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Young children's attributions of causal power to novel invisible entities

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ABSTRACT

In two studies, we investigated the development of children's reasoning about potent invisible entities. In Study 1, children aged 2.2–5.5 years ($N = 48$) were briefly told about a novel invisible substance that could produce a novel outcome—make a novel box turn green. During this introduction, children watched as one container was inverted over a box and the box lit up green, and then another identical container was inverted over the box and the box did not light up. On test trials, the experimenter inserted a spoon in novel (actually empty) containers and inverted the spoon over the box, which turned green in one trial and did not light up in the other trial. For both trials, children were asked whether there was anything in each container. Children across this age range appropriately reported that an invisible substance was present only when the box lit up. In Study 2, children aged 2.4–4.5 years ($N = 48$) watched similar demonstrations but were not explicitly provided information about the invisible substance. Children as young as 3 years spontaneously inferred that an invisible substance was present when the box lit up and was absent when the box did not light up. A final task tested children's ability to use their causal knowledge of invisible substances to *produce* an effect—making the box light up. The youngest children had difficulty with this task, but many children aged 3.5–4.5 years performed capably. These results indicate an early-emerging understanding of potent invisible entities that develops rapidly during early childhood.

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Introduction

Learning is often viewed as a process of updating beliefs in response to observed data. Causal learning is arguably the canonical case; from patterns of observed temporal co-occurrence, we must infer the presence of an unobservable power that links one event to a subsequent event (Hume, 1888/1978; Michotte, 1963). However, there are many instances of unobservable but causally potent entities—chemicals, germs, essences, beliefs, atoms, gods, souls, and Chi—that play central roles in how we explain observable events. In these cases, the causal entities are themselves invisible and temporal co-occurrence is not always observable. So, the inference problem might be more challenging. The world over, children are taught and hear about an array of such causal entities (Bering, 2006; Guerrero, Enesco, & Harris, 2010; Harris & Koenig, 2006; Harris, Pasquini, Duke, Asscher, & Pons, 2006; Lane & Harris, 2014) and have rich concepts of many of them by middle childhood (e.g., Harris et al., 2006; Kalish, 1996; Lane, Wellman, & Evans, 2012; Richert & Harris, 2006). For example, consider germs; by 3.5 years of age children often account for people's illness in terms of their having come into contact with germs (Legare, Wellman, & Gelman, 2009), and by 4 or 5 years children often *predict* that individuals who come into contact with germs will get sick in the future (Kalish, 1996). However, little is known about how young children draw inferences based on newly acquired information about invisible entities. When young children are first introduced to novel invisible entities that purportedly produce observable phenomena, do they report that future instances of those phenomena were produced by those invisible entities? If children are never explicitly taught about the invisible entities, do they then infer their existence to account for observed phenomena? If children do infer the existence of such entities, can they then use their knowledge of the entities to produce novel outcomes? We addressed these questions with the current studies. In what follows, we briefly review the literatures on children's understanding of invisible entities and their understanding of causality.

Prior work demonstrates that young children can and do impute the existence of *certain* invisible entities to account for observable phenomena. Children (and adults) make sense of other people's overt behavior in terms of unobservable desires, knowledge, and beliefs (Wellman, 2014). As well, in some cultures children and adults attribute an invisible "life force" to living beings (Inagaki & Hatano, 2004). Does this early facility in imputing such entities imply that young children readily infer and easily learn about the existence of all types of invisible entities? Not necessarily. Developments in one domain (e.g., naive psychology) do not necessarily parallel developments in other domains (e.g., naive physics) (Wellman & Gelman, 1998). Thus, young children's ability to impute invisible psychological or vitalistic entities is not sufficient evidence for how they make inferences about and learn about other types of invisible entities. In addition, minds and life forces are special kinds of invisible entities. For one, both are always "contained" in other things (i.e., living organisms; or at least they co-occur with the presence of those things); thus, although they are occluded from view, they nevertheless always have an observable physical presence. But many invisible entities are consistently and completely invisible. Indeed, causally potent invisible entities surround us; some are in the air we breathe (oxygen) or on our bodies (germs), some are part of nearly everything in existence (atoms), and others are purported to be *everywhere* (the Judeo-Christian God)—and (unlike minds and life forces) their causal power moves clandestinely from place to place with them. Acknowledging the existence of these entities requires setting aside what we do see (nothing) to entertain the notion that something is indeed there.

Young children are competent causal reasoners and are even capable of reasoning about certain unseen entities. Preschoolers can imagine that a familiar substance being applied to an object will yield a familiar effect; for example, if in a pretend context milk is "poured" from an (empty) milk carton into a container and that container is then inverted over a toy horse, children imagine that the pretend milk has made the horse "wet" (Harris, Kavanaugh, & Meredith, 1994). By 2 years of age, children imagine such causal chains and can identify the correct outcome (from several possibilities) even when the entire sequence of events occurs out of sight (Ganea, Shutts, Spelke, & DeLoache, 2007). Other work reveals that 3- and 4-year-olds infer the identity of novel objects based on their observed novel causal powers (e.g., Gopnik & Sobel, 2000; Gopnik, Sobel, Schulz, & Glymour, 2001) and by at least 4 years infer that observed outcomes might be produced by objects that are temporarily out of sight (Schulz & Sommerville, 2006). But at this young age, how do children make sense of causal sequences that yield novel outcomes when there is *no visible causal substance*? As noted earlier, this conceptual ability is necessary for children to begin to entertain a wide range of ideas.

Some work suggests that young children might easily learn about novel invisible causal entities. Young children's fluency with imputing invisible mental states might extend to imputing other invisible phenomena. As well, the research just reviewed—on children's understanding of causality and their ability to imagine unseen causal events—suggests that children might grasp that invisible entities cause observed effects by about 3 years of age. Other research demonstrates that 3-year-olds understand that visible physical entities can disappear and cause perceivable outcomes; they appreciate that visible sugar crystals that are dissolved (and thus become invisible) in water will make the water sweeter (Au, Sidle, & Rollins, 1993; Rosen & Rozin, 1993). In a classic series of experiments, Shultz (1982) found that children as young as 3 years understood that familiar unseen forces can be generated and transmitted—for example, that a struck tuning fork can transmit (unseen) sound in a resonator and that a fan can transmit (unseen) wind and thus blow out a candle.

Yet other work suggests that this early understanding of invisible entities is quite limited and fragile. For example, children younger than 4 years have difficulty in understanding that sugar *still exists* once it is dissolved in water (Rosen & Rozin, 1993), consistent with work demonstrating that young children often conflate visibility status with existence status (Woolley & Brown, 2015). Relatedly, preschoolers typically report that tasteless substances no longer exist after they are dissolved in water (Rosen & Rozin, 1993). As well, children have difficulty in reasoning about noncontact causality between novel objects before the age of 4 years (Kushnir & Gopnik, 2007; Sobel & Buchanan, 2009), and many invisible entities (including the ones used in the current study) produce outcomes without observable contact. Children younger than 4 years also have difficulty in reasoning that objects' internal (and thus temporarily invisible) properties (rather than their external, fully visible properties) are responsible for their causal powers (Sobel, Yoachim, Gopnik, Meltzoff, & Blumenthal, 2007). Other findings indicate that it is not until around 7 years of age that children begin to infer that observable physical outcomes might be produced by novel intentional invisible entities (Bering & Parker, 2006).

Thus, some research suggests that young children might easily learn about the causal potency of new invisible entities, and other work suggests that young children might have prolonged difficulty in making such inferences. An important point to consider when surveying the literature on concepts of invisible entities is that most work has been focused on entities about which children likely have considerable experience or about which they have likely received considerable testimony. For example, parental talk about mental states and germs is fairly common. Children have likely seen visible substances dissolve and disappear in water. Children in these populations also likely have experience plucking ukulele strings or striking xylophone keys that produce invisible sounds, and they likely have experience from birthday parties of blowing out candles (via invisible air) or watching friends blow out candles. A rare example of a study in which children were introduced to a causal sequence with a novel outcome that was produced by an invisible entity is Shultz's (1982) Experiment 5. In that experiment, 4-year-olds understood that aiming a (visible) flashlight at a novel object (a Crookes radiometer) could yield a novel outcome (the vanes of the radiometer would rotate) via an invisible entity that was transmitted from the flashlight to the novel object. However, even that study falls short of identifying how children reason about invisible entities that do not have consistent physical instantiations or origins; the visible (and familiar) flashlight produced the invisible force, and if the flashlight were turned off that force would disappear. But as discussed earlier, many invisible entities—germs, oxygen, souls, God, Chi—do not have consistent sources, can be transmitted, and continue to exist over time. The current studies depart from prior work to ask how young children conceptualize a completely novel, causally potent invisible entity that has no consistent physical instantiation or origin. Learning about such an entity from scratch might require that children receive substantial testimony about the entity and direct experience with the entity over an extended period of time—learning that young children might be unable to achieve in a brief study session.

A full developmental account of children's concepts of potent, transmittable invisible entities will entail work focused on entities across ontological domains. We conducted two initial studies on this topic, focused specifically on developing concepts of potent physical invisible entities. We employed similar tests as those used in much prior work on children's understanding of visible physical causality (e.g., Gopnik & Sobel, 2000), allowing us to directly compare our findings against that prior work. In Study 1, children were told about a novel substance that can yield a novel outcome—change the color of a box. They then watched as that invisible substance was "poured" from a transparent container onto the novel box, at which time the box turned green. When an identical container was inverted over the box, the box did not change color. Both containers appeared to be empty and were, in reality, empty (aside from the presence of air and other features of the ambient environment). Children were then shown different types of transparent containers (which were also empty), and an action was performed; a spoon was dipped into each container and inverted above the box, and the box either changed color or did not. Children were asked to interpret the change or lack thereof and to report on whether each container had something inside. If children had indeed learned about the entity's causal power after their exposure to this brief explicit testimony and demonstration, they should report that the new containers had something inside when the box changed color and were empty when the box did not change color. In Study 2, we examined how children conceptualize such entities without hearing any explicit testimony; that is, we examined whether they *spontaneously* infer the existence of such causal entities. We also asked whether young children are able to appropriately use such entities to produce novel outcomes.

These studies have the potential to reveal a sequence to children's developing understanding of novel invisible entities. Conceivably, young children might more readily infer the existence of an invisible entity to account for observed phenomena when they are first taught about the entity and its powers (Study 1) as opposed to when they are not provided with such explicit testimony (Study 2). As well, young children might find it easier to account for observed outcomes in terms of an underlying invisible entity before (developmentally) they can use their causal knowledge about such entities to produce a desired outcome; the former relies on children's ability to *explain* causes behind phenomena, and the latter relies on their ability to *predict* phenomena. This developmental pattern would be consistent with work on children's naive psychology and naive biology (Legare et al., 2009; Wellman, 2011); preschoolers' ability to explain phenomena (e.g., explaining how someone's actions were influenced by that person's beliefs) often precedes their ability to predict those same phenomena (e.g., predicting how someone's beliefs will influence that person's future behavior).

Study 1

Method

Participants

Participants were 48 children (28 boys), ranging in age from 2.2 to 5.5 years, who were recruited and tested individually at a science museum and at schools in a large New England city in the northeastern United States. An additional 3 children participated, but 2 chose to stop the session after completing less than half of the study (ages 2.19 and 2.64 years) and 1 was notably distracted by loud activities occurring in the museum (2.86 years old). Participants were primarily Caucasian and from middle- to upper-middle-class socioeconomic backgrounds. To examine age-related differences, the sample was divided into three age groups: children aged 2.2–3.5 years ($n = 16$, $M_{age} = 3.02$ years), 3.6–4.5 years ($n = 16$, $M_{age} = 4.00$ years), and 4.6–5.5 years ($n = 16$, $M_{age} = 4.82$ years). The target sample size for each age group was based on previous causal inference studies (e.g., Gopnik & Sobel, 2000).

Procedures

Each child sat beside the experimenter at a table covered with a black tablecloth. On the other side of the table sat a confederate, who was introduced to children as the experimenter's "friend." On the table was a box (14.50 × 11.25 × 7.25 inches) that, unbeknown to children, was wired to a foot switch beneath the table. When the confederate depressed the switch, it activated a light bulb in the box, making the top of the box appear green. While the experimenter conducted the interviews, the confederate recorded children's responses on paper and surreptitiously operated the foot switch.

Establishment phase. The session began with the experimenter placing on the table two identical, clear empty containers (8-ounce water bottles) and explaining, "Here are two bottles. They look the same, but they're really different. In one bottle, there's stuff called 'plab.' Plab is invisible; you can't see it with your eyes. Plab is really cool. When you put it on this box [experimenter (E) points to box], it makes the box turn green. The other bottle has nothing inside, and it won't change the box." The experimenter then held one container and demonstrated that it contained plab: "Let's see what's inside this one [E inverts bottle above box, and box top turns green]. See, the box turned green, so there's plab inside the bottle [E points to bottle]. I'm going to wipe the plab off the box so it's clean [E wipes box top with towel, and box darkens]. Let's see that again. [E inverts bottle above box, and box top turns green]. See, the plab made the box turn green. I'm going to wipe the plab off the box [E wipes box top with towel, and box darkens]." Thus, in total children observed two instances of the box lighting up after the bottle inversion. Following this demonstration, children were asked a series of questions to check their memories for key details, and their answers were either affirmed (e.g., "Right!") or corrected accordingly: "So, is there anything inside here?" (13 children were corrected), "What's the name of the stuff inside here?" (19 children were corrected), "Can you see the plab?" (15 children were corrected), and "What happens when you put plab on the box?" (5 children were corrected).

The experimenter then placed the first container under the table, held the second identical container, and demonstrated that it was empty: "Now let's see what's inside this one. Look [E inverts bottle above box, and nothing happens]. See, *nothing* happened to the box, so *nothing* is inside this bottle [E points to bottle]. Let's see that again [E inverts bottle above box, and nothing happens]. See, *nothing* was inside, so nothing happened to the box." Thus, in total children observed two instances of the box not lighting up after the bottle inversion. Following this demonstration, children were asked two memory check questions, for which the experimenter either affirmed (e.g., "Right!") or corrected children: "So, is there anything inside here?" (1 child was corrected) and "Is plab inside here?" (2 children were corrected).

Test phase. The test phase involved containers and actions that were distinct from those used during the establishment phase. For the test trials, two new, identical, clear empty containers (4-ounce Tupperware) with lids were placed on the table. The experimenter removed the lid from one container and said, "Let's see what happens with this one. Watch." The experimenter picked up a spoon, scraped it across the bottom of the container several times, and inverted the spoon above the box. For half of the participants the box turned green on this first trial, and for the other half the box did not turn green. Children were then asked an open-ended question, (a) "Huh ... Why did that happen?", followed by a forced-choice question, (b) "Is there stuff inside here [pointing to container]?", and if children responded "yes" to the last question, they were asked (c), "What's the stuff called?" All children were asked this sequence of questions regardless of their specific responses (e.g., they were asked the (b) and (c) questions even if they mentioned "plab" in response to the (a) question). The experimenter proceeded to wipe the box top with a towel, stating, "I'm going to wipe off the box" as the box darkened. The used container and spoon were placed under the table. The experimenter then removed the lid from the second container and said, "Let's see what happens with this one. I'm going to use a new spoon. Watch." A new spoon was used to discourage the inference that a substance might have transferred from one container to the other. For this second container and spoon, the experimenter performed identical actions as those performed with the first container and spoon, and he asked identical questions; the only difference on this trial was whether the box turned green; had the box turned green on the first trial, it did not turn green on the second trial, and vice versa.

Thus, across the two containers, test questions assessed (a) children's tendency to spontaneously report that an invisible substance caused the effect (or that the absence of a substance was the reason for the noneffect), (b) children's reports that a substance was either present inside or absent from the container when asked directly, and (c) children's memory for the name of the substance—plab. Of these questions, the two (b) questions were of the greatest theoretical and empirical interest; of primary concern was whether children reported that the novel containers held a substance when the box turned green and were empty when the box did not change. Because children could answer the (b) questions with a simple "yes" or "no" (or, for some children, a nod or shake of the head), these questions can directly test children's inferences about the containers' contents with little dependence on children's verbal fluency or children's ability to remember the specific name of the novel substance. Thus, these forced-choice questions can more sensitively test the abilities of the youngest children, who are typically less verbally skilled and potentially more reticent.

All interviews were transcribed and (given parental permission) audio-recorded. Answers to the open-ended (a) questions were coded separately by both authors. For trials in which the box turned green, children's responses were coded as either (1) reference to a substance located in the Tupperware or on the spoon (e.g., "Because it has something inside," "Because you scooped plab," "Because it wasn't empty") or (0) no such reference. For trials in which the box did not turn green, children's responses were coded as either (1) reference to nothing being inside the container or on the spoon (e.g., "There's nothing inside," "Because there's no plab in there," "Nothing because it was empty") or (0) no such reference. Interrater reliability across all responses was 98%; the two coding discrepancies were discussed and resolved.

Results

The critical and most direct test of children's understanding of the causal power of the novel invisible entity is whether children responded to the forced-choice questions by affirming that the container held a substance when the box turned green and denying that the container held a substance when the box did not change. Thus, we present these data first. The proportions of children who reported that there was something inside each container for the two forced-choice questions, per age group, are presented in Table 1. Data presented in this table reveal that children in each of the three age groups were much more likely to report the presence of an invisible entity when there was an observable outcome (the light turning on) compared with when there was no observable outcome. A more stringent test of children's understanding involves examining the proportion in each age group who provided an overall correct response *pattern*—both affirming that the container held a substance when the box turned green and denying that the container held a substance when the box did not light up. The probability of providing this pattern by chance is 25%. Children in all three age groups responded with this pattern at rates significantly above chance, with 12 of 16 (75%) children aged 2.2–3.5 years, 13 of 16 (81%) children aged 3.6–4.5 years, and 16 of 16 (100%) children aged 4.6–5.5 years responding with this pattern (all *p*s < .0001 according to binomial tests). Performance did not differ among the three age groups, $\chi^2(2) = 4.26$, *ns*. Moreover, when the 6 2-year-olds were analyzed separately, 4 of them (67%) provided this response pattern, significantly more than predicted by chance ($p = .038$).

When children were asked the open-ended question, "Huh ... Why did that happen?", following the inversion of the spoon over the box, there were significant differences among the three age groups in children's spontaneous reference to the presence of an entity when the box turned green, $\chi^2(2) = 12.00$, $p < .01$, and in children's spontaneous reference to the absence of an entity when the box did not turn green, $\chi^2(2) = 8.50$, $p = .014$. Such explanations were produced by a minority of children aged 2.2–3.5 years (plab trial: 25%; empty trial: 31%) and children aged 3.6–4.5 years (plab trial: 31%; empty trial: 44%), but they were produced by most children aged 4.5–5.5 years (plab trial: 81%, empty trial: 81%). Thus, there was an age-related increase in children's spontaneous reference to a substance being present in the container when the box turned green and to a substance being absent when the box did not change.

Table 1
Study 1: Percentage of children responding "yes" to questions of whether something was inside each container, by age group.

Age group (years)	Outcome		
	Light on (%)	Light off (%)	McNemar's test
2.2–3.5	81	6	$\chi^2(1) = 10.08$, $p < .01$
3.6–4.5	81	0	$\chi^2(1) = 11.08$, $p < .001$
4.6–5.5	100	0	$\chi^2(1) = 14.06$, $p < .001$

Note. McNemar's tests were computed for each age group. These within-participants tests compare the proportion of children who reported that an invisible entity was present when the light turned on with the proportion of children who reported that an invisible entity was present when the light remained off.

Finally, among children who had reported that something was inside the container when the box turned green ($n = 42$), there was a significant difference among the three age groups in the proportion of children who went on to say that the substance was called plab, with 5 of 13 (38%) 2.2-to 3.5-year-olds, 7 of 13 (54%) 3.6- to 4.5-year-olds, and 14 of 16 (88%) 4.6- to 5.5-year-olds recalling this name, $\chi^2(2) = 7.65$, $p = .022$. These numbers reflect an age-graded increase in children's recall for the name of the substance.

Interim discussion

In Study 1, children correctly reported that an invisible transferrable substance was present in order to account for a visible novel outcome, and they also reported that such a substance was absent when the outcome was not produced. Children demonstrated this skill after watching brief demonstrations, accompanied by explicit testimony, of the novel entity being "transferred" from a container to a box, yielding a novel effect—the box lighting up—and another transfer demonstration performed with another container that concluded with the box *not* lighting up. When children later saw novel demonstrations with new stimuli (the experimenter using a spoon to scoop the inside of a container and then inverting the spoon above the box), after which the box either lit up or remained unlit, and were asked whether there was something in each container, they typically responded "yes" in the former instance and "no" in the latter instance.

Despite their performance on the focal forced-choice questions, the youngest children rarely spontaneously explained the boxes' states by citing the presence or absence of an invisible substance, but such responses were common among 4- and 5-year-olds. This is likely attributable to a general tendency for 2- and 3-year-olds to provide uninformative answers to such open-ended questions because of either limitations in their verbal fluency or more general reticence. The youngest children also had difficulty in remembering the name of the invisible substance—plab—during the test phase, but this is not surprising given that half of the children in the youngest group (8 of 16) provided inaccurate answers to memory checks about the name of the substance during the establishment phase (and thus needed to be corrected). More generally, children had been introduced to much new information during the brief testing session (novel containers, substance, actions, and effects); the memory demands were quite substantial. Indeed, these memory demands make it all the more impressive that the youngest children performed so well on the focal closed-ended questions.

Although we prefer the above interpretation of these data, one may argue that the testimony was so explicit (e.g., "See, the box turned green, so there's plab inside the bottle") that children needed only to remember the syntax of the testimony and generalize it to a new context rather than needing to make actual inferences about the contents of the new containers. To limit the influence of such explicit testimony and to more extensively track these early developments, we conducted a second study. Study 2 examined whether, after observing similar causal sequences, young children will infer the presence of an invisible substance to account for observed outcomes if they are not first explicitly taught about the substance. Study 2 further expanded on Study 1 by addressing not just whether children postulate the existence of invisible entities to explain observed outcomes but also whether children can use their knowledge of invisible entities to produce (and thus predict) novel outcomes. Because even the youngest children performed capably in Study 1, we aimed to more finely capture early developmental differences in Study 2. Thus, in Study 2 we more densely sampled children at the youngest end of the age range, particularly at 2 and 3 years, and sampled only through 4.5 years.

Study 2

Method

Participants

Participants were 48 children (22 boys) recruited from a large city in the southeastern United States and tested individually in a quiet room of a university laboratory. An additional 11 children participated but were excluded from analyses; of these children, 8 were too distracted to attend to the tasks (e.g., they were preoccupied with other toys or left the testing area during the study; M_{age} = 2.85 years), 2 responded to fewer than half of the questions (ages 2.98 and 3.91 years), and the parent of 1 child (age 3.35 years) interfered with the procedure. Most participants were Caucasian and from middle -to upper-middle-class socioeconomic backgrounds. To examine age-related differences, we sampled 2-year-olds (n = 18, M_{age} = 2.75 years, range = 2.4–2.9), young 3-year-olds (n = 16, M_{age} = 3.16 years, range = 3.0–3.5), and older 3- and 4-year-olds (n = 14, M_{age} = 4.14 years, range = 3.6–4.5).

Procedures

Each child sat next to the experimenter at a table covered with a black cloth. A confederate sat on the opposite side of the table. The experiment used the same box and foot switch used in Study 1 except that we modified the box to light up red (rather than green) because the red light was more visible in the testing room. When the confederate depressed the switch, it activated a light in the box, making the box top appear red. While the experimenter conducted the interviews, the confederate recorded children's responses and operated the switch. In contrast to Study 1, there was no establishment phase when children were instructed about the invisible substance. All participants completed two *inference* tasks—one employing bottles and the other employing Tupperware and spoons—and a *production* task, employing cotton balls, in that order. Potentially, the open-ended questions asked in Study 1 ("Why did that happen?") might have led some children to think more deeply about the causal sequence, even though children's answers to those questions were not particularly revealing. Thus, to equate the methods (allowing for more direct comparisons between the two studies), the order and wording of questions were identical to those used in Study 1; for each task, children were asked *what* happened to the box, were asked *why* that happened, and were then asked the focal forced-choice question about the container's contents.

Inference: Bottles task. The session began with the experimenter placing on the table two identical, clear empty containers (8-ounce water bottles) and explaining, "Here are two bottles. They look like they're empty, but maybe they really have stuff inside." This introduction was provided to reduce the possibility that children would report that the containers were empty (when in fact they believed that the containers held something) simply because they were worried that the experimenter would think that such a response was silly. Thus, the experimenter's introduction implies that she would entertain the notion that an apparently empty container might actually contain something. Crucially, unlike in Study 1, the experimenter told children nothing about any specific invisible entity (e.g., its name, properties, use, or power).

The experimenter then held one container and said, "Let's see what happens with this one first. Watch." The experimenter inverted the bottle above the box, and the box top turned red. To encourage children's engagement in the task, children were asked, "Huh ... What happened?" (for children who did not report the box's visible state, the experimenter said, "The box turned red"). The experimenter wiped off the box top with a towel, the box darkened, and children were again asked to report what happened (for children who did not report the box's visible state, the experimenter said, "The box isn't red anymore"). The experimenter then performed the same procedure with the second identical bottle, and the box did *not* light up (as before, to help maintain children's attention to the task, children were asked what happened).

For the test trials, the demonstration was performed again with the first bottle, the box again lit up, and children were asked an open-ended question, "So, why did that happen?", and a forced-choice question, "Is there stuff inside here [pointing to bottle]." Answers to the forced-choice question were focal, but the open-ended questions were asked in keeping with the sequence of questions used in Study 1. The box was then wiped off, and the second bottle was again inverted over the box, which again remained unlit. Children were then asked an identical set of test questions as those asked for the first bottle—"So, why did that happen?" and "Is there stuff inside here [pointing to the bottle]." For all children, the inversion of the first bottle resulted in the box lighting up, and the inversion of the second bottle resulted in no change. We decided to use this same order for all children because, unlike in Study 1, children were given no introduction or background about the invisible substance and its power, and thus children might have found it odd and confusing if asked to describe and account for a noneffect (i.e., the box *not* lighting up) on the very first trial of the session.

Inference: Spoons task. The next task was similar to the one used in Study 1 except that the box did *not* light up on the first trial and *did* light up on the second trial; this was to eliminate the possibility that children might produce the correct response pattern on this task by applying a simple rule they might have garnered from the Bottles task—that is, the first container holds something and the second container is empty. Two new, identical, clear, empty 4-ounce Tupperware containers with lids were set on the table, and the experimenter said, "Here are two new containers." The experimenter removed the lid from one container and said, "Let's see what happens with this one. Watch." The experimenter picked up a spoon, scraped it across the container's bottom multiple times, and inverted the spoon above the box. The box did not light up. Children were then asked a question to facilitate their attention to the task: "Huh . . . What happened?" (for children who did not report the box's visible state, the experimenter said, "The box didn't change colors"). The same sequence was performed with the same container and spoon, again the box did not light up, and the experimenter asked the same question. Children were then asked the open-ended test question, "So, why did that happen?", and a focal forced-choice test question, "Is there stuff inside here [pointing to the container]?"

An identical sequence was performed twice with a second identical container and new spoon, but when this spoon was inverted over the box, the box *did* light up red. For this container and sequence, children were asked questions identical to those asked for the other trials and tasks.

Production: Cotton balls task. A final task tested children's ability to use what they had learned about the invisible substance to produce a desired effect. Children were shown a new clear container (a miniature flip-top glass mason jar) and were shown a sequence of demonstrations to establish that the bottle contained something. The opened jar was inverted over the box, and the box lit up red. The box was wiped with a towel, and the box darkened. The jar was again inverted over the box, which again turned red. Then the box was wiped again with the towel. Following each demonstration, to facilitate children's attention to the task, children were asked what happened (for children who did not report the box's visible state, the experimenter said, "The box turned red"). For two test trials, the experimenter placed two cotton balls directly in front of the box approximately 10 inches apart. Children were told, "Here are two cotton balls. Watch." The experimenter inverted the jar over the left cotton ball for approximately 3 s, and then hovered the jar (upright) above the right cotton ball for approximately 3 s. Thus, an action was performed near both cotton balls, but only one of those actions should have "transmitted" the hypothetical substance from the jar to a cotton ball—when the jar was inverted over the left cotton ball. Children were then invited to make the box turn red: "Now, I want you to try to make the box turn red." Children who did not initially respond were given a more direct request, "Use one of these [pointing at both cotton balls] to make the box turn red." If children either placed the correct cotton ball on the box or hovered the correct cotton ball above the box for at least 1 s, the box lit up. Although only children's initial responses are considered in our analyses, to encourage children to succeed on the task (and thus end the task on a positive note), if children's initial response was incorrect (e.g., if they placed the wrong cotton ball on the box), they were told, "Try something else." After the box lit up, the experimenter wiped it with the towel and the box darkened. This same procedure was completed once more with two new cotton balls, the only difference being that the opened jar was hovered upright over the left cotton ball and inverted over the right cotton ball.

Testing sessions were video-recorded, and using these recordings children's responses were categorized along two dimensions for both trials: Cotton ball (correct, incorrect, both, or neither) and Action (placed on box, hovered above box, or no action). Two research assistants unaware of the study's hypotheses coded 20% of the videos and agreed on 100% of their coding. Thus, one of these research assistants coded all remaining videos.

Results

The most direct test of whether children correctly inferred the presence of an invisible entity in the face of observable evidence (i.e., the box lighting up) involves children's responses to the forced-choice questions. The proportions of children who reported that there was something inside each container for the forced-choice (yes/no) questions for the Bottles and Spoons tasks, per age group, are presented in Table 2. As this table illustrates, for both tasks children in the two oldest age groups (3.0–3.5 and

3.6–4.5 years) were much more likely to infer the presence of an invisible entity when there was an observable outcome (the light turning on) compared with when there was no observable outcome. A more stringent test of children's understanding involves exploring the proportion of children in each age group who provided an overall correct *pattern* of responses for the Bottles task and for the Spoons task (i.e., both affirming that the container held a substance when the box turned red and denying that the container held a substance when the box did not light up). For the Bottles task, there was a significant difference in children's rate of providing this pattern among the three age groups, $\chi^2(2) = 11.03$, $p < .01$. Of the youngest children (2-year-olds), only 2 of 18 (11%) provided this pattern ($p = .96$, binomial test against 25% chance). In contrast, many children in the two older groups provided this correct response pattern, including 9 of 16 (56%) young 3-year-olds and 9 of 14 (64%) older 3- and 4-year-olds (*p*s < .01, binomial tests against 25% chance). For the Spoons task, children's rate of providing the correct response pattern also differed among the three age groups, $\chi^2(2) = 8.67$, $p = .013$, revealing a similar developmental pattern. Only 5 of 18 (28%) 2-year-olds responded with the correct pattern ($p = .48$, binomial test against 25% chance). In contrast, many of the young 3-year-olds (10 of 16, 63%) and most of the older 3- and 4-year-olds (11 of 14, 79%) responded with this pattern and did so above chance levels ($p < .01$ and $p < .0001$, respectively, binomial tests against 25% chance). Children's performance was relatively consistent across the Bottles and Spoons tasks, with 75% of participants either failing both tasks ($n = 19$) or passing both tasks ($n = 17$).

What about the very youngest children, 2-year-olds, who typically failed the Bottles and Spoons tasks? Did they respond randomly, or did they provide a common response pattern? For each task, there were three incorrect patterns that children may provide: (a) reporting that both containers were empty, (b) reporting that both containers were full, and (c) reporting that the empty container was full and that the full container was empty. Table 2 depicts the proportion of 2-year-olds who affirmed that there was something inside each of the containers for the two tasks. Among 2-year-olds who failed the Bottles task, the vast majority (12 of 16, 75%) reported that *both* bottles were empty ($p < .001$, binomial test against 33.3% chance). Among 2-year-olds who failed the Spoons task, again the vast majority (10 of 13, 77%) reported that *both* containers were empty ($p < .001$, binomial test against 33.3% chance). Thus, 2-year-olds often responded to these questions according to the appearance of the containers and disregarded the causal evidence; they typically reported that nothing was inside any of the containers.

To examine how children's performance differed based on whether or not they first received explicit testimony and demonstrations involving plab, we can directly compare their performance on the Spoons task in Study 1 (which was prefaced with testimony about the invisible substance along with guided demonstration with the bottles) with their performance on the same task in Study 2 (which was completed after the Bottles task but which included no additional explicit testimony about the substance or guided demonstrations). We first compare the youngest children from both studies, ages 2.2–3.5 years (Study 1 $n = 16$, $M_{age} = 3.02$ years; Study 2 $n = 34$, $M_{age} = 2.94$ years). At this age, children provided the correct response pattern significantly more often in Study 1 than in Study 2 (75% vs. 44%,

Table 2
Study 2: Percentage of children responding "yes" to questions of whether something was inside each container, by age group, task, and outcome.

Age group (years)	Bottles outcome: Light on (%)	Bottles outcome: Light off (%)	McNemar's test	Spoons outcome: Light on (%)	Spoons outcome: Light off (%)	McNemar's test
2.4–2.9	28	22	$\chi^2(1) = 0.00$, $p = 1.00$	44	17	$\chi^2(1) = 3.20$, $p = .074$
3.0–3.5	69	19	$\chi^2(1) = 4.90$, $p = .027$	69	12	$\chi^2(1) = 5.82$, $p = .016$
3.6–4.5	64	0	$\chi^2(1) = 7.11$, $p < .01$	79	0	$\chi^2(1) = 9.09$, $p < .01$

Note. McNemar's tests were computed for each task and age group. These within-participants tests compare the proportion of children who reported that an invisible entity was present when the light turned on with the proportion of children who reported that an invisible entity was present when the light remained off.

$p < .05$). Thus, the experimenter's provision of explicit supportive testimony and demonstrations in Study 1 (but not in Study 2) might have scaffolded these children's inferences that a novel invisible substance was present to account for the observed outcome. In contrast, slightly older children, ranging from 3.6 to 4.5 years (Study 1 $n = 16$, $M_{age} = 4.00$ years; Study 2 $n = 14$, $M_{age} = 4.14$ years), did not differ in how often they provided the correct response pattern for the Spoons task in Study 1 (81%) versus Study 2 (79%), *ns*.

The Cotton Balls task tested children's ability to use what they understood about the invisible substance to produce a desired effect—making the box light up. For this task, children were counted as having produced the correct response pattern if, on both trials, they selected the correct cotton ball (the one above which the jar was inverted) and either placed that cotton ball on the box top or hovered it above the box. We compared the frequency of children who provided this pattern against a 25% chance of producing this pattern randomly (conservatively assuming that chance is 50% on each trial). This is an admittedly stringent test given that children could have provided any number of responses (e.g., some children chose neither cotton ball, one child chose both cotton balls and then threw them toward the box). The rate of providing this pattern differed significantly among the three age groups, $\chi^2(2) = 7.35$, $p = .025$. The 2-year-olds (3 of 18, 17%) and the young 3-year-olds (3 of 16, 19%) rarely responded with this pattern ($p = .86$ and $p = .80$, respectively, binomial tests against 25% chance). The older 3- and 4-year-olds provided this pattern more often and at a rate above chance (8 of 14, 57%, $p = .010$).

A less stringent test would be to consider children correct if they simply selected the correct cotton ball (the one above which the jar had been inverted) on both trials regardless of what exactly they did with the cotton ball. Conceivably, children might infer that a substance was poured onto the cotton ball, but they might be unsure of how to activate the box with this new object. Using this less stringent criterion would yield identical results; all of the children who selected the correct cotton ball on both trials proceeded either to place those cotton balls on the box or to hover them above the box.

General discussion

Children are often introduced to ideas of natural and supernatural invisible entities that are purported to influence the world in profound ways. In many cases, it is not clear what the content of these concepts would be if not for their causal power. Concepts such as God and germs are tied to experience through their (purported) effects on the world, and children often justify their belief in the existence of these entities by referring to their causal powers (Harris, 2012). Given the pervasiveness of invisible causal entities across a variety of domains, and given how frequently they are referred to in everyday conversation, it is advantageous for children to be able to posit many sorts of invisible entities at a young age. Indeed, the current results demonstrate that the ability to attribute observed events to novel, invisible physical entities is present during early childhood. In Study 1, children as young as 2 years reported that an invisible substance was present after observing just two examples, with accompanying testimony, of a novel invisible substance causing a novel effect. Not only were the substance and effects new to children, but on test trials other aspects of the causal chain were different from what children had seen on demonstration trials, notably the type of container that held the substance and the means by which the substance was moved from the containers to the box. Our favored interpretation of these data is that children can begin to understand certain aspects of novel invisible entities before they enter preschool provided that their understanding is supported with explicit testimony. Moreover, as demonstrated in Study 2, by 3 years of age many children inferred the presence of these entities to account for observed outcomes even when they had not earlier been given demonstrations or explicit testimony about the substance's state of matter, its presence, ways that it can be transmitted, or its power.

In the Spoons task, children never observed contact between the stimuli; spoons were inverted above the box but never touched it. Given young preschoolers' difficulty with reasoning about causality at a distance (Kushnir & Gopnik, 2007; Sobel & Buchanan, 2009), we speculate that, for young children, an intuitive explanation for the observed effect is that something was inside the container, transferred to the spoon, and then dripped onto the box, yielding the effect; this sequence of events would satisfy their intuitions about contact causality. Indeed, 2.5-year-olds can articulate such causal chains when describing how imaginary (but familiar) substances would produce an imaginary (but familiar) outcome (Harris & Kavanaugh, 1993). One particularly impressive aspect of children's performance in the current studies is that children not only inferred the causal chain but also inferred the *presence* of a *novel* invisible substance that would complete the causal chain. In contrast to prior work on children's imagination of causal sequences (e.g., Harris & Kavanaugh, 1993), in the current study children reasoned about entities in a more realistic context. Live actors (not puppets or figurines) manipulated the stimuli, and interviewers introduced plab (in Study 1) using language signaling that they were discussing something real: "Here are two bottles. They look the same, but they're really different." Indeed, children are more likely to believe that something is really different from what it appears to be when such language is used (Lane, Harris, Gelman, & Wellman, 2014). Moreover, unlike in prior experiments where an invisible cause leads to a pretend invisible effect (e.g., Harris & Kavanaugh, 1993), the current tasks required children to postulate that an invisible substance was transferred between objects, causing an actual *visible* effect. In Study 2, by 3.5–4 years of age many children understood that this invisible substance could be poured onto another object (a cotton ball), and they often predicted that the second object ("soaked" with the invisible substance) could be used to produce the visible effect. Thus, these data, along with previous research, demonstrate that young children skillfully reason about the power of invisible transferable entities across a variety of contexts and manipulations.

These data begin to reveal an early developmental trajectory in children's understanding of invisible entities. By 2 years of age, children who watch brief demonstrations (with accompanying testimony) of a novel effect produced by a (supposed) invisible entity account for the same effect in the future by reporting that the entity is present. However, as demonstrated in Study 2, in the absence of such testimony, 2-year-olds no longer report that invisible entities are present to account for visible effects. Indeed, 2-year-olds typically denied that there were invisible entities present even in the face of visible effects that had no other obvious cause, consistent with work demonstrating young children's tendency to conflate visibility status with reality status (Woolley & Brown, 2015). Thus, explicit testimony might have scaffolded very young children's reasoning about these entities, helping them to overcome their perceptions (that all containers were empty) to entertain the notion that something unseen was indeed inside some containers, which was then transmitted onto the box. Other work has also highlighted the power of testimony in prompting preschoolers to override their initial perception-based judgments (e.g., Jaswal, 2004; Lane, Harris, Gelman, & Wellman, 2014). In the absence of such explicit testimony, many children as young as 3 years *spontaneously* inferred the existence of such invisible entities (although young 3-year-olds performed even better when they were presented with the explicit testimony in Study 1). What might account for this developmental shift between 2 and 3 years of age? One factor might be an understanding of the appearance–reality distinction, which typically undergoes substantial development during early childhood (Flavell, Flavell, & Green, 1983; Flavell, Green, & Flavell, 1986) and is likely implicated in children's developing ability to distinguish entities' invisibility status from their existence status (Woolley & Brown, 2015).

Further development in children's understanding of potent invisible entities was evident in their performance on the Cotton Balls task. It was not until 3.5–4 years of age that children began to accurately predict which of two cotton balls (one of which was "soaked" with the invisible entity) would activate the light. This developmental sequence—children first inferring the existence of entities to account for observed phenomena and later predicting effects produced by those same entities—is not exclusive to children's reasoning about physical invisible entities. Indeed, it might be a broader theme in children's developing causal reasoning—seen, for example, in children's reasoning about biological and psychological entities and their relation to human illness and behavior (Legare et al., 2009; Wellman, 2011). Despite these apparent similarities across ontological domains, it is important to reiterate that conceptual development often proceeds differently among domains—for example, naive physics, biology, psychology (Wellman & Gelman, 1998). Thus, the specific timing and sequence of the developments identified in the current studies, and the role of testimony in such development, might differ for other types of potent invisible entities. Examining these questions about other types of invisible entities is an important direction for future work.

Intriguingly, we found that even older 3- and 4-year-olds did not perform at ceiling in Study 2; there was variability in their performance. This inspires questions concerning what contributes to such individual differences. One likely possibility is that individual differences in other cognitive competencies (e.g., understanding the appearance–reality distinction or inhibitory control) relate to children's understanding of the presence and power of invisible entities. As well, sociocultural exposure to information about other sorts of powerful invisible entities (e.g., germs, gods, minds) could influence how readily children infer the existence of other potent novel invisible entities. These questions provide fertile ground for future research.

Considerable research remains to chart the full developmental sequence in children's understanding of invisible causal entities across a variety of domains. One exciting avenue for future work is to explore children's concepts of the properties of invisible entities. Do children expect invisible physical entities to behave like most other physical entities or to behave differently? For example, some invisible entities apparently violate causal regularities that are strongly entrenched in children's naive intuitions. Even infants expect unsupported objects to drop to the ground, and they expect that one object cannot pass through another object (Needham & Baillargeon, 1993; Spelke, Breinlinger, Macomber, & Jacobson, 1992), yet some invisible entities can float (e.g., gases that are lighter than air) and others can pass through solid objects (e.g., WiFi signals, ghosts). Infants and children expect that hidden objects will obey many of the same causal rules as visible objects (e.g., Baillargeon, 1987), but is this also true of their concepts of completely invisible entities? It will also be important to consider how temporal contiguity influences children's reasoning about invisible causal entities. For example, whereas some invisible entities have immediately tangible causal outcomes (e.g., wind blowing against one's skin is immediately felt), others have delayed outcomes (e.g., ingesting germs one day may lead to symptoms that are expressed the following day).

In summary, the current findings indicate that very young children can postulate the presence of novel invisible physical entities to account for observed effects, a capacity that likely serves as an important foundation for later conceptual development. This ability develops rapidly during early childhood. Among toddlers, these inferences might be scaffolded by testimony, and by at least 3 years of age children may begin to make such inferences spontaneously.

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