Journal of Experimental Child Psychology 205 (2021) 105080

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Young children's metacognitive awareness of confounded evidence

Özgün Köksal [a,*], Beate Sodian [a], Cristine H. Legare [b]

[a] Department of Psychology, Ludwig-Maximilians-Universität München, 80802 Munich, Germany
[b] Department of Psychology, The University of Texas at Austin, Austin, TX 78712, USA

ARTICLE INFO

Article history:
Received 3 February 2020
Revised 12 December 2020

Keywords:
Scientific reasoning
Causal learning
Evidence evaluation
Confounded evidence
Metacognition
Explanation

ABSTRACT

Young children selectively explore confounded evidence—when causality is ambiguous due to multiple candidate causes. This suggests that they have an implicit understanding that confounded evidence is uninformative. This study examined explicit understanding, or metacognitive awareness, of the informativeness of different qualities of evidence during early childhood. In two within-participants conditions, children (N = 60 5- and 6-year-olds) were presented with confounded and unconfounded evidence and were asked to evaluate and explain their knowledge of a causal relation. Children more frequently requested further information in the confounded condition than in the unconfounded condition. Nearly half of them referred to multiple candidate causes when explaining confounded evidence. Our data demonstrate that young children can reason explicitly about the informativeness of different kinds of evidence.

Introduction

It is November and roses are still blooming. Is it because this fall has been unusually warm or because the soil is especially fertile? This example illustrates one of the central problems in reasoning about causality both in daily life and in science. Evidence is often confounded: Potential causes often appear together, and their effects cannot easily be separated. A careful evaluation of confounded

* Corresponding author.
E-mail address: ozgun.koksal@psy.lmu.de (Ö. Köksal).

https://doi.org/10.1016/j.jecp.2020.105080
0022-0965/

evidence is the first step toward designing the kind of controlled experiment necessary to reveal cause–effect relations.

The capacity to judge the informativeness of evidence is essential for reaching accurate conclusions about causality, a foundational skill for the development of scientific reasoning (Kuhn et al., 1988). Although formal scientific reasoning is effortful and its development requires explicit training (e.g., Carey, Evans, Honda, Jay, & Unger, 1989; Klahr, Fay, & Dunbar, 1993; Kuhn, Black, Keselman, & Kaplan, 2000; Kuhn & Pease, 2008; Schauble, 1996), a growing literature on young children's causal learning abilities suggests an early-developing sensitivity to the quality of evidence. Research on the duration, variability, and complexity of young children's exploratory behavior shows that young children can differentiate confounded evidence from unconfounded evidence (Cook, Goodman, & Schulz, 2011; Gopnik, 2012; Gweon & Schulz, 2008; Lapidow & Walker, 2020; Schulz, 2012; Schulz & Bonawitz, 2007). This suggests that young children have, at a minimum, an implicit capacity to reason about confounded evidence.

Scientific reasoning requires metacognitive awareness of epistemic states and knowledge acquisition processes (see Kuhn, 2000, 2014, and Demetriou, Makris, Kazi, Spanoudis, & Shayer, 2018, for discussions of the role of metacognition in the development of higher-order reasoning). Explicit understanding of this kind is a component of metacognition (Schneider, 2008) and can be defined as "knowing about knowing" (Kloo, Rohwer, & Perner, 2017, p. 280). Taking the quality of evidence into account in causal learning appears to be an implicit form of understanding evidence as a source of information, whereas scientific reasoning depends on an explicit understanding of the role of evidence in the knowledge formation process.

The objective of the current study was to examine young children's metacognitive awareness of the informativeness of confounded evidence. In the next sections, we discuss findings from two literatures that are particularly informative for the development of metacognitive awareness of confounded evidence during early childhood: causal learning and metacognitive awareness of knowledge.

Causal learning

Young children have precocious abilities to draw accurate causal inferences from different evidence patterns (see Gopnik & Wellman, 2012, for a review). Some of these abilities are especially pertinent to reasoning about confounded evidence and may underlie mature forms of understanding confounded evidence. For example, reasoning about confounded evidence requires taking into account conditional dependence and independence of causes and outcomes. As young as 3 years, children make causal inferences based on conditional probabilities rather than associative information (Sobel, Tenenbaum, & Gopnik, 2004). Furthermore, reasoning about confounded evidence requires being able to diagnostically infer the cause(s) of an observed effect when there is uncertainty. Correctly diagnosing unknown causes improves over the course of early childhood (Sobel, Erb, Tassin, & Weisberg, 2017). When children are presented with an outcome (i.e., a sound effect) but did not directly observe the cause of it, 4- and 5-year-olds have basic abilities to infer that an object whose effect they did not see earlier might be the cause of the sound effect when there are no other alternative causes available (Erb & Sobel, 2014), and 6- and 7-year-olds can do so when there are multiple unknown causes (Sobel et al., 2017).

Revealing accurate causes when evidence is confounded often requires making interventions. Children actively make informative interventions during exploratory play to reveal causal information that is not readily available to them, for instance, when evidence is inconsistent (Legare, 2012) or violates expectations (Bonawitz, van Schijndel, Friel, & Schulz, 2012; van Schijndel, Visser, van Bers, & Raijmakers, 2015). Young children selectively explore more when evidence is confounded than when it is unconfounded. For example, 4- and 5-year-olds play longer (Schulz & Bonawitz, 2007) and even test the effects of potential individual causes to reveal further information (Cook et al., 2011). Young children's information-seeking behaviors are evidence for a sensitivity to detecting insufficient causal information when evidence is confounded, which may reflect an implicit metacognitive understanding of their own ignorance. However, these findings do not tell us whether young children explicitly represent their own epistemic states when provided with sufficient or insufficient causal information. One recent study by Moeller Bachhuber, Sobel, and Sodian (2019) investigated 4- to 6-year-olds'

explicit epistemic judgments when evidence was confounded. Approximately half of the children admitted that they did not know what caused the light effect when the evidence was confounded. This study did not systematically investigate reasoning about confounded versus unconfounded evidence, however, and to our knowledge there is no other study on causal learning that has assessed children's explicit understanding of their own epistemic states.

Some indirect evidence for epistemic awareness comes from children's explanations, which provide insight into their explicit understanding of causality and (possibly) their awareness of insufficient causal information (Callanan et al., 2019; Legare, 2014; Legare & Gelman, 2014; Legare, Sobel, & Callanan, 2017; Wellman, 2011). Beginning from a young age, children seek to explain causal functions (Legare & Lombrozo, 2014), and they refer to unseen causal mechanisms (Bonawitz, van Schijndel et al., 2012; Legare, Wellman, & Gelman, 2009; Schulz, Goodman, Tenenbaum, & Jenkins, 2008). Children provide different types of explanations in response to different evidence patterns (Legare, Gelman, & Wellman, 2010), and the type of explanation they generate predicts their future exploratory behavior (Legare, 2012). Young children can also revise their causal inferences (Kushnir & Gopnik, 2007; Schulz, Bonawitz, & Griffiths, 2007) and explanations (Legare, Schult, Impola, & Souza, 2016) in response to new evidence. These studies show that some form of an explicit understanding of causality and causal mechanisms is present during the early childhood years, which is required for an epistemic awareness of the quality of evidence. Little is known, however, about young children's ability to revise their metacognitive beliefs about their own knowledge.

Metacognitive awareness of knowledge

The acquisition of early theory of mind and perspective-taking abilities is related to the development of metacognitive awareness of one's own knowledge and ignorance (Kloo, Sodian, Kristen-Antonow, Kim, & Paulus, 2020). Theory of mind research has shown that preschoolers possess a basic explicit understanding of visual and verbal information as a means to acquire knowledge. Around 3 years of age children begin to understand that seeing leads to knowing (Pratt & Bryant, 1990), and around 4 years they understand that people's knowledge states (true vs. false) are based on the information available to them (Wellman & Liu, 2004). Children's flexibility in understanding the relation between different qualities of evidence and knowledge states develops substantially from 4 or 5 years of age. Children understand that people may form false beliefs based on fake covariation evidence (Koerber, Sodian, Thoermer, & Nett, 2005; Ruffman, Perner, Olson, & Doherty, 1993) and that evidence can be used as a means to refute false claims by others (Köksal-Tuncer & Sodian, 2018).

Notably, accurately assessing *own* knowledge is important for scientific reasoning (Kuhn et al., 1988). Although the early childhood years are generally characterized by overconfidence in judgments (e.g., Beck, McColgan, Robinson, & Rowley, 2011), young children indeed communicate their ignorance when they lack complete information. As young as 2 years, children begin to express their ignorance via flip or shrug gestures (Harris, Ronfard, & Bartz, 2017). In addition, 3-year-olds correctly express that they know when they have full access to information and do not know when they have no available information (Rohwer, Kloo, & Perner, 2012), and 4- and 5-year-olds correctly report own knowledge and ignorance in the case of determinate evidence patterns (Fay & Klahr, 1996; Klahr & Chen, 2003).

Reasoning about partial evidence and recognizing a lack of sufficient information pose greater cognitive demands than total ignorance. The saliency of the available information might lead reasoners to think that they have enough information even though their information is insufficient to draw correct inferences (see Kloo et al., 2017). In the case of partial information, Rohwer et al. (2012) reported that children younger than 5 years often mistakenly judge themselves as knowledgable when they have partial but insufficient, knowledge. Only around 5 or 6 years of age do children begin to acknowledge that partial information is inconclusive (Rohwer et al., 2012). Similarly, children begin to consistently differentiate between degrees of (un)certainty expressed by the epistemic terms *know, think,* and *guess* around 5 or 6 years of age (Kristen-Antonow, Jarvers, & Sodian, 2019; Moore, Bryant, & Furrow, 1989). This capacity improves over the course of childhood and enables reasoning about different types of partially informative evidence such as ambiguous or inconsistent evidence patterns (Busch & Legare, 2019).

Children's confidence judgments also point to developing metacognitive abilities during the early childhood years in the case of uncertainty. This line of research investigates children's metacognitive abilities by asking children how confident they are about their memory or judgments (Coughlin, Hembacher, Lyons, & Ghetti, 2015; Hembacher & Ghetti, 2014; Lapidow, Killeen, & Walker, 2020). Whereas even 3-year-olds have some abilities to report decreased confidence when they are inaccurate (Coughlin et al., 2015; Lyons & Ghetti, 2011, 2013), around 5 years of age children are relatively more accurate in reporting decreased confidence in the case of uncertainty. For instance, 5-year-olds are more accurate than younger children at reporting decreased confidence when they remember items inaccurately (Hembacher & Ghetti, 2014) and when they have partial or no information (Lapidow et al., 2020). Taken together, these findings show that at 5 years of age children already have some ability to reason about their insufficient knowledge in the case of simple patterns of inconclusive evidence. This suggests that the ability to reason about confounded evidence may also be present at this age.

The current study

The current study investigated young children's metacognitive awareness of the uninformativeness of confounded evidence. We focused on children's verbal judgments and explanations as a conservative measure of their explicit understanding of their own epistemic states in response to evidence. Our first objective was to investigate children's judgments of their knowledge states when presented with confounded evidence as a measure of their metacognitive awareness of different informational qualities. Using a "blicket detector paradigm" (Gopnik & Sobel, 2000), in two within-participants conditions, we presented children with confounded and unconfounded evidence about the cause of a light effect. We asked children whether they *knew* or whether they *required more information to know* whether an object was causally effective or not. In the unconfounded (control) condition, children observed that there was only one object that was associated with the light. In the confounded condition, children observed that two objects were associated with the light effect, but it was unclear which object was the true cause. Based on previous research on the development of causal learning (Cook et al., 2011; Lapidow & Walker, 2020; Schulz & Bonawitz, 2007), metacognitive awareness in the case of partial information (Lapidow et al., 2020; Rohwer et al., 2012), and understanding of mental terms (Kristen-Antonow et al., 2019) during early childhood, we focused our study on 5- and 6-year-old children. We predicted that children would be more likely to selectively acknowledge that they require more information to know the effectiveness of an object in the confounded condition than in the unconfounded condition. In light of the previous findings, we did not expect a difference between 5-year-olds and 6-year-olds; however, we included age as an exploratory control variable in our analyses because our knowledge of the development of these abilities is limited.

Our second objective was to investigate consistency and change in children's metacognitive beliefs about their knowledge in the case of same versus changing evidence patterns. In the confounded condition children observed the same confounded evidence in two repeated trials, whereas in the unconfounded condition children observed confounded evidence in the first trial and unconfounded evidence in the second trial. Previous research has demonstrated that young children can revise their beliefs about the cause of outcomes based on new evidence (Legare et al., 2016; Schulz et al., 2007; Schulz & Gopnik, 2004); however, it is unclear whether they also flexibly revise their knowledge judgments. We predicted that children would be more likely to revise their knowledge judgments (from ignorance to knowledge) in the unconfounded condition than in the confounded condition.

Our final objective was to investigate children's explanations for why confounded evidence is uninformative. After children provided their knowledge judgments, we asked them to explain why they did not know. We looked at the frequency of children who provided evidence-based explanations for their ignorance and information seeking by elaborating on the presence of multiple candidate causes when evidence was confounded. We also asked children to describe what they should do to know for certain and documented the frequency with which children used the isolation of objects strategy to gain further information. We predicted that children would provide evidence-based explanations and use the isolation of variables strategy as a means to reveal further information when evidence is confounded.

Method

Participants

Participants were 60 5- and 6-year-olds (31 girls; M_{age} = 70 months, range = 60–81). To determine the minimum required sample size to reach sufficient statistical power, we performed an a priori power analysis using G*Power 3.1.2 (Faul, Erdfelder, Lang, & Buchner, 2007). For a medium effect size (McNemar's test, odds ratio = 3.5, with power [$1 - \beta$] set at .08, α set at .05, and proportion of discordant pairs set at .30), a minimum of 60 participants was required. Participants were typically developing children of lower- to upper-middle-class backgrounds from a large German city, and they were from heterogeneous socioeconomic backgrounds. Parents signed written consent for their children's participation in accordance with the university ethics committee guidelines.

Materials

A light box, which was a 30 × 20 × 14-cm custom-built wooden box with a LED light strip attached around, it was used. The light box had an RFID (radio frequency identification) reader inside, and it was automatically activated when objects with RFID chips were put on it. Cubes (3 × 3 × 3 cm) in different colors were used as objects. The cubes with and without RFID chips were perceptually identical. Each participant was presented with eight individual cubes in 10 different colors (see Fig. 1). To prevent any systematic effect of color preference, the colors of the cubes used in each phase of the study and the matched effects of the colors were counterbalanced. Novel labels were used for the effective and ineffective cubes. Children were told that effective cubes were called "toma" (or "baffe") and ineffective cubes were called "not-a-toma" (or "not-a-baffe"). To ensure that the labels themselves did not differentially influence children's learning, half of the children learned the category labels toma and not-a-toma and the other half of the children learned the category labels baffe and not-a-baffe.

Design

Two within-participants conditions were designed, with the order counterbalanced across participants. Each condition consisted of two trials. The second trial of each condition served as the experimental comparison of the knowledge judgments in the case of confounded and unconfounded evidence. The change and consistency of knowledge judgments in the same versus changing evidence patterns were examined by looking at the change from the first trial to the second trial in each condition. The first trial of each condition included confounded evidence. The second trial of the confounded condition also included confounded evidence (see Fig. 2). In contrast, the second trial of the unconfounded condition included unconfounded evidence. In sum, children received three confounded evidence trials and one unconfounded evidence trial. In each condition, different cubes were used. The two trials of each condition included the same cubes, with the exception that the second

Fig. 1. Picture of object stimuli (effective cubes on the right, ineffective cubes on the left) and the light box.

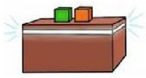
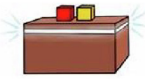
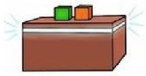
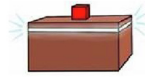
	Evidence		Questions
	Confounded condition	Unconfounded condition	
Trial 1			(1) Do you know whether the green/red cube is a toma or not-a-toma or do you not know? (2) Why?
Trial 2			(3) Do you know whether the green/red cube is a toma or not-a-toma or do you need to know more about it? (4) Why? (5) What do we have to do to know for sure? (optional)

Fig. 2. Schematic of the evidence patterns and the questions in each trial. The light box was activated in all trials. The first trial of each condition and the second trial of the confounded condition are confounded evidence trials. When children reported sufficient knowledge in response to the first and third questions, they were asked an additional know–guess control question: "Do you really know or are you just guessing?".

trial of the unconfounded condition included only one of the cubes. Half of the children received the confounded condition first and the four trials in this order: confounded, confounded, confounded, unconfounded. The other half of the children received the unconfounded condition first and the four trials in this order: confounded, unconfounded, confounded, confounded.

Procedure

Sessions were carried out in separate rooms of kindergartens and were recorded by a video camera. Each child was tested individually in a session lasting approximately 15 min. In the beginning, the experimenter and children played a warm-up game together. Children never interacted with the cubes and the light box themselves, but they observed the experimenter interacting with the cubes and the light box. The study consisted of a learning phase and a test phase. The test phase included two conditions: the confounded condition and the unconfounded condition.

Learning phase

The aims of this phase were to (a) familiarize children with the materials and their effects, (b) teach children novel category labels for the effective and ineffective cubes, and (c) demonstrate the effects of cube pairs when they were placed on the box together. The latter point is critical because the cubes were presented in pairs in the test phase, and the learning phase taught children the baseline for cause–effect relationships when cubes were placed on the box in pairs. We used a disjunctive cause–effect relationship in this study, meaning that each object individually activated or did not activate the light. The box activated when one effective object and one ineffective object or two effective objects were placed on the box. It did not activate when two ineffective objects were placed on the box (Fig. 2). The effects of novel cubes cannot be known when they are placed on the box simultaneously and the box lights up (i.e., the test phase of the study) because one or both of the cubes could be effective. In the first part of the learning phase, the experimenter explained that the cubes that activate the box were called tomas (or baffes) and the cubes that do not activate the box were called not-tomas (or not-baffes). The experimenter placed an effective cube on the box and labeled the object (e.g., "This is a toma"). Subsequently, the experimenter placed an ineffective cube on the box and labeled the object (e.g., "This is not-a-toma"). The same procedure was repeated with two novel cubes: one effective and one ineffective. In the second part of the learning phase, children were shown the individual effects of the four cubes again and were presented with pairs of the cubes placed on the box together to show them the effect of two cubes (see Fig. 3). During the demonstrations of the individual cubes, the experimenter asked children to label the cubes. All children correctly reproduced the novel labels for the effective and ineffective objects at least one time.

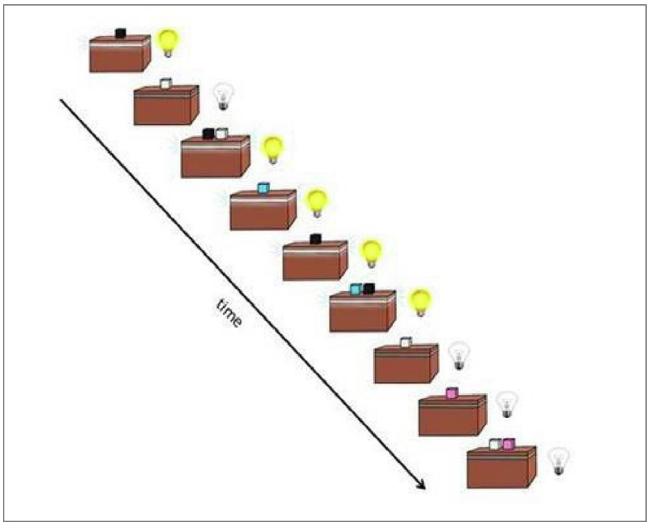


Fig. 3. Schematic of the order of the individual cubes and cube pairs in the second part of the learning phase. The colors of the cubes were counterbalanced. Evidence suggests a disjunctive activation rule: Each object individually activates or does not activate the light. Yellow light bulbs represent that the box is activated. (For interpretation of the reference to color in this figure legend, the reader is referred to the Web version of this article.)

Test phase, confounded condition

In this phase, children were presented with evidence and were asked about their knowledge of the effectiveness of a "target cube." In the first trial, the experimenter put a target cube (e.g., green) together with another cube (e.g., orange) on the box simultaneously, and the box lit up. The experimenter asked children whether they have sufficient information to know the effectiveness of the target cube: (1) "Do you know whether the [green/red] cube is a toma or not-a-toma?" Because children might interpret the task as a guessing game, if children initially provided sufficient knowledge, they were asked whether they really knew or just guessed as a control for their knowledge judgment (i.e., "know–guess" question). Next, children were asked (2) "Why?" to explain their knowledge judgment. In the second trial, the experimenter put the same two cubes on the box again and asked, (3) "Do you know whether the [green/red] cube is a toma or not-a-toma, or do you need to know more about it?" Similar to the first trial, if children said that they knew, they were asked the know–guess question. Then, they were asked (4) "Why?" to explain their knowledge judgment. Finally, if children said that they require more information, they were asked, (5) "What should we do to know for sure?" We used two different question formats in the first and second trials of each condition ("Do you know whether . . .?" or "Do you not know . . .?" vs. "Do you need to know more about it?") in order to avoid repeating the same question.

Test phase, unconfounded condition

This condition was identical to the confounded condition in terms of the structure and the questions. The only difference was that two novel cubes were used (e.g., red and yellow), and the experimenter put the target cube (e.g., red) alone on the box in the second trial and the box lit up. Similar to the confounded condition, children who initially reported sufficient knowledge were asked the know–guess control question.

Coding

All verbal responses and gestures that pragmatically conveyed critical information (e.g., head nod, head shake) in response to the interview questions were transcribed.

Knowledge judgments

Children's knowledge judgments about the effectiveness of the target object (i.e., responses to Questions 1 and 3 in Fig. 2) were coded into two primary categories: "sufficient knowledge" and "insufficient knowledge." Children who initially said that they knew, children who provided an object category label (e.g., it is a toma/not-a-toma), and children who subsequently answered the know–guess question by saying that they really knew were classified as providing sufficient knowledge.

Children who said that they did not know, children who required more information, and children who first said that they knew or provided an object category label but then answered the know–guess question by saying that they just guessed were classified as providing insufficient knowledge. We coded these three subcategories of insufficient knowledge to provide more information on the nature of children's responses, although the main analyses were based on the two primary categories (i.e., sufficient knowledge and insufficient knowledge). There was slight variation in children's responses in the first and second trials because of the kind of question asked. In the first trials, children were asked whether they knew or did not know, and they answered this question by saying that they did not know (see Question 1 in Fig. 2). These responses were coded as "ignorance judgments." In the second trials, children were asked whether they knew or required more information (see Question 3 in Fig. 2), and they answered this question by saying that they required more information. These responses were coded as "information-seeking judgments." Moreover, children who first stated that they knew but later answered the know–guess question by saying that they only guessed were classified as providing "guessing" judgments because stating that one only guessed is an acknowledgment of insufficient knowledge. A few children suggested trying the target cube alone (isolation of variables strategy). Those cases were also classified as insufficient knowledge judgments because they pragmatically convey that information is insufficient by referring to how to gain the required information.

Explanations

We coded children's explanations for their awareness of multiple potential causes in the three confounded evidence trials (see Questions 2 and 4 in Fig. 2). Children were classified as providing a "confounded evidence explanation" when they mentioned typical characteristics of confounding as a reason for why they could not know. These were explanations such as saying that they could not know because there were two objects on the light box (e.g., "Because both the cubes were put on the light box") or one of the two objects could be effective (e.g., "I don't know which of them makes the box light up"). Children who only emphasized evidence without any distinctive reference to confounding (e.g., "The box lit up"), who provided alternate hypotheses (e.g., "Because the green one is not as strong as the pink one"), and who did not provide a proper causal explanation (e.g., repeated knowledge judgments, "Because I just don't know") were classified as providing no explanations on confounding. Because providing elaborate evidence-based explanations is challenging for younger children, we set a liberal criterion for children's competence for explaining confounding in their justifications by referring to the multiple candidate causes; we examined whether children explained the confounding at least once out of three confounded trials.

Describing the correct test: Isolation of objects

In the second trial of each condition, children's answers to the testing question "What do we have to do to know for sure?" were coded into two main categories (see Question 5 in Fig. 2). Children who described the correct test of isolating the cubes (e.g., "Have to put that one [target cube] alone") were coded as a correct test. All other responses or missing responses were coded as other/no response.

All data were coded by one rater. A second rater coded one third of the data (20 participants). Interrater reliability for all codes was calculated by Cohen's kappa, and all scores were nearly perfect ($\geq$.80) (Landis & Koch, 1977). The interrater reliabilities ranged from .91 to 1.00 for knowledge judgments and from .83 to .93 for explanations. The interrater reliability was 1.00 for the description of correct test responses.

The data that support the findings of this study are available on the Open Science Framework (https://doi.org/10.17605/OSF.IO/SWB92).

Results

There were no significant effects of the order of the conditions and the different object labels (i.e., toma, baffe) on children's knowledge judgments, their explanations for confounded evidence, or their descriptions of the correct test. First, we report the descriptives on children's knowledge judgments across all four trials. Second, we report the comparison of children's knowledge judgments in the second trial of each condition. Then, we report the comparison on children's revision of their knowledge judgments in the confounded versus unconfounded conditions. Finally, we report the frequency of children's explanations and their descriptions of the correct test.

Knowledge judgments

Children were presented with confounded evidence in the first trial of each condition. In the second trial of the confounded condition, children were presented with confounded evidence, and in the second trial of the unconfounded condition, they were presented with unconfounded evidence. Table 1 presents the percentages of children who provided sufficient and insufficient knowledge judgments and the percentages of subcategories of insufficient knowledge judgments in all four trials.

To assess whether there is a significant difference in children's knowledge judgments in the case of confounded and unconfounded evidence, McNemar's test was employed. Children's knowledge judgments (insufficient vs. sufficient knowledge) in the second trial of each condition (confounded vs. unconfounded) was the dependent variable. The proportion of insufficient knowledge judgments was significantly higher in the confounded condition than in the unconfounded condition, $\chi^2(1) = 25.290$, two-sided, $p < .001$. As an exploratory control analysis for age (months of age entered continuously) and gender, a generalized estimating equations (GEE) model with an independent working correlation, a logit link function, and binomial distribution (Zeger & Liang, 1986) was employed. The main effect of condition remained significant ($p < .001$), and age ($p = .401$) and gender ($p = .868$) were not significant predictors of performance.

Consistency and change of knowledge judgments

To investigate children's revision of their knowledge judgments in response to changing evidence patterns, we conducted a McNemar's test to compare the number of children who changed their judgments across the two trials of the unconfounded and confounded conditions. The proportion of children who changed their knowledge judgment was significantly higher in the unconfounded condition than in the confounded condition, $\chi^2(1) = 11.28$, two-sided, $p = .001$. In the unconfounded condition, 57% of the children (34/60) changed their knowledge judgments. In the confounded condition, 23% of the children (14/60) changed their knowledge judgments.

Table 1
Percentages of children who provided insufficient knowledge judgments (with subcategories) and sufficient knowledge judgments in the first and second trials of each condition.

	First trials		Second trials	
Knowledge judgments	CC[a]	UC[a]	CC[a]	UC[b]
Insufficient knowledge	60% (36)	58% (35)	53% (32)	5% (3)
Ignorance	37% (22)	37% (22)	N/A	N/A
Information seeking	N/A	N/A	43% (26)	2% (1)
Guessing	20% (12)	15% (9)	7% (4)	3% (2)
Isolation of variables	3% (2)	7% (4)	3% (2)	0
Sufficient knowledge	40% (24)	42% (25)	47% (28)	95% (57)

Note. $N = 60$. Numbers of participants are in parentheses. CC, confounded condition; UC, unconfounded condition.
[a] Confounded evidence trials.
[b] Unconfounded evidence trials. Ignorance and information-seeking judgments are not available (N/A) in certain cells due to different questioning in the first and second trials.

In the confounded condition, the correct evaluation was to report insufficient knowledge in both trials. Among the children who provided insufficient knowledge judgments in the first trial, 75% (27/36) also provided insufficient knowledge judgments in the second trial. In the unconfounded condition, the correct choice was to change the knowledge judgment from insufficient knowledge to sufficient knowledge in the two trials. Among the children who provided insufficient knowledge judgments in the first trial, 94% (33/35) accurately changed their judgments and provided sufficient knowledge judgments in the second trial. The results of exploratory control analysis (GEE) showed that the main effect of condition was significant ($p < .001$), and months of age ($p = .703$) and gender ($p = .973$) were not significant.

Explanations for knowledge judgments in the confounded trials

Of the 60 children, 24 (40%) provided confounded evidence explanations at least once across three confounded trials. The liberal success criterion for explanations (i.e., correct at least once) was susceptible to order or learning effects over the course of the task. To check this, we compared children's success in the three confounded evidence trials. There was no effect of order across the three confounded evidence trials for the children who received the confounded condition first and the unconfounded condition second [$n = 31$, Friedman test, $\chi^2(2) = 1.50$, $p = .472$] or for the children who received the unconfounded condition first and the confounded condition second [$n = 29$, Friedman test, $\chi^2(2) = 2.66$, $p = .264$]. These results show that learning and order did not play a role in children's success in providing explanations. Exploratory control analysis (logistic regression) revealed a significant effect of months of age ($p = .011$) but no significant effect of gender ($p = .646$). Older children were better than younger children at providing confounded evidence explanations.

Describing the correct test: Isolation of objects

In the second trial of each condition, children who provided insufficient knowledge judgments were asked what should be done to know more (2 children were not asked this question due to experimenter error, although they provided insufficient knowledge judgments). In the confounded condition, of 30 children who provided insufficient knowledge judgments, 23 (77%) of them (38% of the complete sample) suggested putting the target cube alone on the light box in order to determine the causal category of the target cube. According to the exploratory control analysis (logistic regression, $n = 30$), there was no effect of months of age ($p = .173$) or gender ($p = .191$) in terms of describing the correct test in the confounded condition. In the unconfounded condition, of 3 children who provided insufficient knowledge judgments, none of them mentioned putting the target cube alone on the light box.

Discussion

An explicit understanding of evidence as a source of knowledge is foundational for scientific reasoning (Kuhn, 2014). The current study investigated 5- and 6-year-olds' metacognitive awareness of the informativeness of confounded evidence, a measure of the extent to which they can explicitly reason about the sufficiency of evidence. It is the first study to investigate children's explicit understanding of their own epistemic states when provided with sufficient or insufficient evidence in a causal learning paradigm. Previous studies have yielded some indirect evidence on possible metacognitive awareness in such conditions, but no study has addressed the explicit language-based distinction between knowledge and ignorance. We investigated the extent to which young children can (a) correctly judge their own knowledge in the case of confounded and unconfounded evidence, (b) revise their knowledge judgments in line with changing evidence patterns, and (c) explain confounding evidence and describe the isolation of variables strategy as a means to gain further information.

Our first objective was to examine whether young children can accurately differentiate confounded evidence from unconfounded evidence and can judge that they do not know and thus require more information when evidence is confounded. The proportion of children who assessed that they required

more information was significantly higher in the confounded condition than in the unconfounded condition. Half of the children acknowledged that they did not know or that they required more information at least twice in the three confounded trials, thereby demonstrating a differentiation of the informativeness of confounded and unconfounded evidence.

Metacognitive awareness may differentiate early causal reasoning from scientific reasoning (Kuhn, 2014); however, the difference between the two does not appear to be straightforward. Children's metacognitive awareness of confounded evidence and their explicit ability to differentiate confounded evidence from unconfounded evidence have not been documented previously in an experimental paradigm (e.g., Cook et al., 2011; Gopnik, 2012; Moeller Bachhuber et al. (2019)). Our data demonstrate that there is an explicit metacognitive awareness of the informativeness of confounded versus unconfounded evidence at 5 years of age, and they provide new insight into young children's understanding of evidence as an epistemic category (e.g., Koerber et al., 2005; Ruffman et al., 1993).

Our second objective was to examine whether children revise their own knowledge judgments in response to changing evidence patterns. The proportion of children who revised their knowledge judgments in the changing evidence pattern (unconfounded condition) was higher than that in the same evidence pattern (confounded condition). Children's consistency in their knowledge judgments for the same object with the same pattern of evidence and their correct revision of their judgments in response to different evidence patterns demonstrate their flexibility in correctly revising their epistemic state attributions with respect to variable patterns of evidence. In the confounded condition, 75% of the children who judged themselves to be ignorant in the first trial also said that they required more information in the second trial. In contrast, 94% of the children who said that they did not know in the first trial of the unconfounded condition revised their response in the second trial and said that they knew. These findings are informative for understanding young children's metacognition of their knowledge acquisition and revision processes because they show that children not only can revise their causal beliefs (Bonawitz, Fischer, & Schulz, 2012; Legare et al., 2016; Schulz et al., 2007; Schulz & Gopnik, 2004) but also can correctly revise their knowledge judgments (sufficient/insufficient knowledge or information seeking) about their causal beliefs.

Our third objective was to examine children's evidence-based explanations for their insufficient knowledge and information seeking in the case of confounded evidence. Across the three confounded evidence trials, 40% of the children explained confounding at least once by saying that there were two objects; hence, they could not know the causal effectiveness of the target object. A few children even explained the evidence patterns that they observed in the learning phase as a reason (e.g., "Because when you put a toma and not-a-toma before, it glowed") or elaborated on the alternative possibilities regarding the objects' effects ("Because I don't know whether one makes the box light up and the other doesn't or both make the box light up"). Furthermore, 38% of the children described the correct test (i.e., the isolation of variables strategy) to gain the required information. This shows that at 5 or 6 years of age, there is already a beginning metacognitive understanding that the co-occurrence of multiple candidate causes is uninformative to draw causal inferences and that the strategy to find out the true causal relations is to test the effects of the objects in isolation. These findings suggest not only that the information-seeking behavior shown in causal learning studies is sensitive to the utility of evidence but also that children (at least 5- and 6-year-olds) have an explicit understanding of the evidence characteristics and why the evidence is uninformative. The metacognitive awareness of the intuitive forms of information seeking might provide children with the opportunities to practice their early abilities, which in turn supports developing more sophisticated forms of causal inference and experimentation that are necessary to reason scientifically.

Approximately half of the children in the current study correctly assessed that they did not know when evidence was confounded. This frequency is lower than the success rates of the children in the noncausal partial information paradigm, which were approximately 60% and 80% in Experiments 1 and 2 of the study by Rohwer et al. (2012). Relatedly, when we compare children's information-seeking behaviors in the case of confounded evidence and noncausal partial information, the frequency of the former is lower than that of the latter. To illustrate, approximately 50% sought information in the case of confounded evidence in the study by Cook et al. (2011), whereas approximately 90% of 4- and 5-year-olds sought information in the noncausal incomplete information task in the study by

Kloo et al. (2020). Based on these findings, we speculate that reasoning about causally confounded information might be harder than reasoning about noncausal partial information.

Along this line, the frequencies of children who engaged in exploratory behaviors and of those who showed an explicit understanding in the case of confounded evidence are similar. In the study by Cook et al. (2011), half of the 4- and 5-year-olds sought information and performed the isolation of objects strategy. Similarly, approximately half of the children reported insufficient knowledge in the case of confounded evidence in the current study. It is possible that the spontaneous tendency to associate the effect with a causal factor may hinder children both from seeking unconfounded evidence during exploration and from correctly assessing their knowledge state when evidence is causally confounded. This may be the reason for the similar frequencies of success rate in the implicit and explicit paradigms on confounded evidence.

Limitations

The interview format of this study had both advantages and disadvantages, especially regarding investigating children's explanations. To measure children's ability to explain their knowledge judgment, we asked only a general question ("Why?"). The case that 40% of the children explained the confounding even in response to such a general question shows that children were straightforward in referring to the confounded nature of evidence as a justification for their epistemic states. However, the fact that we did not ask follow-up questions when children provided unclear explanations might have led to an underestimation of children's abilities. This applies especially to the cases where children provided explanations by repeating their epistemic state (e.g., "Because I don't know exactly"). In such cases, asking children follow-up questions might have revealed more information regarding their competence for understanding confounded evidence.

The revision of knowledge judgments can happen in two directions. The current study focused on one of these directions: After children had insufficient knowledge (confounded evidence), they received unconfounded evidence, and we investigated whether they could correctly revise their knowledge judgments from having insufficient knowledge to having sufficient knowledge. In daily life, it is often the case that people initially think that they have sufficient evidence to know something. Only after receiving some new evidence do they realize that in fact they have insufficient knowledge. To have a complete picture of young children's revision of their knowledge judgments, it is necessary to investigate whether children can also flexibly revise their knowledge judgments in the direction from sufficient knowledge to insufficient knowledge.

Future directions

Both the current study and the isolation of variables task by Cook et al. (2011) yielded evidence on considerable individual differences in preschoolers' causal and scientific reasoning. To date, very little research has addressed these individual differences. General cognitive abilities (i.e., executive function and language) were found to be related to young children's causal reasoning (Bauer & Booth, 2019), scientific reasoning (van der Graaf, Segers, & Verhoeven, 2016, 2018), and how much children benefit from interventions targeting scientific reasoning (van Schijndel, Jansen, and Raijmakers, 2018). Moreover, children differ in their attentiveness to causal information (Alvarez & Booth, 2016) and in the types of causal explanations they provide for inconsistent evidence, which in turn informs their exploratory behavior (Legare, 2012). Further studies are necessary to investigate the role of individual differences in the development of understanding confounded evidence. With respect to the development of explicit metacognitive understanding, it is particularly important to address the developmental relations among causal learning, scientific reasoning, and mental state understanding (theory of mind and metacognition) in young children.

The current findings of 5- and 6-year-olds' metacognitive awareness of the utility of confounded evidence and information seeking raises the question of the development of these abilities in older children. The problems that children come across in science are complex, often require manipulation of multiple variables, and require reasoning in contexts where children already have some prior beliefs (Carey et al., 1989; Klahr et al., 1993; Kuhn et al, 2000; Kuhn & Pease, 2008; Schauble, 1996). Our findings show that

young children have metacognitive awareness of the informativeness of confounded evidence in simple evidence patterns; however, they do not show to what degree children can apply their early metacognitive abilities to problems that require a more sophisticated understanding of informativeness of evidence and causal inference. Moreover, the current study dealt with a subcomponent of metacognition, namely metacognitive awareness of one's own knowledge and ignorance. A complete understanding of the development of metacognition in relation to causal and scientific reasoning abilities requires an exhaustive investigation of young children's developing metacognitive understanding of origins of knowledge, hypothesis–evidence coordination, and inference as a source of knowledge (Callanan et al., 2019). Future studies should examine the developmental progression from early forms of awareness as shown in the current study to the more advanced forms of monitoring and controlling of the epistemic activities (e.g., experimentation, evidence evaluation).

Our intention was to investigate whether there is metacognitive awareness of the uninformativeness of confounded evidence during the early childhood years at all; thus, we focused our investigation on 5- and 6-year-olds who are generally better at providing verbal elaborations. The control age analyses suggest that there were no differences between 5-year-olds and 6-year-olds in terms of assessing whether they knew or required more information in the two conditions. However, older children were better than younger children at elaborating on the confounding as a reason for their lacking knowledge. Future research should examine whether this difference points to a developmental change in children's reasoning about confounded evidence or whether it is due to improved language skills. Another open question is the developmental progression of reasoning about confounded evidence in elementary school children given that the current study showed that there is ample room for improvement. Future studies are required to investigate at what age children show ceiling performance in reasoning about confounded evidence in similar task complexities. Finally, we should note that the participants of the current study were from WEIRD (Western, educated, industrialized, rich, and democratic) populations (Heinrich, Heine, & Norenzayan, 2010). All our participants were enrolled in early education programs where there are learning opportunities for developing early science skills. Further studies are required to examine whether the findings of the current study can be generalizable to diverse cultural groups.

Conclusion

Growing evidence demonstrates rapid early development of capacities for scientific reasoning, yet young children are often considered to lack a metacognitive awareness of these capacities. The current study demonstrates that there is a metacognitive awareness of insufficient knowledge in the case of confounded evidence during early childhood. This demonstrates that young children not only have an implicit sensitivity to confounding evidence but also have an explicit understanding of the informativeness of confounded versus unconfounded evidence. These data demonstrate that the development of scientific reasoning and that of causal learning have substantial common ground. We hope that the current work will be a step in bringing together the two research lines to reach a more comprehensive understanding of young children's early abilities to learn from evidence. We argue that examining the development of metacognition can provide a unique insight into how advanced scientific reasoning develops (or fails to develop) and inform the design of formal and informal learning environments.

Acknowledgments

This work was funded by the German Research Council (DFG SO 213/34-1) and by the REASON program, Elite Network of Bavaria (Project K-GS-2012-209). We are grateful to the staff and children of various kindergartens in Munich for participating in this research and for their friendly cooperation.

References

Alvarez, A., & Booth, A. E. (2016). Exploring individual differences in preschoolers' causal stance. *Developmental Psychology, 52*, 411–422.

Bauer, J. R., & Booth, A. E. (2019). Exploring potential cognitive foundations of scientific literacy in preschoolers: Causal reasoning and executive function. *Early Childhood Research Quarterly, 46*, 275–284.

Beck, S. R., McColgan, K. L., Robinson, E. J., & Rowley, M. G. (2011). Imagining what might be: Why children underestimate uncertainty. *Journal of Experimental Child Psychology, 110*, 603–610.

Bonawitz, E., Fischer, A., & Schulz, L. (2012). Teaching 3.5-year-olds to revise their beliefs given ambiguous evidence. *Journal of Cognition and Development, 13*, 266–280.

Bonawitz, E. B., van Schijndel, T. J., Friel, D., & Schulz, L. (2012). Children balance theories and evidence in exploration, explanation, and learning. *Cognitive Psychology, 64*, 215–234.

Busch, J. T. A., & Legare, C. H. (2019). Using data to solve problems: Children reason flexibly in response to different kinds of evidence. *Journal of Experimental Child Psychology, 183*, 172–188.

Callanan, M., Legare, C. H., Sobel, D., Jaeger, G., Letourneau, S., McHugh, S., ... Rubio, E. (2019). Exploration, explanation, and parent–child interaction in museums. *Monographs of the Society for Research in Child Development, 85*, 7–137.

Carey, S., Evans, R., Honda, M., Jay, E., & Unger, C. (1989). "An experiment is when you try and see if it works": A study of Grade 7 students' understanding of the construction of scientific knowledge. *International Journal of Science Education, 11*, 514–529.

Cook, C., Goodman, N. D., & Schulz, L. E. (2011). Where science starts: Spontaneous experiments in preschoolers' exploratory play. *Cognition, 120*, 341–349.

Coughlin, C., Hembacher, E., Lyons, K. E., & Ghetti, S. (2015). Introspection on uncertainty and judicious help-seeking during the preschool years. *Developmental Science, 18*, 957–971.

Demetriou, A., Makris, N., Kazi, S., Spanoudis, G., & Shayer, M. (2018). The developmental trinity of mind: Cognizance, executive control, and reasoning. *Wiley Interdisciplinary Reviews: Cognitive Science, 9*(4), e1461.

Erb, C. D., & Sobel, D. M. (2014). The development of diagnostic reasoning about uncertain events between ages 4–7. *PLoS One, 9* (3), e92285.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*, 175–191.

Fay, A. L., & Klahr, D. (1996). Knowing about guessing and guessing about knowing: Preschoolers' understanding of indeterminacy. *Child Development, 67*, 689–716.

Gopnik, A. (2012). Scientific thinking in young children: Theoretical advances, empirical research, and policy implications. *Science, 337*, 1623–1627.

Gopnik, A., & Sobel, D. M. (2000). Detecting blickets: How young children use information about novel causal powers in categorization and induction. *Child Development, 71*, 1205–1222.

Gopnik, A., & Wellman, H. M. (2012). Reconstructing constructivism: Causal models, Bayesian learning mechanisms, and the theory theory. *Psychological Bulletin, 138*, 1085–1108.

Gweon, H., & Schulz, L. E. (2008). In *Stretching to learn: Ambiguous evidence and variability in preschoolers' exploratory play* (pp. 570–574). Austin, TX: Cognitive Science Society.

Harris, P. L., Ronfard, S., & Bartz, D. (2017). Young children's developing conception of knowledge and ignorance: Work in progress. *European Journal of Developmental Psychology, 14*, 221–232.

Heinrich, J., Heine, S. J., & Norenzayan, A. (2010). Most people are not WEIRD. *Nature, 466*, 29.

Hembacher, E., & Ghetti, S. (2014). Don't look at my answer: Subjective uncertainty underlies preschoolers' exclusion of their least accurate memories. *Psychological Science, 25*, 1768–1776.

Klahr, D., & Chen, Z. (2003). Overcoming the positive-capture strategy in young children: Learning about indeterminacy. *Child Development, 74*, 1275–1296.

Klahr, D., Fay, A. L., & Dunbar, K. (1993). Heuristics for scientific experimentation: A developmental study. *Cognitive Psychology, 25*, 111–146.

Kloo, D., Rohwer, M., & Perner, J. (2017). Direct and indirect admission of ignorance by children. *Journal of Experimental Child Psychology, 159*, 279–295.

Kloo, D., Sodian, B., Kristen-Antonow, S., Kim, S., & Paulus, M. (2020). Knowing minds: Linking early perspective taking and later metacognitive insight. *British Journal of Developmental Psychology. Advance online publication.*. https://doi.org/10.1111/bjdp.12359.

Koerber, S., Sodian, B., Thoermer, C., & Nett, U. (2005). Scientific reasoning in young children: Preschoolers' ability to evaluate covariation evidence. *Swiss Journal of Psychology/Schweizerische Zeitschrift für Psychologie/Revue Suisse de Psychologie, 64*, 141–152.

Köksal-Tuncer, Ö., & Sodian, B. (2018). The development of scientific reasoning: Hypothesis testing and argumentation from evidence in young children. *Cognitive Development, 48*, 135–145.

Kristen-Antonow, S., Jarvers, I., & Sodian, B. (2019). Preschoolers' developing understanding of factivity in mental verb comprehension and its relation to first- and second-order false belief understanding: A longitudinal study. *Journal of Cognition and Development, 20*, 354–369.

Kuhn, D. (2000). Metacognitive development. *Current Directions in Psychological Science, 9*, 178–181.

Kuhn, D. (2014). What is scientific thinking and how does it develop? In U. Goswami (Ed.), *The Wiley-Blackwell handbook of childhood cognitive development* (pp. 497–523). Malden, MA: Wiley-Blackwell.

Kuhn, D., Amsel, E., O'Loughlin, M., Schauble, L., Leadbeater, B., & Yotive, W. (1988). *The development of scientific thinking skills (Developmental Psychology series)*. San Diego: Academic Press.

Kuhn, D., Black, J., Keselman, A., & Kaplan, D. (2000). The development of cognitive skills that support inquiry learning. *Cognition and Instruction, 18*, 495–523.

Kuhn, D., & Pease, M. (2008). What needs to develop in the development of inquiry skills? *Cognition and Instruction, 26*, 512–559.

Kushnir, T., & Gopnik, A. (2007). Conditional probability versus spatial contiguity in causal learning: Preschoolers use new contingency evidence to overcome prior spatial assumptions. *Developmental Psychology, 43*, 186–196.

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics, 33*, 159–174.
Lapidow, E., Killeen, I., & Walker, C. M. (2020). *Exploration decisions precede and improve explicit uncertainty judgments in preschoolers*. Austin, TX: Cognitive Science Society.
Lapidow, E., & Walker, C. M. (2020). Informative experiments in intuitive science: Children select and learn from their own causal interventions. *Cognition, 201*, 104315.
Legare, C. H. (2012). Exploring explanation: Explaining inconsistent evidence informs exploratory, hypothesis-testing behavior in young children. *Child Development, 83*, 173–185.
Legare, C. H. (2014). The contributions of explanation and exploration to children's scientific reasoning. *Child Development Perspectives, 8*, 101–106.
Legare, C. H., & Gelman, S. A. (2014). Examining explanatory biases in young children's biological reasoning. *Journal of Cognition and Development, 15*, 287–303.
Legare, C. H., Gelman, S. A., & Wellman, H. M. (2010). Inconsistency with prior knowledge triggers children's causal explanatory reasoning. *Child Development, 81*, 929–944.
Legare, C. H., & Lombrozo, T. (2014). Selective effects of explanation on learning during early childhood. *Journal of Experimental Child Psychology, 126*, 198–212.
Legare, C. H., Schult, C. A., Impola, M., & Souza, A. L. (2016). Young children revise explanations in response to new evidence. *Cognitive Development, 39*, 45–56.
Legare, C. H., Sobel, D. M., & Callanan, M. (2017). Causal learning is collaborative: Examining explanation and exploration in social contexts. *Psychonomic Bulletin & Review, 24*, 1548–1554.
Legare, C. H., Wellman, H. M., & Gelman, S. A. (2009). Evidence for an explanation advantage in naïve biological reasoning. *Cognitive Psychology, 58*, 177–194.
Lyons, K. E., & Ghetti, S. (2011). The development of uncertainty monitoring in early childhood. *Child Development, 82*, 1778–1787.
Lyons, K. E., & Ghetti, S. (2013). I don't want to pick! Introspection on uncertainty supports early strategic behavior. *Child Development, 84*, 726–736.
Moeller Bachhuber, A., Sobel, D. M., & Sodian, B. (2019). Young children's understanding of controlled tests for diagnostic inference. [Manuscript submitted for publication]. Developmental Psychology Department, Ludwig Maximilian University of Munich.
Moore, C., Bryant, D., & Furrow, D. (1989). Mental terms and the development of certainty. *Child Development, 60*, 167–171.
Pratt, C., & Bryant, P. (1990). Young children understand that looking leads to knowing (so long as they are looking into a single barrel). *Child Development, 61*, 973–982.
Rohwer, M., Kloo, D., & Perner, J. (2012). Escape from metaignorance: How children develop an understanding of their own lack of knowledge. *Child Development, 83*, 1869–1883.
Ruffman, T., Perner, J., Olson, D. R., & Doherty, M. (1993). Reflecting on scientific thinking: Children's understanding of the hypothesis–evidence relation. *Child Development, 64*, 1617–1636.
Schauble, L. (1996). The development of scientific reasoning in knowledge-rich contexts. *Developmental Psychology, 32*, 102–119.
Schneider, W. (2008). The development of metacognitive knowledge in children and adolescents: Major trends and implications for education. *Mind, Brain, and Education, 2*, 114–121.
Schulz, L. (2012). The origins of inquiry: Inductive inference and exploration in early childhood. *Trends in Cognitive Sciences, 16*, 382–389.
Schulz, L. E., & Bonawitz, E. B. (2007). Serious fun: Preschoolers engage in more exploratory play when evidence is confounded. *Developmental Psychology, 43*, 1045–1050.
Schulz, L. E., Bonawitz, E. B., & Griffiths, T. L. (2007). Can being scared cause tummy aches? Naive theories, ambiguous evidence, and preschoolers' causal inferences. *Developmental Psychology, 43*, 1124–1139.
Schulz, L. E., Goodman, N. D., Tenenbaum, J. B., & Jenkins, A. C. (2008). Going beyond evidence: Abstract laws and preschoolers' responses to data. *Cognition, 109*, 211–223.
Schulz, L. E., & Gopnik, A. (2004). Causal learning across domains. *Developmental Psychology, 40*, 162–176.
Sobel, D. M., Erb, C. D., Tassin, T., & Weisberg, D. (2017). The development of diagnostic inference about uncertain causes. *Journal of Cognition and Development, 18*, 556–576.
Sobel, D. M., Tenenbaum, J. B., & Gopnik, A. (2004). Children's causal inferences from indirect evidence: Backwards blocking and Bayesian reasoning in preschoolers. *Cognitive Science, 28*, 303–333.
van der Graaf, J., Segers, E., & Verhoeven, L. (2016). Scientific reasoning in kindergarten: Cognitive factors in experimentation and evidence evaluation. *Learning and Individual Differences, 49*, 190–200.
van der Graaf, J., Segers, E., & Verhoeven, L. (2018). Individual differences in the development of scientific thinking in kindergarten. *Learning and Instruction, 56*, 1–9.
van Schijndel, T. J., Jansen, B. R. J., & Raijmakers, M. E. J. (2018). Do individual differences in children's curiosity relate to their inquiry-based learning?. *International Journal of Science Education, 40*, 996–1015.
van Schijndel, T. J., Visser, I., van Bers, B. M., & Raijmakers, M. E. (2015). Preschoolers perform more informative experiments after observing theory-violating evidence. *Journal of Experimental Child Psychology, 131*, 104–119.
Wellman, H. M. (2011). Reinvigorating explanations for the study of early cognitive development. *Child Development Perspectives, 5*, 33–38.
Wellman, H. M., & Liu, D. (2004). Scaling of theory-of-mind tasks. *Child Development, 75*, 523–541.
Zeger, S. L., & Liang, K. (1986). Longitudinal data analysis for discrete and continuous outcomes. *Biometrics, 42*, 121–130.