They also received 14 questions regarding how often they engaged in protective behaviors such as wearing a mask or social distancing, adapted from Gallup. All items can be found in Labotka and Gelman (2022).

Parent-child COVID-19 conversations. Parents were asked how often they discussed four aspects of COVID-19 with their children: definition (“What is COVID-19”), prevention (“What can you do so that you and others don’t get COVID-19”), consequences (“What happens if you get sick with COVID-19”), and causal mechanisms (“How the COVID-19 germ works and what it does inside the body”). Responses were from 1 (Never) to 5 (Almost all the time).

Demographics. Parents received a set of demographic questions assessing age, highest education level, profession, family’s combined yearly income, number of children living at home or for whom they have regular responsibility, marital status, gender, race/ethnicity, and zip code (from which voting behavior in the 2020 U.S. presidential selection was determined). Voting behavior by zip code was available for 82% of participants; county-level voting behavior was imputed for the others. This was calculated as a Biden-Trump difference score, ranged from -52% to +87%, with a mean of +33%. Participants were also asked if they personally knew someone who has been diagnosed as having COVID-19.

Procedure

Children were tested individually by a trained researcher via online video-conferencing, using Zoom software on a university-sponsored platform that provided extra security measures. Following parent consent and child assent, the researcher shared their screen with the child so that children could see the pictures that accompanied the questions. Sessions were recorded and automatically transcribed, and transcripts were later checked for accuracy and corrected. Less than 1% of children's responses were missing due to an inaudible response, technical problems, or a researcher accidentally skipping a question. Children were queried about both COVID-19 and the common cold (counterbalanced order, in separate sessions; 48% of children received the COVID-19 session first and 52% received the cold session first). Parents were instructed to sign their child up for their second session at least two weeks after the first session; for 4 children, the second session was scheduled a bit before this date, but all were at least 10 days apart (M range 3.9 weeks; range 1.5-25 weeks).

Parents completed the COVID-19 survey only (there was no cold survey) via a Qualtrics survey completed privately at their own pace, following their children's second testing session.

Families received $10 per child testing session and $10 for completing the parent survey. Child sessions were typically approximately 20 minutes in length.

Coding

Composite scales. We pre-registered an *Accuracy* scale (average of responses to the 29 closed-ended items marked "AC" (for Accuracy Composite) in Table 1, each of which was coded as correct or incorrect; scores could range from 0-29, with higher scores corresponding to greater accuracy) and a *Self-appraised knowledge* scale (average of the 2 knowledge self-appraisal items; higher scores corresponded to more knowledge). We also created three composite scales for parents only: *COVID-19 attitudes* scale (average on a scale of 1-4, where higher scores corresponded to more serious attitudes), *COVID-19 protective behaviors* scale (average on a scale of 1-3, where higher scores corresponded to more engagement in protective behaviors), and *Parent illness conversation* scale (average on a scale of 1-5, with higher scores indicating more frequent discussion).

Children's Cronbach's alphas were as follows: Accuracy (COVID-19 $\alpha = .51$, cold $\alpha = .55$) and Self-knowledge (COVID-19 $\alpha = .77$, cold $\alpha =.64$). Parents' Cronbach's alphas were as follows: Accuracy ($\alpha = .26$), Self-knowledge ($\alpha = .79$), Attitudes ($\alpha = .75$), Protective behaviors ($\alpha = .73$), and Parent illness conversations ($\alpha =.80$). For both children and parents, the low alphas for the Accuracy composite indicate that it should not be treated as a unidimensional scale. We therefore treat the composite strictly as a summary assessment of accuracy, and also report the data item-by-item.

Qualitative coding. As pre-registered, responses to the 22 open-ended questions in the Viral transmission survey were coded to assess 12 distinct concepts (see items marked as 'OE' in Table 2, and details in Labotka & Gelman, 2022; see also Au et al., 2008, for coding of germ survival and death, germ replication, explicit and implicit germ movement, folk beliefs, and points of entry). The codes were not mutually exclusive, meaning that a given response could receive multiple codes (for example, a particular response might be coded as "explicit germ movement," "points of entry," and "animism"). A given participant could provide multiple instances of a given code (for example, a child might provide an animism response on multiple items), and these scores were summed to provide a single score for each code, for each participant. However, a given code could be provided no more than once for a given item (e.g., a child who used multiple animism responses when explaining why a COVID germ is alive would receive an animism score of '1' for that item). For each coding category, 20% of responses were coded by two independent coders, with agreement ranging from 87-99%, and kappas ranging from .62-.94. All the Kappas had at least "substantial" (.61–.80) levels of interrater reliability, and most had "near perfect" (.81 and above) levels (Landis & Koch, 1977).

Table 2. Qualitative coding, coding categories and examples drawn from the data.

Coding category	**Child example**	**Parent example**
Germ survival or death	Because soap kills the germs and water kills the germs. Because those two mixed together creates a kind of vaccine that kills germs.	[Washing hands] kills the germs.
Germ replication	Because they can, I think they can mutate -- uh not mutate, multiply.	The virus can multiply in your body until your immune system is able to fight the virus.
Explicit germ movement	Don't shake hands because then it will just make a bridge for COVID to go on.	[Social distancing] prevent you from breathing in virus.
Implicit germ movement	Because they might like cough on you or something and you could get sick from them.	It [mask] provides a barrier from the larger droplets getting in and out.
Folk beliefs	They might be in the rain with the wrong type of clothes and they could, or they could eat too much candy, and get a cold or they could be outside in the winter without winter clothes on and summer clothes on.	Although it may help kill the virus if you drink hot liquids, no food will 100% protect you if you get the virus in your body.
Points of entry	Well, there are like a couple ways for germs to get in through your face like your mouth, your nose, your eyes. And I don't know about it, but I think ears.	Germs on our hands can enter our noses, mouths, eyes and make us sick.
Viruses require a host	No [would not get COVID touching a package that was on a shelf for a week] because the germs would have like aired off the package or probably died because it wouldn't have any source.	[Can kill virus by] Sanitizing and depriving it of a host.
Immune system response	[Why it took a few days for a person to feel sick:] Well because they had to fight the things protecting his body.	The virus can multiply in your body until your immune system is able to fight the virus.
Vaccines as preventive	Vaccines give you a little bit of the dead germs. So, your body will react to it and know how to protect you against the germ in the future.	A vaccine has the potential to provide immunity to some people, the body can "learn" how to protect itself against a version of COVID which can't reproduce.
Vaccines as curative	It [the vaccine] just basically sucks the germs out.	Vaccines are designed to help fight against sickness
Animism	Because the germs don't like soap.	It [COVID virus] seeks out hosts to thrive on.
Undifferentiated illness	Because the soap kills all the bacteria or something.	It depends on how sick they are. Some just need rest while others need antibiotics, steroids.

Results

The results are organized into three main sections. First, we report the findings of the viral transmission survey. Next, we present the qualitative coding of participants' open-ended explanations. Finally, we turn to additional measures (knowledge self-appraisal, attitudes, behaviors, and demographics), including how these measures correlated with child and parent beliefs and explanations. In each section, we examine condition (COVID-19 vs. cold) and age comparisons, as appropriate.

Viral transmission survey

In this section, we report results of the viral transmission survey, including: the accuracy composite (including individual items), mask-wearing, life status of germs, and wanting a vaccine. These data provide insights into children's causal understanding of counterintuitive aspects of viral transmission, as well as how they construe germs, and their attitude toward an important public health recommendation (vaccines). We also conducted an exploratory analysis to assess how children's knowledge of causal mechanisms may relate to their understanding of protective behaviors.

Accuracy composite. We begin by conducting a linear mixed-effects model on children's accuracy composite scores, with condition (COVID-19, cold), child age at first session (as continuous; mean-centered), and their interaction as fixed effects, and participant as a random effect. The data can be seen in Figure 1. There was a main effect of Condition (B = .019, SE = .007, t = 2.76, p = .006, 95% CI [0.01, 0.03]), revealing that children were more accurate when reasoning about COVID-19 (M = .769, SE = .007) than the common cold (M = .750, SE = .007). There was also a main effect of age (B = .028, SE = .003, t = 9.56, p < .001, 95% CI [.022, .034]), revealing greater accuracy with age. The age x condition interaction was non-significant

(B = -.003, SE = .003, t = 1.11, p = .27, 95% CI [-.003, .01]).

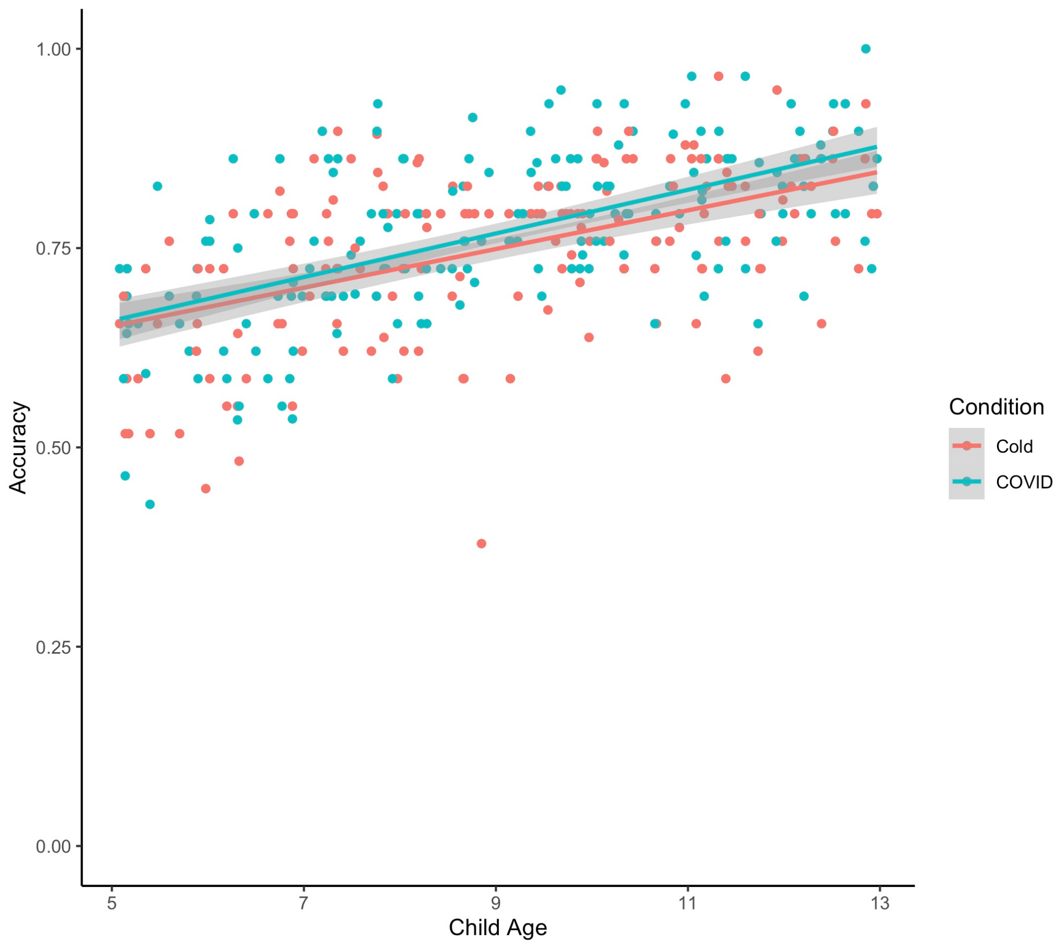


Figure 1. Children's accuracy composite scores as a function of Age and Condition. Shaded portions indicate SEs.

Tables 3 and 4 provide the means for each item. As pre-registered, comparisons against chance were conducted via binomial tests, except for the inside-outside question, which was analyzed via t tests because responses of 0.5 were possible. Alphas were set to ≤ .01 due to the multiple tests. As can be seen, children's performance varied considerably by age and by item.

By 7-8 years of age, children were highly knowledgeable about transmission risks, correctly reporting that certain behaviors (e.g., sneezing, coughing, exchanging high-fives) could lead to infection whereas others (e.g., talking on the phone, standing on opposite sides of a glass door) could not. Even the youngest children (5-6 years) did very well on these questions, although they were less certain that seemingly innocuous behaviors (singing, blowing out candles, or [in the case of colds] playing cards) could transmit disease. Children had more difficulty with questions tapping into internal bodily processes or novel situations, with even the oldest children (11-12 years of age) often incorrectly reporting that a virus could move by itself and grow bigger, that symptoms would appear within a day of exposure, and that one could get sick if a virus was on the bottom of one's foot. Still other questions showed substantial improvements with age. For example, the youngest children generally reported that it was not possible to have asymptomatic disease, asymptomatic transmission, or viral replication, in contrast to near-perfect performance by 11-12 years of age. For example, when asked whether someone who felt great and wasn't coughing or sneezing could have COVID, one 6-year-old said, "It doesn't even make sense." The youngest children were also more likely to endorse the folk belief that foods could prevent COVID-19 or colds, whereas by 11-12 years of age, children consistently responded accurately, that they could not.

Parents' performance on the Accuracy composite (COVID-19 condition only) was near ceiling ($M = .92$, $SD = .05$), and significantly above chance (.50), $t(124) = 87.83$, $p < .001$. Comparisons against chance were conducted via binomial tests, with alphas set to < .01 due to the multiple tests. All 29 of the items exceeded chance, with scores ranging from 67%-100% correct.

Table 3. COVID-19 condition, proportion correct per item, as a function of age group. * significantly different from chance, $p \leq .01$; ** significantly different from chance, $p \leq .001$; ps > .01 were not reported, due to the multiple tests. The "inside-outside" item was analyzed via t tests because children could respond "both," and thus responses were non-binary; all remaining items were analyzed via binomial tests. Green cells are above chance, red cells are below chance, and white cells do not differ from chance.

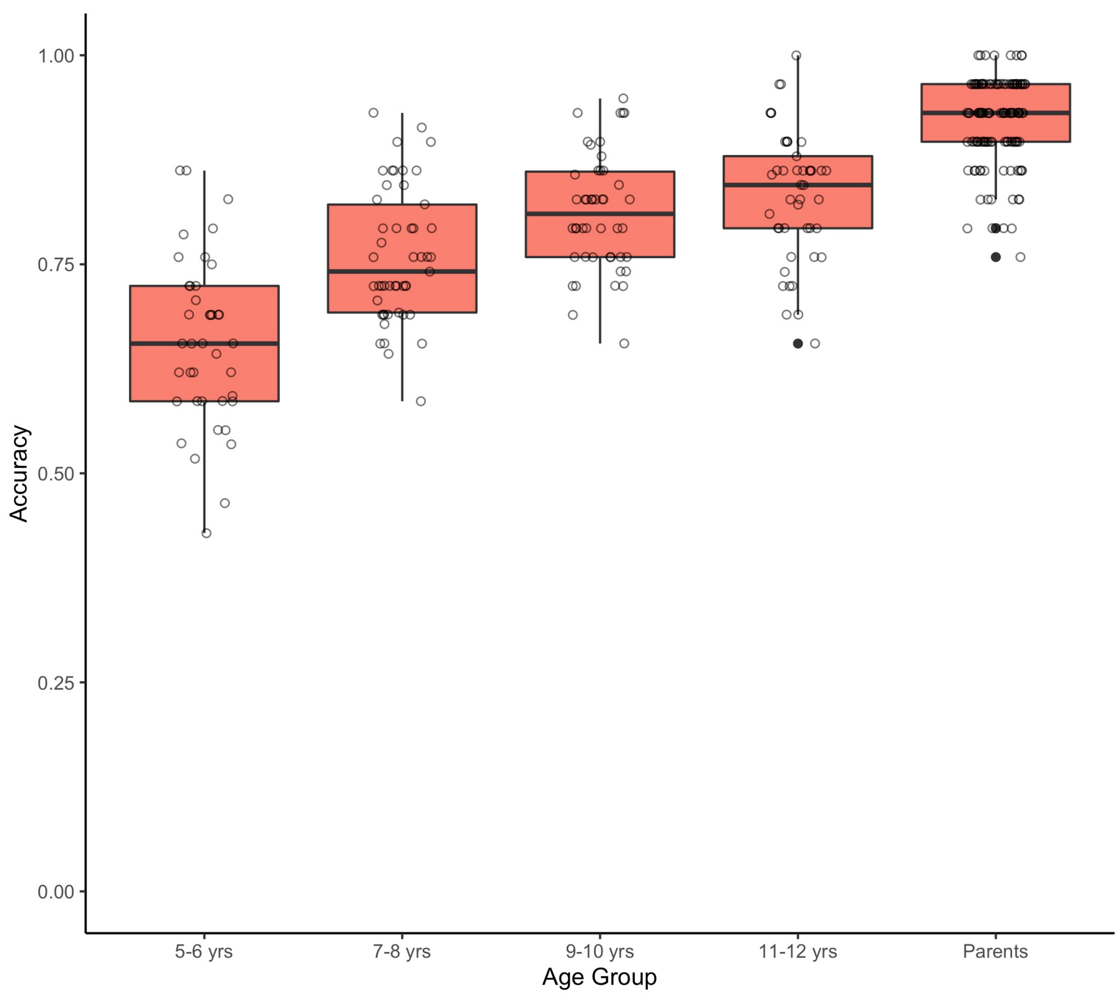
Concept	Item (see Table 1 for wording)	5-6 years	7-8 years	9-10 years	11-12 years	Parents
Invisibility	Size	.63	.80**	.96**	.87**	.98**
Biological features	Grow	.41	.35	.33	.51	.84**
	Move by itself	.23**	.41	.53	.56	.82**
	Need food	.85**	.86**	.83**	.67	.67**
Alive/dead	Dead sick	.55	.73**	.65	.64	.79**
	Kill shoes	.83**	.96**	1.00**	1.00**	.99**
	Kill freezer	.83**	.82**	.76**	.84**	.83**
	Wash out	.68	.92**	.89**	.91**	.96**
Delayed onset	Symptom delay	.34	.41	.74*	.67	.82**
Viral replication	Inside-outside	.28**	.49	.51	.82**	.97**
Fomites	Package	.95**	.92**	.89**	.93**	.86**
	Package delay	.32	.43	.54	.56	.90**
Asymptomatic disease	Asymptomatic	.20**	.47	.74*	.89**	.98**
	Asymptom. transmit	.32	.55	.76**	.93**	.98**
Points of entry	Foot	.40	.35	.50	.53	.89**
	Nose	.98**	.98**	1.00**	.96**	1.00**
	Eyes	.70	.94**	.96**	.80**	.99**
Transmission risks	Sneeze	.95**	1.00**	1.00**	.98**	1.00**
	Cough	.93**	1.00**	1.00**	1.00**	1.00**
	Candles	.55	.78**	.87**	.82**	.97**
	High-five	.83**	.86**	.91**	.96**	.92**
	Sing	.60	.83**	.87**	.91**	.98**
	Cards	.78**	.96**	.96**	.96**	.91**
	Phone	1.00**	.98**	1.00**	1.00**	1.00**
	Door	.88**	.90**	.93**	1.00**	.98**
	Park	.93**	.96**	.93**	.91**	1.00**
Reinfection	Get again	.83**	.90**	.85**	.76**	.88**
Folk beliefs	Foods prevent	.53	.67	.80**	.91**	.94**
	Summer	.75*	.84**	.83**	.89**	1.00**

Table 4. Cold condition, proportion correct per item, as a function of age group. * significantly different from chance, $p \leq .01$; ** significantly different from chance, $p \leq .001$; *ps* > .01 were not reported, due to the multiple tests. The "inside-outside" item was analyzed via t tests because children could respond "both," and thus responses were non-binary; all remaining items were analyzed via binomial tests. Green cells are above chance, red cells are below chance, and white cells do not differ from chance.

Concept	Item (see Table 1 for wording)	5-6 years	7-8 years	9-10 years	11-12 years
Invisibility	Size	.69	.92**	.91**	.91**
Biological features	Grow	.36	.31*	.35	.47
	Move by itself	.46	.39	.48	.53
	Need food	.79**	.90**	.76**	.67
Alive/dead	Dead sick	.41	.80**	.70	.62
	Kill shoes	.85**	.96**	1.00**	1.00**
	Kill freezer	.79**	.86**	.74*	.89**
	Wash out	.79**	.94**	.87**	.93**
Delayed onset	Symptom delay	.45	.22**	.41	.44
Viral replication	Inside-outside	.36	.56	.62	.78**
Fomites	Package	.87**	.92**	.83**	.93**
	Package delay	.51	.51	.64	.60
Asymptomatic disease	Asymptomatic	.18**	.43	.72*	.73*
	Asymptomatic transmit	.32	.45	.73*	.82**
Points of entry	Foot	.28*	.59	.43	.60
	Nose	.90**	.98**	1.00**	.98**
	Eyes	.69	.92**	.89**	.80**
Transmission risks	Sneeze	.95**	.94**	1.00**	.98**
	Cough	.95**	.96**	1.00**	.98**
	Candles	.44	.67	.80**	.82**
	High-five	.82**	.92**	.87**	.96**
	Sing	.49	.65	.78**	.73*
	Cards	.67	.85**	.89**	.93**
	Phone	1.00**	1.00**	1.00**	1.00**
	Door	.90**	.90**	.98**	1.00**
	Park	.90**	.94**	.93**	.98**
Reinfection	Get again	.90**	.88**	.89**	.84**
Folk beliefs	Foods prevent	.51	.63	.74*	.78**
	Summer	.67	.67	.70	.67

When comparing children and parents in accuracy, our preregistration plan was to conduct a linear regression model on the accuracy composite score, with child age as continuous, relationship status (parent, child), and their interaction as factors. This would have required assigning to each parent a corresponding child age. However, given that some of our child participants were siblings within families, we were unable to assign a single child age to each parent. We therefore dropped relationship status and treated age group as a categorical variable in the regression (five levels: 5-6 years, 7-8 years, 9-10 years, 11-12 years, and parents), with parents as the reference level. Parents were significantly more accurate than each of the child ages, all *p*s < .001: 5-6 years (*M* = .66, *SD* = .10), 7-8 years (*M* = .76, *SD* = .08), 9-10 years (*M* = .81, *SD* = .07), 11-12 years (*M* = .83, *SD* = .08), parents (*M* = .92, *SD* = .05).

Figure 2. Accuracy composite as a function of age group.



Mask-wearing. The four questions regarding mask-wearing indirectly examined understanding non-obvious aspects of viral transmission, by assessing whether participants considered risks when the nose and/or mouth were exposed to the air. These were asked in the COVID-19 condition only (as mask-wearing for colds is not typical in the U.S.), and thus could not be included in the accuracy composite. We found that children -- and even many parents -- seemed more focused on which elements of the face were visible than whether there were opportunities for breath to enter or exit. Thus, children and parents were close to ceiling in reporting that a mask was worn correctly when it tightly covered the mouth and nose (100% children, 98% parents), that a mask was worn incorrectly if below the chin (98% children, 98% parents), and that a mask was worn incorrectly if below the nose (92% children, 98% parents). However, only 27% of children and 50% of parents were correct in reporting that a mask with gaps along the sides was worn incorrectly. A binomial logistic regression revealed that parents were more accurate than children at ages 5-6 years (18% correct; $p < .001$), 7-8 years (22% correct, $p = .002$), and 9-10 years (31% correct, $p = .035$), but not 11-12-year-olds (35% correct, $p = .098$).

Life status of germs. Two questions probed beliefs about the life status of COVID-19 or cold germs: Are they alive? Can they die? These questions were not included in the accuracy composite because they cannot be scored as correct or incorrect, given the lack of scientific consensus. Children typically reported that germs are alive (COVID-19 81%, cold 79%), and can die (COVID-19 84%, cold 85%). Similarly, parents typically reported that COVID-19 viruses are alive (77%) and can die (87%). For comparison, participants were highly accurate on the comparison questions regarding animals (horse, pig: 99% alive [children], 100% alive [parents]), plants (tree, grass: 84% alive [children], 97% [parents]), non-living natural kinds (cloud, moon:

79% not alive [children], 83% [parents]), moving artifacts (sled, bicycle: 96% not alive [children], 100% [parents]), and simple artifacts (hat, cup: 96% not alive [children], 100% [parents]).

Wanting a vaccine. Overall, 72% of children indicated that they wanted a COVID-19 vaccine, 20% indicated that they did not, and 7% were unsure. By comparison, 61% of children indicated they wanted a cold vaccine, 26% indicated they did not, and 9% were unsure. Overall, 62% of parents indicated that they wanted a COVID-19 vaccine (scoring 5, 6, or 7 on the 7-point scale), 22% indicated that they did not (scoring 1, 2, or 3), and 16% were unsure (scoring 4).

Relation of causal mechanisms to understanding of protective behaviors. As an exploratory analysis, we conducted three non-preregistered correlations to examine how children's knowledge of causal mechanisms may relate to their understanding of protective behaviors. To assess knowledge of protective behaviors, we used: (a) a composite score of the 9 'transmission risks' items in the Accuracy composite, (b) a composite score of accuracy on the 4 mask items, and (c) whether the child wanted a COVID-19 vaccine. For this analysis we focused exclusively on children's responses in the COVID-19 interview, given that two of the protective behaviors were either included for the COVID-19 interview only (mask-wearing) or not relevant to the common cold (vaccines). For knowledge of causal mechanisms, we created a composite score of all the remaining items in the Accuracy composite that did not involve transmission risks (20 items). This revealed that children's causal knowledge correlated significantly with knowledge of transmission risks (.36, $p < .001$), knowledge of how to wear a mask correctly (.16, $p = .033$), and desire for a vaccine (.28, $p < .001$).

Qualitative coding

The qualitative coding of participants' open-ended responses provides insights into the causal frameworks that children and parents provide (see Table 5). The codes that children most consistently expressed were explicit germ movement, implicit germ movement, and animism. In contrast, biological process codes (germ survival or death, germ replication, viruses require a host, and immune system response) were expressed by fewer than half the children in each age group.

For each code, we conducted a linear mixed-effects model on the summary scores for children, with condition (COVID-19, cold), child age at first session (as continuous; mean-centered), and their interaction as fixed effects, and participant as a random effect (see Table 6). The COVID-19 condition elicited more mention of viral transmission (explicit germ movement, implicit germ movement, and points of entry) than did the cold condition. In contrast, the cold condition elicited more mention of misconceptions (folk beliefs and undifferentiated illness) than did the COVID-19 condition. Several codes increased with child age, including explicit germ movement, germ replication, immune system, folk beliefs, vaccines as preventive, and animism.

Table 5. Qualitative coding for children (COVID-19 and cold conditions) and parents (COVID-19 condition only). Top line in each cell provides the mean number of times the code was produced; bottom line in each cell (in brackets) provides the percentage of participants providing the code. For the COVID-19 condition, parentheses indicate which child ages are significantly less than the parents (<) or significantly greater than the parents (>), via Tukey's HSD tests.

Concept	**Code**	**COVID-19 CONDITION**					**COLD CONDITION**			
		5-6 years	**7-8 years**	**9-10 years**	**11-12 years**	**Parents**	**5-6 years**	**7-8 years**	**9-10 years**	**11-12 years**
Transmission	Explicit germ movement	2.40 (<) [80%]	2.49 (<) [86%]	3.07 [87%]	3.33 [91%]	3.61 [97%]	1.28 [55%]	2.35 [96%]	2.20 [91%]	2.44 [87%]
	Implicit germ movement	1.53 [80%]	2.57 (>) [92%]	2.71 (>) [93%]	2.64 (>) [89%]	1.83 [86%]	1.10 [65%]	1.29 [71%]	1.87 [89%]	1.51 [73%]
	Points of entry	0.58 [45%]	0.88 [61%]	0.89 [63%]	0.64 [51%]	0.98 [64%]	0.23 [23%]	0.43 [39%]	0.50 [43%]	0.36 [33%]
Biological processes	Germ survival or death	0.20 (<) [13%]	0.55 (<) [31%]	0.61 (<) [37%]	0.62 (<) [44%]	1.46 [70%]	0.33 [23%]	0.43 [31%]	0.61 [37%]	0.67 [33%]
	Germ replication	0.23 (<) [13%]	0.39 (<) [24%]	0.48 (<) [37%]	0.60 (<) [44%]	1.16 [70%]	0.25 [15%]	0.41 [29%]	0.41 [33%]	0.60 [47%]
	Viruses require a host	n.s (<) [0%]	0.10 (<) [6%]	0.09 (<) [7%]	0.22 (<) [20%]	0.61 [49%]	0.05 [5%]	0.14 [8%]	0.04 [4%]	0.13 [13%]
	Immune system response	0.03 (<) [3%]	0.39 (<) [20%]	0.46 (<) [33%]	0.51 (<) [40%]	1.01 [66%]	0.08 [5%]	0.22 [14%]	0.37 [28%]	0.58 [40%]
Misconcept.	Folk beliefs	0.33 [23%]	0.29 [24%]	0.26 [24%]	0.18 [18%]	0.26 [20%]	0.53 [35%]	0.73 [47%]	0.72 [54%]	0.84 [49%]
	Undifferentiated illness	0.08 [8%]	0.18 [18%]	0.30 [26%]	0.31 [24%]	0.30 [21%]	0.30 [20%]	0.65 [31%]	0.61 [28%]	0.60 [42%]
Vaccines	Vaccines as preventive	0.20 (<) [20%]	0.43 (<) [43%]	0.70 [70%]	0.76 [73%]	0.78 [78%]	0.25 [25%]	0.43 [43%]	0.57 [54%]	0.58 [56%]
	Vaccines as curative	0.33 [33%]	0.41 (>) [37%]	0.61 (>) [54%]	0.51 (>) [42%]	0.14 [12%]	0.38 [38%]	0.43 [39%]	0.26 [24%]	0.40 [33%]
Animism	Animism	0.95 [43%]	1.63 [51%]	1.54 [78%]	1.82 [73%]	1.76 [78%]	0.95 [45%]	1.49 [57%]	1.70 [74%]	2.04 [82%]

Table 6. Summary of analyses of child qualitative coding in the linear mixed-effects models. Statistical information is provided for significant effects; all others are indicated as 'n.s.' for non-significant.

Code	Age					Condition					Age x Condition				
	B	**SE**	***t***	***p***	**95% CI**	**B**	**SE**	***t***	***p***	**95% CI**	**B**	**SE**	***t***	***p***	**95% CI**
Explicit germ movemnt	.16	.05	3.04	.003	.07, .26	.73	.13	5.64	<.001	.48, .99	n.s.				
Implicit germ movemnt	n.s.					.94	.13	7.50	<.001	.70,1.19	n.s.				
Points of entry	n.s.					.37	.06	6.13	<.001	.25, .49	n.s.				
Germ survival or death	n.s.					n.s.					n.s.				
Germ replication	.05	.02	2.27	.024	.01, .10	n.s.					n.s.				
Viruses require a host	n.s.					n.s.					n.s.				
Immune system	.08	.02	3.55	<.001	.04, .13	n.s.					n.s.				
Folk beliefs	.06	.03	2.14	.033	.01, .11	-.45	.08	-5.43	<.001	-.61,-.29	-.08	.04	-2.27	.025	-.16,-.01
Undifferentiated illness	n.s.					-.33	.09	-3.70	<.001	-.50,-.15	n.s.				
Vaccines as preventive	.05	.02	2.97	.003	.02, .08	n.s.					.04	.02	2.15	.033	.004,.09
Vaccines as curative	n.s.					n.s.					n.s.				
Animism	.17	.06	3.00	.003	.06, .29	n.s.					n.s.				

To compare children's and parents' qualitative responses in the COVID-19 condition (the only condition that parents received), for each of the qualitative codes, we conducted a linear regression on the number of responses receiving that code, with age group as a categorical variable (five levels: 5-6 years, 7-8 years, 9-10 years, 11-12 years, and parents) and parents as the reference level. Parents were significantly more likely than children in all age groups to explain answers by appeal to biological processes: germ survival or death (*p*s < .001), germ replication (*p*s < .001), viruses requiring a host (*p*s < .001), and immune system response (*p*s < .01). They were also more likely to appeal to explicit germ movement (*p*s < .001) and vaccines as preventive (*p*s < .001) than children 5-6 and 7-8 years of age; more likely to appeal to points of entry than children 5-6 and 11-12 years of age (*p*s < .03); and more likely to appeal to undifferentiated illness ($p < .05$) and animism ($p < .01$) than children 5-6 years of age. In contrast, parents less often appealed to implicit movement (*p*s < .005) or vaccines as cures (*p*s < .005) than children 7-8, 9-10, and 11-12 years of age. Finally, there were no differences between parents and any of the child age groups in appeal to folk beliefs.

Themes. The qualitative coding revealed several patterns or themes, including competing frameworks for construing a virus, animism, folk beliefs, and challenges with internal bodily processes.

Competing frameworks. Children made use of several different ontologies or frameworks when discussing germs, treating them as mechanical, biological, intentional, and/or stable/inert entities. As can be seen in Table 5, children most commonly talked about germs in terms of mechanical movement (explicit and implicit germ movement). They often referred to germs being transferred from one person to another, from one location to another, or from one part of the body to another. At times children talked about germs in terms of human-sized movements or obstacles (e.g., “Since he’s [the character in the vignette] dancing, so the germs might’ve got moved around a bit.”; “COVID germs could probably travel better when it’s a clean room, because stuff like a toy truck would stop them … a little bit like a barrier.”). A mechanical causal framework was sometimes used instead of a more appropriate biological one, as seen by the low rates of children appealing to either germ survival/death or germ replication. For example, children often explained the benefit of washing hands solely in terms of removing germs rather than killing or destroying them, as this quote illustrates: “Because when you use soap and water, the soap helps your hand, it cause[s] it [to be] slippery and then the water makes it even slippery-er and then the germs slip off. But if you don’t use soap, it’s not slippery enough and then the germs won’t slide off.” Similarly, they sometimes explained that cleaning surfaces is effective by wiping off germs (rather than killing them): “Cause it gets the germs [onto] a piece of paper towel and then you throw them away.” As another example, when asked to explain why someone would get sick all over their body following exposure to germs, children rarely mentioned germ replication, instead talking about germs moving or spreading through the body.

Despite the ready availability of mechanical explanations, children also often talked about germs as if they were small creatures, thereby overextending their biological nature. This was evident in a variety of ways. For example, they often mentioned germs crawling, jumping, climbing, or flying. Some examples include the following (emphases added): “germs can ***jump*** from one person to another”; “Because germs can’t ***jump*** that far or ***fly*** that far”; “COVID could ***climb*** on you and invade you”; “if you touch your face and you have like even one germ, then it could go. It could ***crawl*** into your mouth or into your nose and then it could affect you.” Some children used mental state language when talking about germs (emphases added): “Yeah, it’s alive. Because it like kinda has like ***a mind*** and so it has to be alive to die."; "I think it kinda like ***knows*** where it wants to go"; "It [washing hands] helps ***scare*** away the cold"; "If you stand six feet away from them, the germs might get pretty ***bored*** floating for you, especially if you're on the other side of the earth."

In contrast, a number of children construed a virus as inert and requiring external human action to be destroyed (i.e., failing to understand viruses can become inactive without human interference). This was often seen when asked whether someone would get sick if they picked up a package a week after it had gotten germs all over it. Examples include: "Because like it's not like the germ will just go away in like in a couple weeks or something; like you have to do stuff to get it away, like clean air or something."; "Because if the package was just sitting um, it's not like someone came and like cleaned it off, possibly."; "Because um germs don't get off of stuff just by leaving them there. You get, they get off by washing the thing that got germs on it."; "Because it's still like on it, it's not just gonna like dissolve or something."; "'Cause I know that germs don't melt, germs don't melt like ice"; "Because it's not like snowmen. And it can't just melt away."

Animism. This broad coding category encompassed both animism (treating viruses or viral processes as having properties of animals; e.g., reporting that a virus had agency, could fly, or could grow) and anthropomorphism (treating viruses or viral processes as having properties of humans; e.g., reporting that a virus could talk, think, or be mean). These could include genuine attributions as well as analogy, metaphor, or pretense. Animism was common, found in roughly half the younger children (5-8 years) and three-fourths of the older children (9-12 years). At times children seemed to suggest that germs are in fact small organisms, capable of self-movement (as in the examples above that referred to jumping, crawling, etc.), mental states ("I think it kinda like knows where it wants to go."), emotional states ("Because um viruses can't stand hotness, that's why um winter and fall are the flu season."), sensations ("It will get hot and go into people's bodies to cool off."), or personality traits ("The germs are mean."; "The COVID germs can be sneaky, get inside, and make you really sick.").

At other times children made use of animism as a metaphor. Often these involved using the language of war (fight, attack, invade) to describe germs or the body's response. As one child said, "The good blood cells are … trying to grab more armor by eating more foods." In other cases, children came up with their own metaphors. For example, one highly articulate child said, "So I'm pretty sure a COVID germ can take hold of the one of the well cell factories in your body that creates more cells for you. They hijack it and then they use it for that cell factory to produce more COVID germs." Similarly, another child responded to the question of whether someone can get an illness more than once, "Not that particular strain. Your body knows how to fight off that particular strain. Now it's like having a cheat code in a video game. Once you learn how to do the puzzle, then, boom, you're good to go. At least until the puzzle changes." As another example, a 10-year-old explained why it took a few days for a person to get sick after COVID-19 got in their body this way: "It's like when you move into a house...It takes you a while to get unpacked in the house entirely, so it's like the germ. The germ needs to get in and know its surroundings, and then it will attack you."

Animism at times reflected children engaging in pretense, with germs playing an active role in an imaginary scenario: "Because the germs just fall off and they're, 'Oh no, I'm falling off – bye!'"; "They can only jump a certain part by height bar. And it's I think it's six feet so they're like they're like, 'Ahhhh!' -- boom." As another example, a child made swishing sword sounds after saying the following: "Some of his immune system soldiers were standing at the front battling… [The germ] was trying to invade." One child explicitly noted that their animistic language was not to be taken literally: "Sometimes like the virus is kind of retreating and then comes back. That's just an expression."

Animism was also common among parents, although in contrast to children, it seemed most often to be metaphorical, a vivid means of communicating about viral processes. Examples include (emphases added): "The germs multiplied and were carried throughout his body **attempting** to **attack** multiple systems."; "Most viruses **prefer** dry, cold conditions however COVID appears to transmit just fine in most weather conditions."; "The vaccines will **trick** your immune system into **thinking** that you have been exposed to COVID and hopefully your immune system will make antibodies in response."; "Basically, the vaccine **gives your body an instruction manual** for how to manufacture antibodies to **fight** COVID, rather than giving you inactive COVID virus for your body to react to."

Mechanical versus animistic frameworks: Implications for knowledge. The findings summarized above indicate that children expressed both mechanical frameworks (which under-rely on animacy) and animistic frameworks (which over-rely on animacy). This raises the question of how these distinct causal models related to children's knowledge about viral transmission. To explore this question, we conducted a set of non-preregistered analyses that grouped children as a function of the causal model(s) they were using, and then examined how this related to performance on the Accuracy Composite. For the animate model, we split the children into those who provided an animism response at least once (COVID n = 111, Cold n = 117; animate model group) and those who did not provide any such response (COVID n = 69, Cold n = 63). For the mechanical model, we split the children into those who mentioned germ movement at least once but no mention of germ survival or death (COVID n = 120, Cold n =

116; mechanical model group), and those who either mentioned germ movement as well as germ survival, or did not mention germ movement (COVID $n = 60$, Cold $n = 64$). For each illness, we then sorted children into three groups, as a function of the joint contingency of these two mental models: those who endorsed the animate model only (COVID $n = 42$, Cold $n = 49$), those who endorsed the mechanical model only (COVID $n = 51$, Cold $n = 48$), and those who endorsed both (COVID $n = 69$, Cold $n = 68$). (There were only 18 children in the COVID condition and 15 children in the Cold condition who did not fit into one of these three groups; they were not analyzed further.)

For each condition, we conducted a univariate ANOVA on the Accuracy scores and obtained a significant difference as a function of model group, for both COVID (F(2, 159) = 19.17, $p < .001$) and Cold conditions (F(2, 162 = 4.74, $p = .010$). In the COVID condition, those who used the animate-only model scored highest on the accuracy composite ($M = .83$), followed by those who used both models ($M = .78$), followed by those who used the mechanical-only model ($M = .71$), all ps < .02, Tukey's. In the Cold condition, those who used the mechanical-only model scored lowest on the accuracy composite ($M = .72$), followed by both other groups ($M = .77$ for each), ps $\leq .023$, Tukey's.

Challenges with internal bodily processes. A striking pattern in the qualitative coding was that children rarely mentioned any of the four internal biological processes that we coded for: germ survival or death, germ replication, viruses requiring a host, or the immune system. Indeed, as can be seen in Table 5, these levels were much lower than those of their parents. Each of these codes was mentioned by less than half of even the oldest group of children (11- to 12-year-olds). For example, when directly asked to explain why there was a delay between exposure to germs and feeling sick, or why someone would have more germs in their body over time, or why a person would feel sick all over their body a few days after exposure, children rarely considered germ replication, instead mentioning germs traveling through the body, or breaking apart into smaller pieces ("I think it splits apart and it will go to different parts of your body to make other parts of your body sick"). Similarly, when asked whether someone could get an illness more than once, children rarely mentioned the immune system, instead typically focusing on motivational processes (e.g., that someone who got COVID-19 once may not take it as seriously the next time: "Because once they are feeling better they decided, I'm feeling better. Let's go. And then he high fives somebody and then he could get COVID again.") or the persistence or ubiquity of germs ("Because even if you get rid of the germs. There's still going to be more so you could get sick again."; "The germs may have left your body, but you could have made a contact that could just bring them back."). Children (especially those in the two younger age groups) also had difficulty explaining how vaccines worked, and often expressed misconceptions. To illustrate, one child said that vaccines suck germs out. Another acknowledged not knowing how vaccines work but proposed that one vaccine can stop you from getting COVID-19, and another could kill off the germs, adding, "Maybe there's one vaccine that can do both."

Folk beliefs. Folk beliefs were more frequently expressed to explain the common cold than COVID-19, perhaps due to the greater opportunity for folk causal accounts to develop and be transmitted over time for the more familiar illness (see also Labotka & Gelman, 2022). The two most common sets of folk beliefs that were expressed concerned temperature (e.g., going outside with wet hair; not wearing warm enough clothing in cold weather) and food (either as preventive or curative).

Food as preventing illness was discussed in two competing ways by children. On the one hand, food was sometimes noted as a way to treat viral illness – eating healthy or avoiding 'bad' food ("Sugar is COVID's friend. If [food] has not sugar in them, then COVID gets smaller."). On the other hand, numerous children indicated that food would not be an effective remedy, because food is not medicine – foods are meant for eating when hungry ("If you eat something, [it would] have to have like some kind of like medicine in it and I don't think there's really a food with medicine in it."; "Foods just helps your hunger and not like any disease"). Such responses are consistent with Carey's (1985) classic work showing that children at times construe physiological processes (such as eating) in terms of psychological benefits (easing hunger).

Attitudes, behaviors, and demographics

This section includes data from measures assessing attitudes, behaviors, and demographics, to determine how these factors may relate to children's causal understanding (for evidence of such links in adults, see, for example, Chinn & Brewer, 1993; Keil, 2006; Murray et al., 2021; Sanchez & Dunning, 2021; and Thoma et al., 2021).

Knowledge self-appraisal. We conducted a linear mixed-effects model on children's scores on the Self-knowledge scale, with condition (COVID-19, cold), time (Time 1 [beginning of interview], Time 2 [end of interview]), child age at first session (as continuous; mean-centered), and their interactions as fixed effects, and participant as a random effect. There was a main effect of Time (B = .339, SE = .056, $t = 6.02$, $p < .001$, 95% CI [0.23, 0.45]), revealing that children rated their knowledge higher at Time 2 than Time 1 (*M*s = 2.13 [SE = .043] and 1.79 [SE = .043], respectively). There were no other significant effects, *p*s > .44.

Parents rated their own knowledge about how the COVID-19 virus works on average between somewhat and moderately knowledgeable (time 1 $M = 3.72$ (SD 0.57); time 2 $M = 3.72$

(SD 0.54)). There were no differences in their ratings provided at the beginning versus end of the survey. We had preregistered comparing the knowledge self-appraisal scores for children with that for parents. However, given that the scales for children and parents were different from one another, they were not directly comparable and so we did not conduct this analysis.

Parent-child COVID-19 conversations. We were interested in how often parents reported discussing different aspects of COVID-19 with their children. We therefore conducted a univariate repeated-measures ANOVA on parental scores, with 4 levels of conversational topic (definition, prevention, consequences, causal mechanisms). This yielded a main effect of topic, $F(3,309) = 63.77$, $p < .001$, $\eta_p^2 = .38$. Pairwise comparisons revealed that parents reported most likely to have conversations about prevention (*M* (SE) = 4.08 (.08), then definitions (3.71 (.07)), then consequences (3.26 (.09)), and least causal mechanisms (3.00 (.10)), all *p*s ≤ .003.

Attitudes scale. Parents' scores on the COVID-19 attitudes scale ranged from 1-4, with an overall mean of 3.55 on the 4-point scale, indicating that participants overall thought that social distancing measures were effective (*M* = 3.63, *SD* = 0.62), viewed coronavirus as a serious threat (*M* = 3.58, *SD* = 0.78), and had confidence in medical scientists (*M* = 3.43, *SD* = 0.76).

Protective behaviors. Parents' scores on the self-reported protective behaviors scale ranged from 1-3, with an overall mean of 2.76 on the 3-point scale, indicating that they overall either considered doing the behaviors or had done so.

Personal knowledge. Parents were also asked if they personally knew someone who had been officially diagnosed with COVID-19. Of the 123 participants who answered the question, 79% (*n* = 97) responded ‘yes’. There were no significant differences between those who did or did not personally know someone diagnosed, on accuracy, interest in being vaccinated, knowledge self-appraisal, COVID-19 attitudes, protective behaviors, or COVID-19 conversations with their children.

Correlations. We preregistered four correlations, examining pairwise how parent scores related to child scores on each of the following four measures: COVID-19 accuracy composite, COVID-19 knowledge self-appraisal composite, COVID-19 interest in being vaccinated, and COVID-19 animism (qualitative coding). We obtained a significant correlation between children and parents in wanting a vaccine (.28, $p < .001$). There were no significant correlations on the other three measures.

We also examined whether children's scores on the COVID-19 accuracy composite and children's desire for a vaccine correlated with the following parental measures: accuracy composite, wanting a vaccine, conversations about COVID-19, attitudes, protective behaviors, and demographics (income, education, age, and community voting behavior). These comparisons were not preregistered but are presented for exploratory purposes. Only p-values $\leq .01$ are reported. Scores on the child COVID-19 accuracy composite correlated significantly with the parent conversation composite (.21, $p = .007$)[1], parent wanting a vaccine (.20, $p = .009$), parent age (.28, $p < .001$), and parent education (.24, $p = .002$). Children's interest in receiving a vaccine significantly correlated with parent attitudes (.29, $p < .001$), parent protective behaviors (.24, $p = .002$), parent age (.29, $p < .001$), parent education (.39, $p < .001$), and community voting behavior (.22, $p = .005$).

We pre-registered correlations among the following variables for children, separately for the COVID-19 and cold conditions: accuracy, knowledge self-assessment, willingness to be

[1] We also conducted exploratory correlations between parents' self-reported talk with their children about how germs work (i.e., the causal mechanism question in the set of items regarding parental conversations about COVID) and children's knowledge of COVID protective behavior (transmission risks and mask-wearing). This analysis yielded no significant correlations. However, parents' self-reported talk about how germs work did show a small but significant correlation with children's accuracy on the causal mechanism composite, .18, $p = .035$. See the section entitled "Relation of causal mechanisms to understanding of protective behaviors" for description of these measures.

vaccinated, and animism. Additionally, for exploratory purposes, we examined whether children's willingness to be vaccinated correlated with their mention of vaccines as preventative or curative in the qualitative coding. Only effects significant at $p \leq .01$ are reported. In the COVID-19 condition, children's accuracy composite correlated positively with their interest in getting a vaccine (Pearson's r = .33, $p < .001$) as well as their animism (.24, $p < .001$). Additionally, children's interest in being vaccinated correlated positively with their characterizing vaccines as preventative ($r = .23$, $p = .002$). In the cold condition, children's accuracy composite correlated positively with their animism (.24, $p = .001$).

For the parents, we pre-registered correlations among the following variables: accuracy, knowledge self-assessment, willingness to be vaccinated, and animism. For these and all correlations reported in this section, only *p*s ≤ .01 are reported. We also included parents' COVID-19 attitudes, COVID-19 protective behaviors, and illness conversations with their children, as exploratory correlates. Accuracy correlated with willingness to get a vaccine, $r = .24$, $p < .01$, and COVID-19 attitudes (taking the disease seriously), $r = .32$, $p < .001$. Willingness to get a vaccine also correlated with COVID-19 attitudes (.49, $p < .001$) and protective behaviors (.28, $p = .001$). COVID-19 attitudes and protective behaviors also correlated with one another (.49, $p < .001$). No other correlations were significant.

Finally, as pre-registered, we examined how parent accuracy related to demographic variables. Accuracy correlated significantly with parent education, $r = .29$, $p = .002$, but not income ($r = .18$, $p = .045$), age ($r = .028$, $p > .75$), or community voting ($r = .09$, $p > .31$). Accuracy also did not differ by gender. For exploratory purposes, we also examined how demographic variables related to COVID-19 attitudes, COVID-19 protective behaviors, and interest in being vaccinated. COVID-19 attitudes correlated significantly with education ($r = .34$,

$p < .001$), income (.28, $p = .002$), and community voting (.36, $p < .001$), but not age. COVID-19 protective behaviors did not correlate significantly with any of the demographic variables. Willingness to be vaccinated correlated with income ($r = .31$, $p < .001$), education ($r = .27$, $p = .003$), and community voting (.23, $p = .009$).

Discussion

Understanding the transmission of viral disease is central to an intuitive theory of biology, achieving scientific literacy, and engaging in health-promoting behaviors—and this understanding is especially important during periods of rapid transmission of serious illness, as with the COVID-19 pandemic. The current study provided an in-depth examination of causal understanding of viruses and viral illness, in children 5-12 years of age and their parents. We also explored how parental factors (including conversations about illness and parents' own attitudes and behaviors) related to children's reasoning. Open-ended and close-ended questions probed counter-intuitive aspects of viral transmission that are diagnostic of the relevant underlying biological processes (including what viruses are, how they function within the body, and why behaviors such as mask-wearing, social distancing, or vaccines are effective means of disease control). We queried participants during the first year of the COVID-19 pandemic, focusing on both COVID-19 and the common cold (to examine the generality of children's understandings). Of central interest was identifying the understandings, gaps, and misconceptions in children's understanding of viral illness transmission, throughout the elementary-school years. In so doing, we sought to discover what causal frameworks children were using, and how these understandings develop.

In the remainder of this discussion, we first descriptively summarize the findings ("Knowledge, gaps and misconceptions"), then turn to the causal frameworks that children were using, and parental factors that corresponded to children's accuracy and interest in being vaccinated. We then turn to future directions and conclusions.

Knowledge, gaps, and misconceptions

Children in this high-SES group were overall highly accurate on the close-ended questions, answering correctly on roughly three-fourths of the accuracy composite overall. Performance was largely similar across the two conditions (COVID-19 vs. common cold), though when differences were obtained, they were consistently in the direction of greater accuracy when reasoning about COVID-19. Although it may seem surprising that children reasoned more accurately about the less familiar illness, this replicates prior findings with adults (Labotka & Gelman, 2022), and is consistent with the idea that surprising events can trigger children's causal explanatory reasoning (Legare et al., 2010). Additionally, children may have been more highly motivated to learn about COVID-19, given how massively it disrupted their lives and how much attention it received during this period. As one child told us, when asked whether they had heard of COVID-19, "Are you kidding me??"

Children in every age group typically reported that COVID-19 and cold germs are too small to be seen, and even the youngest children talked about germs being transmitted from one person to another. Indeed, a belief in disease transmission seemed to be stronger in children than adults, with children more often than adults reporting that a germ could enter the body through the feet, or that one could get sick from touching a sneezed-on package even after it was sitting untouched for a full week. Children were also knowledgeable about many of the behaviors that transmit or block germs, including points of entry, mask-wearing, and social distancing. This is consistent with prior research indicating that even preschoolers understand disease as transmissible through proximity or direct contact (DeJesus et al., 2021).

Nonetheless, performance improved markedly with age. Performance on the accuracy composite increased as a function of child age, and the themes expressed in the qualitative coding of children's open-ended responses revealed greater accuracy with child age as well. In addition, parents displayed more consistently accurate knowledge than their children, including even the oldest child age group. The concepts that appeared most challenging for children—especially the youngest children but to some extent throughout the child age range—were those tapping into what processes are taking place inside the body, and what viruses can and cannot do.

Children appeared to have difficulty grasping the progression of illness, consistently underestimating the delay of symptom onset following exposure, and (for those younger than 9-10 years of age) failing to appreciate that illness or illness transmission can be asymptomatic. Most children made no mention of the biological concepts of germ survival or death, germ replication, the need for a host, or the immune system response (see also Jee et al., 2015). Even in the oldest age group (11-12 years of age) these concepts were mentioned by less than half the participants. For example, when directly asked why the number of germs in a person's body would increase over time, or why a person would increasingly feel sick all over their body, children typically generated reasons that were unrelated to viral replication. And although children were generally knowledgeable about basic dos and don'ts, such as washing hands, social distancing, and wearing masks, they typically failed to mention biological processes to explain these recommendations. Instead, children often focused on the movement of viruses across space. For example, many children reported that washing hands with soap is an effective prevention strategy because soap and water wash away the germs (rather than that soap kills the germs). The youngest children may also have focused more on direct contact as a means of transmission rather than aerosolized transfer, given that they often reported that disease would not be spread by singing or blowing out birthday candles.

Children also revealed misconceptions about what viruses can and cannot do. When directly asked if COVID-19 or cold germs can grow bigger or move by themselves, none of the child age groups responded correctly (i.e., "no") above chance, and up through 9-10 years of age, children tended to agree that germs could do both. In their open-ended responses as well, children often characterized germs as small creatures that eat food, grow bigger (rather than replicate), and crawl around. They did not seem to understand that viruses decay over time if left outside the host's body, nor (as noted previously) that they can replicate.

We also saw some evidence for folk theories in children's explanations for why people get sick with COVID-19 or the common cold and/or how to treat such illnesses, primarily in appealing to exposure to cold or special foods. Folk theories were endorsed consistently more often for the common cold than for COVID-19. Conversely, accuracy was consistently higher for COVID-19 than for the common cold. The differences obtained between these two viral illnesses suggests that young children may not be operating with a single, undifferentiated "germ" model of contagious illness, but rather hold illness-specific beliefs. Given that viral diseases can differ substantially from one another (e.g., whether transmission is through the air, blood, saliva; the risk of fomites; degree of transmissibility; length of incubation period; range of symptoms), it is appropriate for children to recognize such differences. At the same time, other aspects of viral disease are common across illnesses, thus raising the question of how to best teach children to generalize appropriately from one disease to another. These are important questions for future research.

Causal frameworks

Altogether, the findings summarized above suggest that during the elementary-school years, children's reasoning about viral transmission includes at least two distinct mental models: (a) a mechanical model that underestimates the role of biological processes in illness transmission, progression, and recovery, and (b) an animal model than overattributes biological and psychological attributes to viruses.

On the one hand, converging evidence suggests that children made use of a mechanical causal framework that focused on how germs move through space—akin to how one would explain the movement of balls on a billiards table. They talked about germs spreading through the body rather than replicating, germs getting stuck behind obstacles such as masks or toys in a messy room, and hand-washing as rinsing off germs rather than killing them. Alongside this focus on germs as mechanical entities, children often failed to appreciate biological causal mechanisms of viral disease, such as that viruses replicate, require a host, and evoke an immune system response. An appreciation of biological causal mechanisms was primarily confined to the oldest children, and relatively rare even among those age groups. The finding that children often evoked mechanical rather than biological causal mechanisms to understand COVID-19 and colds is consistent with prior research on children's predictions and explanations for a range of other viral illnesses (SARS, HIV, the flu; e.g., Au & Romo, 1999; Au et al., 2008), extends this result to how children reason about COVID-19, and provides an in-depth examination of how this understanding compares over a broad age range (5-12 years) and to parents of the same children.

On the other hand, children also characterized viral processes in animistic terms, appealing to animate, biological, and psychological attributes at every age. They reported that germs can grow and move by themselves. They made extensive use of animistic or anthropomorphic talk (*want, try, eat, crawl, battle*, etc.) when describing how germs move from one person to another, how they get into the body, why people feel sick all over after contracting a disease, and how the body itself battles disease. Animism was consistent throughout the child sample, and even increased with child age. It appears that animism may have functioned in at least two distinct ways—with some attributes (e.g., self-propelled movement) reflecting an ontological classification of germs as small organisms (consistent with the high rate of reporting that germs are alive; see also Byrne, 2011), but other attributes (e.g., the body fighting viruses) reflecting a non-literal way of characterizing processes for which children have no specialized terminology. It is interesting in this regard to note that there was a positive correlation between children's animism and their accuracy composite score. It may be that analogies such as "An infection is like a war" provide a graspable scaffold for understanding processes and mechanisms in viral disease that are not directly visible (Jee et al., 2015).

The "over-biologizing" tendency just described may appear to contradict some claims in the literature, suggesting that children deny that germs engage in biological processes, such as eating, having babies, and moving by themselves (Shtulman & Walker, 2020; Shtulman & Legare, 2020; Solomon & Cassimatis, 1999). However, such findings were reported with younger children (those under 6 years of age). It may be that very young children (e.g., preschoolers) fail to appreciate that germs can be biological entities, but then once children treat germs as biological, they over-extend this understanding, with a differentiation between bacteria (living organisms) and viruses ("edge" entities that are not clearly either alive or not-alive) emerging only much later (if at all). Relatedly, biological attributions may depend critically on the particular feature being tested, as seen in our data, wherein most children reported that germs can move by themselves but do not eat.

Altogether, then, children seem to be using two distinct mental models of what viruses are and how they operate – one that *under*-relies on biology and one that *over*-relies on biology—that superficially at least seem contradictory. In our data, underreliance on biology -- that is, expressing a mechanical model of illness in the qualitative data -- corresponded to lower performance on the Accuracy composite. In contrast, overreliance on biology -- that is, expressing an animistic model of illness in the qualitative data -- corresponded to higher performance on the Accuracy composite. More work is needed to understand how these models relate to one another, as well as how each relates to a more mature, adult-like understanding. Yet one notable point from this study is that more than one-third of children expressed both a mechanical model and an animistic model simultaneously. This finding is consistent with a growing body of evidence that scientific explanatory models do not necessarily replace prior intuitive theories but rather may co-exist (Kelemen & Rosset, 2009; Legare et al., 2012; Legare & Gelman, 2008; Shtulman & Harrington, 2016; Shtulman & Legare, 2020; Shtulman & Valcarcel, 2012). In this respect, children may hold construals of viral illness without knitting them together into a coherent or singular whole (see also di Sessa et al., 2004). It is perhaps not surprising that viruses evoke competing intuitions on the part of children. They pose an ontological puzzle, even for adult scientists (Villarreal, 2004), and children do not have access to observable features to help guide these inferences.

It also may be that children have a 'placeholder' notion of germs, in which germs are believed to play a causal role in illness, but precisely how is not understood. We had hypothesized that children may recognize the limitations to their knowledge after completing the detailed interview, in accordance with adults' response to being confronted with their own illusory sense that they understand complex phenomena more than they actually do (Rozenblit & Keil, 2002), but this was not the case. Rather, children actually rated their knowledge as *higher* after completing the interview than at the start, suggesting that they may have difficulty gauging the limits of their own understanding (see also Mills & Keil, 2004).

Parental factors

Children's accuracy on the COVID-19 interview correlated positively with parental self-reported conversations with their children about disease. Nonetheless, we also found that conversations about viral mechanisms (how the disease 'works') was the least common among the topics queried, consistent with recent research finding that parental conversations with their children regarding the COVID-19 pandemic tended to focus primarily on risks/safety, lifestyle changes, and preventative behaviors rather than causal mechanisms of disease transmission (Leotti et al., 2021; Menendez et al., 2021). We also found that parental education, age, and interest in being vaccinated correlated with child accuracy on the COVID-19 composite, and that children's interest in receiving a vaccine significantly correlated with parent attitudes and protective behaviors regarding COVID-19 (i.e., taking the disease more seriously), as well as parent age, parent education, and community voting behavior. These findings point to the importance of further examining environmental and social transmission factors that may play a role in children's developing understandings.

Future directions

Although the current study provides an in-depth portrait of how children reason about viral illness, several important questions remain. First, this was a high-SES sample, with many participants living in or near a university community with two science museums within walking distance of campus, one designed specifically for children. The high level of education of the parents and the availability of scientific resources makes it all the more striking that we observed sustained gaps in children's understanding. Still, it would be important to determine how children without these resources reason about illness, especially those living in communities that have been hard-hit by COVID-19, or are skeptical of scientific advice regarding masking and vaccination.

Second, the study was conducted during the first year of the COVID-19 pandemic, and thus we cannot know how the findings would generalize to other points in time. For example, perhaps children in our sample were relatively less knowledgeable, because they were still learning about this brand-new disease. Or, perhaps they were relatively more knowledgeable, given the ready availability of information during a period when COVID-19 was the major news event nearly every day.

Third, we focused on COVID-19 and the common cold, which are different in many respects. The comparison was chosen to provide a test of the generality of children's causal models for illnesses that vary markedly in their consequences. However, in future research, it will also be important to tease apart when and why children evoke different causal understandings for different disease content.

Fourth, the extensive use of animism and anthropomorphism in our data raises important questions about their consequences – specifically whether they help or hurt when teaching children about invisible disease processes. Animism and anthropomorphism were common in parents as well as children, with 78% of parents using such language (e.g., "The germs are fighting his body inside him, they are attacking his cells and his cells are trying to fight back."). Similarly, anthropomorphism is found in educational materials geared toward children, including websites, books, and museum exhibits (Geerdts et al., 2016; Wood, 2019). Traditionally anthropomorphism has been viewed negatively, as leading to inaccurate concepts and inferences even among scientists (Davies, 2010; Martin, 1991). However, others have suggested that anthropomorphism may have benefits, by making a complex scientific concept more familiar, approachable, and memorable, and thus resulting in more sustainable learning (Jee et al., 2015; Kattmann, 2008; Salaudeen, 2020; Stoos & Haftel, 2017; Zohar & Ginossar, 1998). Still others have argued that anthropomorphism has no consistent effects on understanding (McGellin et al., 2021) or may have mixed effects, being both misleading and helpful to young learners (Bruni et al., 2018; Jahic Pettersson et al., 2020). It is interesting in this regard that in our own data, animism correlated positively with children's accuracy in reasoning about both COVID-19 and the common cold.

Fifth, it is crucial to consider how children's COVID-19 beliefs may relate to their behaviors. There is now growing evidence that children's causal theories provide an important basis for behavior change (Au et al., 2008; Weisman & Markman, 2017). There are hints of this as well in our own data, where for both children and parents, accuracy in reasoning about COVID-19 correlated positively with wanting to be vaccinated, and children's knowledge of causal mechanisms regarding COVID-19 correlated with their knowledge of transmission risks, as well as how to wear a mask correctly. However, the question of how knowledge translates into behavior requires more direct study.

Conclusions

The study of children's understanding of viral disease transmission provides an opportunity to learn how children construe an important scientific topic that has direct, real-world consequences. Given that viral processes are largely invisible, children are reliant on testimony from others to construct their causal understandings (Gelman, 2009; Harris et al., 2018). The present findings indicate a mixture of knowledge (awareness of behaviors that transmit or block viral disease, such as sneezing and mask-wearing; understanding germs as disease-causing, too small to be seen, and able to enter the body through the nose) and misconceptions (e.g., inaccurately assessing the transmission risk of new situations; difficulty appreciating the biological processes that play out over time within the body). The data suggest that young children's reasoning about viral transmission reflects two seemingly competing mental models, one in which viruses operate strictly via mechanical processes (movement through space), and one in which viruses are small living creatures, capable of growth and self-generated movement. Ultimately, children will need to learn the extent and limits of a biological model of viral illness.

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