Exploring Explanation: Explaining Inconsistent Evidence Informs Exploratory, Hypothesis-Testing Behavior in Young Children

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Explaining inconsistency may serve as an important mechanism for driving the process of causal learning. But *how* might this process generate amended beliefs? One way that explaining inconsistency may promote discovery is by guiding exploratory, hypothesis-testing behavior. In order to investigate this, a study with young children ranging in age from 2 to 6 years (N = 80) examined the relation between explanation and exploratory behavior following consistent versus inconsistent outcomes. Results indicated that for inconsistent outcomes only, the kind of explanation children provided informed the kind of exploratory behavior they engaged in and the extent to which children modified and generated new hypotheses. In sum, the data provide insight into a mechanism by which explaining inconsistent evidence guides causal cognition.

Children's explanations provide insight into the development of causal knowledge and conceptual understanding (Callanan & Oakes, 1992; Frazier, Gelman, & Wellman, 2009; Gopnik, 2000; Hickling & Wellman, 2001; Keil, 2006; Keil & Wilson, 2000; Legare, Wellman, & Gelman, 2009; Wellman, 2011; Wellman, Hickling, & Schult, 1997). However, explanations reveal more than just what children know; a growing literature supports the possibility that explanation plays an important role in the process of knowledge acquisition (Chi, DeLeeuw, Chiu, & LaVancher, 1994; Wellman & Liu, 2007) and may constitute a mechanism for learning (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Crowley & Siegler, 1999; Lombrozo, 2006). For example, when children are asked to explain events, they learn more than when they are given feedback about the accuracy of their predictions (Amsterlaw & Wellman, 2006; Siegler, 1995).

Although there is evidence that engaging in explanation has distinct cognitive benefits, the means by which explanation informs the process of knowledge acquisition are underspecified. If explanation is a mechanism for learning, children should be interested in and benefit from providing explanations for events that have the potential to teach them something new, and events that are inconsistent with prior knowledge provide just such an opportunity. An explanatory tendency of this kind could aid in learning by focusing children on events that challenge current causal knowledge and provoke additional, amended causal reasoning.

Recent work by Legare and colleagues (Legare, Gelman, & Wellman, 2010) has examined explanatory triggers that inform causal cognition by motivating children to construct explanations. In a series of studies with preschool children, they investigated the kinds of events that prompt explanation and how this provides insight into the function of explaining. Their results indicate that outcomes inconsistent with prior knowledge are especially powerful triggers for children's explanations and that the explanations children provide for inconsistent outcomes refer to unobserved causal mechanisms and internal causal properties, overriding perceptual appearances. This provides promising evidence that explanation gives children the opportunity to articulate new hypotheses for events that, at first, disconfirm their current knowledge. Although this research did not directly measure learning, the data are consistent with the proposal that children's explanations play an active

role in the learning process and provide an empirical basis for investigating the mechanisms by which children's explanations function in the service of discovery.

Prior research has established that inconsistent outcomes trigger causal explanations more often than consistent outcomes (Legare et al., 2010); however, merely attending to inconsistency does not always lead to belief revision and theory change (Bindra, Clarke, & Shultz, 1980; Dunbar & Klahr, 1988; Fay & Klahr, 1996; Kuhn, 1989; Vosniadou & Brewer, 1992, 1994). In an influential article, Chinn and Brewer (1993) emphasize the importance of inconsistent data in learning but also identify several strategies for maintaining current beliefs in light of inconsistency or anomaly. For example, one can ignore inconsistent evidence, reject it, declare it beyond the scope of the theory in question, or postpone coming to terms with the new evidence. This suggests that inconsistent evidence alone is not necessarily sufficient for acquiring new ways of thinking. One possibility is that encouraging children to *explain* inconsistency may be an especially productive combination; simultaneously confronting children with the inconsistent evidence most likely to foster theory revision and providing an opportunity for children to engage in explanatory activity (thereby reducing the likelihood of engaging exclusively in theory-preserving strategies like rejection and postponement). Explaining inconsistency may therefore serve as a critical mechanism for integrating and reconciling discordant information with existing theories or knowledge structures.

But *how* might the process of explaining inconsistency generate amended beliefs? One possibility is that explaining inconsistency triggers a process of hypothesis generation that encourages learners to formulate and entertain hypotheses they would not have spontaneously considered otherwise. Generating hypotheses in the service of explanation may influence the kinds of hypotheses formulated, as well as their impact on cognition. In particular, both children and adults have strong intuitions about what makes something a good explanation (e.g., Bonawitz & Lombrozo, in press; Frazier, Gelman, & Wellman, 2007; Lombrozo, 2007), and explanation-triggered hypothesis generation may promote the production of hypotheses that make for informative explanations.

One way to test the hypotheses generated in the course of explaining inconsistency is to explore the evidence directly. Thus, explaining inconsistency may promote discovery by guiding exploratory, hypothesis-testing behavior. Building on classic research on children's play (Hutt & Bhavnani, 1972; Switzky, Haywood, & Isett, 1974), new research provides converging evidence that inconsistent or problematic events also trigger exploration (Baldwin, Markman, & Melartin, 1993; Bonawitz, Lim, & Schulz, 2008; Schulz & Bonawitz, 2007; Schulz, Standing, & Bonawitz, 2008). Although there is considerable work demonstrating that young children (and adults) have difficulty designing informative experiments (Chen & Klahr, 1999; Koslowski, 1996; Kuhn, 1989), Schulz and colleagues (Schulz & Bonawitz, 2007; Schulz, Hooppell, & Jenkins, 2008) have demonstrated that in the process of exploratory play preschool children can generate information that is relevant to uncovering causal relations and reconciling ambiguous information. For example, children's exploratory play is affected by the quality of the evidence that they observe (Cook, Goodman, & Schulz, 2011). When multiple candidate causes are available for the same outcome, and underlying causal structure is ambiguous, children preferentially explore confounded (as opposed to unconfounded) causal relations, show more variable play when presented with probabilistic (as opposed to deterministic) information (Schulz, Hooppell, et al., 2008), and can spontaneously disambiguate confounded variables (Schulz & Bonawitz, 2007).

Despite the evidence that anomalous or inconsistent information motivates both explanation and exploration, the way in which the two processes may jointly facilitate or drive causal knowledge acquisition remains underdetermined. Additionally, little is known about the extent to which children spontaneously generate and test hypotheses in the context of free play (Karmiloff-Smith & Inhelder, 1978). Does the process of constructing a causal explanation for inconsistent outcomes inform and constrain children's exploratory behavior? Do causal explanation and exploratory behavior operate in tandem as hypothesis-generating and hypothesis-testing mechanisms? This study was designed to investigate these questions across early childhood.

The present study examines how the process of explaining inconsistency with prior knowledge informs children's exploratory, hypothesis-testing behavior. The objective of the experimental design was to differentiate children's explanations and subsequent exploratory behavior following consistent events from those following inconsistent events. I propose that explaining inconsistency informs the knowledge acquisition process by guiding exploratory behavior. The first hypothesis was that for inconsistent outcomes only, the kind of

explanation provided should differentially predict the kind of exploratory behavior children engage in. The second hypothesis was that the kind of explanation children provide should influence the extent to which children spontaneously engage in exploratory behavior and the extent to which children modify existing explanatory hypotheses in the face of disconfirming evidence.

Two conditions were designed in order to isolate inconsistent events as a trigger for both explanations and exploratory play behavior: an *inconsistent condition*, in which the final trial included an inconsistent outcome, and a *consistent condition*, in which events were always consistent with prior knowledge. The objective was to investigate not only w*hat* children explain and explore but also *how* they do so, by examining whether their explanations and subsequent behavior are concerned only with surface features and imitation, or instead with less-obvious causal mechanisms and category membership.

To address these issues experimentally, a set of novel, experimenter-controlled ''light boxes'' were designed (modeled after Gopnik & Sobel, 2000; Gopnik, Sobel, Schulz, & Glymour, 2001). These materials were used first to teach children briefly about different categories of objects that turned a box on or did nothing. The training objects were given novel labels: *tomas* or *blickets* (which lit the light box when placed on top), and *not-tomas* or *not-blickets* (which neither lit nor unlit the light box). Items within each object category were perceptually identical.

After training, in the inconsistent condition, children were presented with scenarios in which a new object that looked like one type (e.g., it looked like a toma but did not function like a toma, and did not activate the light box) was simultaneously paired with a contrasting object that looked and behaved like those previously seen (e.g., it looked like a toma and behaved like a toma). Upon viewing such paired outcomes, children were asked a nonspecific explanatory question ambiguously referring to either (visible) outcome: ''Why did that happen?'' Children were then given the opportunity to interact with the objects and light boxes. The structure of the consistent condition was identical to the inconsistent condition except that all outcomes were consistent with prior knowledge. If inconsistency with prior knowledge motivates the process of causal knowledge acquisition by guiding exploration, the kind of explanations children provide and the subsequent exploratory behavior they engage in should be mutually informative, and should be more oriented toward generating new information and uncovering underlying causal relations when an inconsistent (as opposed to consistent) outcome is present.

Method

Participants

In order to investigate developmental differences in the relation between explanation and exploration, sixteen 2-year-olds (*M* age = 2.7, range = 2.3–2.11), sixteen 3-year-olds (*M* age = 3.6, range = 3.0–3.11), sixteen 4-year-olds (*M* age = 4.4, range = 4.1–4.7), sixteen 5-year-olds (*M* age = 5.3, range = 5.0–5.8), and sixteen 6-year-olds (*M* age = 6.2, range = 6.0–6.6), were recruited from two university towns. Participants were primarily Euro-American and from middle-class families. Approximately equal numbers of boys and girls participated in the study. Four children were replaced in the course of data collection due to failure to complete the training trial or experimenter error: two 2-year-olds, one 3-year-old, and one 4-year-old.

Materials

A set of four novel light boxes were designed—devices that glowed brightly when activated. The activation of the boxes was experimenter controlled but appeared to be caused by placing an object on top of the boxes (modeled after Gopnik & Sobel, 2000; Gopnik et al., 2001). The identical boxes (5 in. × 5 in. × 5 in.) were made of wood with thin translucent laminate wooden tops. Each pair of boxes (red or yellow) was attached to a switch box that was operated surreptitiously by a confederate. If the switchbox was turned on, the box would light up and stay on until it was switched off. Alternately, if the switchbox was turned off, the box would turn off and stay off until it was switched on. For objects with a causal effect, each box was turned on as soon as an object made contact with it, and would stay on until the object was removed. This yielded the strong impression that some objects turned the boxes on, and some had no effect on the boxes. The switchbox was hidden from the children's view, and none of the participants mentioned the confederate or indicated any suspicion that the confederate influenced the functioning of the boxes. The light boxes were comparable to stimuli developed by Legare et al. (2010).

There were four perceptually distinct sets of objects, as shown in Figure 1, each consisting of 4
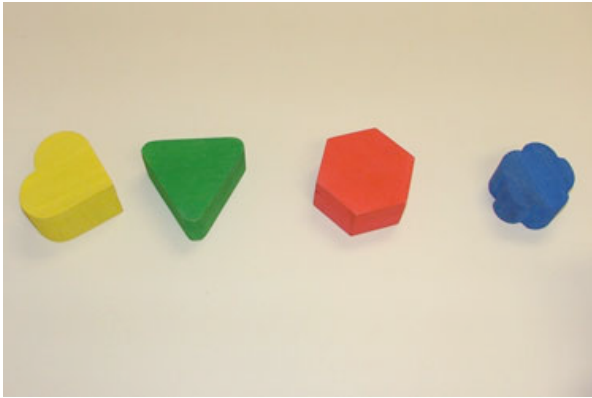
Figure 1. Picture of object stimuli.

identical wooden objects (16 objects total). The objects were wooden containers that, upon close inspection, could be opened. The perceptual features of different kinds of objects were not indicative of the observed causal properties of the objects (lighting or not lighting the boxes). Additionally, the placement of the objects on the boxes was counterbalanced across trials.

Design

Two within-subjects conditions were designed in order to isolate inconsistent events as a trigger for both explanations and exploratory play behavior: an *inconsistent condition*, in which the final trial included an inconsistent outcome, and a *consistent condition*, in which events were always consistent with prior knowledge. An important feature of the design was differentiating children's explanations and subsequent exploratory behavior following consistent events from those following inconsistent events.
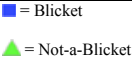
Procedure

Children were tested individually in a session lasting approximately 20 min. The child was seated across from the experimenter and the confederate at a table on which a pair of light boxes was placed. The boxes (either yellow or red, counterbalanced across children) started with the light off. Each child participated in two counterbalanced conditions: an inconsistent condition and a consistent condition. In both conditions, participants began the session with a training trial in which the objects' functions and novel labels were presented individually. During the training trial, an active object was given a novel label (e.g., *blicket* in the

inconsistent condition, *toma* in the consistent condition) and then placed successively on each light box. Upon contact, each light box lit up, and upon removal, each light box turned off. Then, another perceptually identical active object was presented, given the same label, and placed on each light box (in counterbalanced order). As with the first object, the boxes activated only when in contact with the object. After each demonstration, the object was placed on the table. Following the demonstration of two active objects, the procedure was repeated with a demonstration of two inactive objects (e.g., *not-a-blicket* in the inconsistent condition, *not-a-toma* in the consistent condition). Neither inactive object turned the light boxes on.
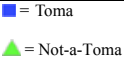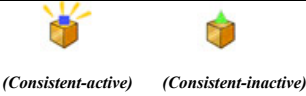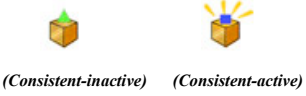
Upon completion of the training trial, the four training objects (two active, two inactive) were removed from the table and the child had no further interaction with those objects. Next, participants took part in two experimental trials. Although the objects in the experimental trials were perceptually identical to the objects seen in the training trial, they were never labeled for the child. The first experimental trial was the confirmation trial. Following the confirmation trial, participants took part in a test trial.

Inconsistent condition. In the first (confirmation) trial, an object that looked like a blicket was placed on one of the light boxes at the same time as an object that looked like it was not-a-blicket was placed on the other light box. The object that looked like a blicket turned the box on and the object that looked like a not-a-blicket had no effect on the box (it remained off). Notably, both outcomes in the confirmation trial were consistent. In the test trial, another object that looked like a blicket was placed on one of the light boxes at the same time as an object that looked like it was not-a-blicket was placed on the other light box. However, unlike the confirmation trial, both light boxes remained off. Thus, a consistent outcome was simultaneously contrasted with an inconsistent outcome. The object that looked like it was not-a-blicket produced an outcome consistent with prior knowledge (light box stayed off), and the object that looked like a blicket produced an outcome inconsistent with prior knowledge (light box failed to turn on; see Figure 2a).

After each of the two experimental trials (confirmation trial and test trial), participants were asked a nondirected explanatory question referring to either visible outcome, ''Why did that happen?'' Children were prompted several times in a nondirected manner after that initial causal question to

a. Inconsistent Condition

b. Consistent Condition

Figure 2. (a) Inconsistent condition. (b) Consistent condition.

provide additional explanatory information. For example, children were asked, ''Can you tell me more?'' or ''Do you have any other ideas?''

One potential pragmatic concern that could be raised is that asking children explicit explanatory questions could bias their attention to the inconsistent outcome. To address this concern with the procedure, children's spontaneous explanations were also analyzed (provided prior to an explicit explanatory question from the experimenter). Namely, if children's spontaneous explanations reflect the same pattern as their elicited explanations, it would be unlikely that children were simply generating the explanation they believed the experimenter was requesting. Replicating results from Legare et al. (2010), for first explanations, spontaneous explanations revealed the same pattern of responses as elicited explanations. Fourteen of 80 children (18%) provided a spontaneous explanation at least once in the test trial. For 93% of the spontaneous explanations, children explained the inconsistent outcome first.

Following the test trial only, children were provided with an unstructured opportunity to interact with the objects (total of four, two from each exper-

imental trial), and asked ''Do you want to play with these?'' During each trial, after demonstrating the outcome of the objects on the light box, the experimenter had placed the objects on a mat in between the light boxes in counterbalanced order (i.e., for half of the participants in each age group the objects from the confirmation trial were placed closest to the child, for the other half of the participants the objects from the test trial were placed closest to the child). During the period of free play following the final (test) trial, both the light boxes and the mat with the four objects were placed in close proximity to the child. During the exploratory play period, the confederate continued to operate the light boxes surreptitiously. Children were given no direction or instructions from the experimenter about how to engage with the stimuli and were allowed to engage in unstructured, free play with the objects and the light boxes until they lost interest or disengaged.

Due to the challenge of accurately controlling the light boxes in the face of rapid and unpredictable placement of the objects on the boxes on the part of the child, the experimenters received extensive training prior to data collection. When a child placed a consistent object on either of the light boxes (operated surreptitiously by the confederate), the consistent objects always produced consistent outcomes. The *consistent-active* object (blicket) always turned the box it was in contact with on, even if a child placed it on the same box as a *consistent-inactive* object (not-a-blicket) or the *inconsistent* (*inactive*) object (the object that looked like a blicket, but did not function like a blicket). Any contact or variation in placement of the consistent-active objects on a box activated the light. With the exception of being paired or combined with the consistent-active object (blicket) on the same light box, the inconsistent object never activated either box. Individual or paired consistent-inactive objects also never activated the boxes.

Consistent condition. Unlike the inconsistent condition, both outcomes in each trial were consistent; there was no inconsistent outcome. The object that looked like a toma turned the box on and the object that looked like it was not-a-toma had no effect on the box (it remained off). In each trial, two new objects were placed on the light boxes in counterbalanced order (see Figure 2b).

As in the inconsistent condition, following each trial, after viewing the paired outcomes of each trial, children were asked a nonspecific explanatory question referring to either visible outcome, ''Why did that happen?'' After the initial explanatory

question, nondirected follow-up questions were asked.

After the final (test) trial only, participants were provided with the same unstructured opportunity to interact with the objects as in the inconsistent condition (total of four, two from each trial). The objects always produced consistent outcomes; consistent-active objects (tomas) always turned the boxes on when placed on top, even if participants placed one on the same box as a consistent-inactive object (not-a-toma). As in the inconsistent condition, any contact or variation in placement of the consistent-active objects on a box activated the light. Individual or paired consistent-inactive objects never turned either of the boxes on.

Transcription and Coding

Interviews were videotaped and transcribed verbatim. In the final test trial in each condition, children's explanations and exploratory behavior were coded for several different kinds of information. Explanations were coded for the kind of explanation provided. Children's exploratory behavior was coded for the amount of time children interacted with the stimuli, the object(s) they played with first, the object(s) they played with most overall, and the kind of exploratory behavior they engaged in. Patterns of spontaneous hypothesis testing were also analyzed and most often took the form of spontaneous explanations or *evidence evaluation statements* that children provided while engaging in exploratory behavior. These hypothesis-testing explanations were most often verbal evaluations of disconfirming evidence and often indicated what the child intended to try next. For example, "Uh oh, nothing! That didn't work! This one lights up, but this one still doesn't. So that means I need to try this different way, like *this*."

Coding causal explanations. For each test trial, children's explanations were coded for content, separately for consistent and inconsistent outcomes. The coding categories were based on work by Legare et al. (2010) using a similar methodology. Causal explanations for inconsistent outcomes were coded into three primary categories: causal function, causal action, and category switch. Explanations that discussed a problem with the functioning of the object were coded as *causal function* explanations. These explanations included reference to the object being broken ("The blicket is not working anymore. It is broken"), the box being broken ("The box does not light anymore. It is broken"), or differences among the objects ("This one is heavier

than the others"). Explanations that referred to insides or internal parts were also included in the causal function category ("There isn't energy power inside" or "All out of batteries"). Explanations that referred to problems using the objects or problems with the placement of the objects were coded as *causal action* explanations ("You set the blicket/toma on the wrong sides" or "It's on the wrong box").

When providing *category switch* explanations, children answered the explanation question by referring to a switch in category membership based on function. For example, "It is not-a-blicket, it doesn't work like a blicket" or "It's not really a blicket; it only looks like one" were coded as category switch explanations. Note that to provide such explanations children had to ignore and go beyond perceptual identities and the past history of perceptually identical objects.

Causal explanations for consistent outcomes were coded into three primary parallel categories: causal function, causal action, and category label. *Causal function* and *causal action* explanations for consistent outcomes were coded using the same criteria as explanations for inconsistent outcomes. Explanations that referred to category membership using a label were coded as *category label* explanations (e.g., "Because this one is a blicket" or "This one is not-a-toma"). Unlike the category switch explanations for inconsistent outcomes, category label explanations involved providing a label that was consistent with the past history of perceptually identical objects.

Coding noncausal explanations. Noncausal explanations for both inconsistent and consistent outcomes were coded into four other categories: expectation violation, descriptive statements, psychological references, and do not know. Explanations that described what could be expected to happen on the basis of appearance or past events without providing a cause were coded as *expectation violation* (e.g., "It wasn't supposed to turn on"). Unlike noncausal explanations for inconsistent outcomes, expectation-violation explanations were not provided and so were not coded for consistent outcomes. Explanations that referred to the criteria children were using as a basis for their conclusion without further explanation of the cause were coded as *descriptive statements* (e.g., "It's not on because it's not glowing up"). Explanations that referred to psychological constructs such as preference or desire (e.g., "Maybe it wanted to") were also recorded, although these were quite rare. If children were unable to provide an explanation or

stated that they did not know, their responses were coded as *do not know*.

Coding exploratory behavior. Coding categories for exploratory behavior were based on extensive review of children's activity during this task. In each condition there were a total of four objects with which children could engage during the exploratory play period (two objects from each trial). In the consistent condition, there were two kinds of objects for the children to explore: consistent active (toma) and consistent inactive (not-a-toma). In the inconsistent condition, there were three kinds of objects for the children to explore: consistent active (blicket), consistent inactive (not-a-blicket), and inconsistent (object that looks like a blicket, but does not function like a blicket). There was only one inconsistent object in the study and, unlike other objects that looked like blickets, the inconsistent object did not turn the light boxes on.

Exploratory behavior was quantified and coded in several ways in both conditions in order to quantify the amount, variability, and objective of children's exploratory behavior.

The amount of time children interacted with the objects and light boxes was recorded as the time elapsed between a child's first opportunity to play and the time when they stopped engaging with the stimuli. The object(s) children touched first were also coded, as well as the object(s) they engaged with most. Engagement with objects was quantified as the number of times they touched each object.

The kind of exploratory behavior children engaged in and the way in which children interacted with individual objects and the light boxes were analyzed for the following variables: whether the child engaged only with the objects or with both the objects and the light boxes, the number of times children placed each individual object on the boxes, the number of times children placed two individual objects simultaneously on the two boxes, the number of times children stacked more than one object on an individual box (next to each other or on top of each other), and the different combinations of individual object placement and stacking that occurred. Individual object pairings were coded based on the kinds of objects available in the control versus the experimental conditions.

Children's spontaneous exploratory behavior was also coded for a variety of potential *hypothesis-testing strategies*. Exploratory behavior of this kind was oriented toward investigating the source of the problem with the inconsistent object and/or how the underlying causal relation functioned. These strategies included stacking or combining a "bro-

ken'' object with a functioning object, trying out different combinations of objects on the light boxes, experimenting with object placement and orientation, switching or substituting the locations of an object pair with each other, engaging with more than one light box, and opening the inconsistent object. A unique code was generated for the presence or absence of each strategy (as 1 or 0, respectively). Exploratory behavior was then coded for combinations of these strategies in order to quantify variability. Variability in exploratory behavior was calculated by creating a summary score of the number of distinct hypothesis-testing strategies each child engaged in.

Sorting behavior consisted of spontaneously placing objects in two different categories based on function after testing each object individually on the boxes. For example, children would first place individual objects on each light box to verify the causal effect of the boxes, and then sort them into two groups on the table in front of them. In the inconsistent condition, children engaging in sorting behavior would place the consistent-active object by itself, label it a blicket, place the other three remaining objects (two consistent-inactive objects, one inconsistent-inactive object) into a pile together and indicate that they were "not-blickets.''

Notably, children's exploratory behavior was self-generated and was not simply a reflection of what they had seen the experimenter do. For example, the experimenter never placed more than one object on a box at a time, never changed the orientation or placement of the objects on the boxes, and never opened or sorted the objects.

Interrater reliability was established by coding 100% of the data. A coding rubric was developed based on extensive review of children's exploratory behavior and two experimenters blind to condition independently coded the presence or absence of each specific behavior with agreement ranging from 94% to 100%. Reliability was also calculated for explanatory coding categories for both consistent and inconsistent outcomes, with Kappas ranging from .84 to .94. All of the Kappas for this coding fall within near-perfect (.80 and above) levels (Landis & Koch, 1977).

Results

As the purpose of the confirmation trial was to remind children of how various objects functioned, and the final test trials in each condition were of primary interest, only data from those trials were

analyzed. Analyses of children's explanations are based on prior work by Legare et al. (2010) and will be presented in the context of the relation between children's explanations and their exploratory behavior. Coding of children's exploratory behavior was based on extensive review of the spontaneous exploration that took place in this task. The amount, kind, and variability of the behavior children engaged in was quantified in order to investigate whether the kind of explanation provided by children (a) predicted the kind of behavior they engaged in during the inconsistent versus consistent condition, and (b) determined whether the children would engage in spontaneous hypothesis-testing behavior and generate new explanatory hypotheses in the face of disconfirming evidence. There were no significant order effects for condition or trial type.

Children's explanations were coded into three primary causal categories: causal function, category switch/category label, and causal action explanations. In the consistent condition, causal function explanations ($M = 0.23$ of 1, $SD = 0.42$), causal action explanations ($M = 0.14$, $SD = 0.35$), and category label explanations ($M = 0.33$, $SD = 0.47$) remained constant across age groups. Importantly, the kind of explanations children provided for outcomes in the consistent condition, or for consistent outcomes in the inconsistent condition, did not predict the amount or kind of exploratory behavior children engaged in. This suggests that causal explanations for consistent outcomes do not differentially predict the quantity and orientation of children's exploratory behavior and that explanation does not always provoke or motivate exploratory behavior in all situations, especially when outcomes are consistent with their expectations.

Table 1 presents the percentage and proportion of total explanations for inconsistent outcomes by

age group. It shows that in the inconsistent condition causal function explanations were most common ($M = 0.40$ of 1, $SD = 0.49$), followed by category switch explanations ($M = 0.25$, $SD = 0.44$) and causal action ($M = 0.11$, $SD = 0.32$) explanations. This trend was found across age groups and replicates prior work by Legare et al. (2010), indicating that causal function explanations are common across all age groups and category switch explanations increase with age.

Table 2 provides an overview of key findings about the relation between the kind of explanation provided for inconsistent outcomes and the amount and kind of exploratory behavior children engaged in. An Age Group (2-, 3-, 4-, 5-, 6-year-olds) × Explanation Type (causal function = 1, causal action = 2, category switch = 3, noncausal = 4) univariate analysis of variance (ANOVA) with age group and explanation type as between-subjects factors, and length of play time as the dependent variable produced a main effect for the kind of explanation provided on length of play, $F(3, 60) = 5.79$, $p = .002$, partial $\eta^2 = .23$. Post hoc tests indicate that children giving causal function explanations played for a longer time than children giving category switch explanations, $p = .002$. This suggests that children were more compelled to explore the objects when they determined there was a problem to be solved (i.e., providing a causal function explanation) than if they merely recategorized the inconsistent object by function, overriding perceptual appearances (i.e., providing a category switch explanation). Importantly, this finding provides direct support for the proposal that for inconsistent outcomes, the kind of explanation children provide predicts the amount of exploratory behavior they engage in (see Table 2). There was no significant age group or Age Group × Explanation Type interaction.

Although the amount of time children played differed based on the kind of explanation they provided, all children were willing to engage with the task. For example, regardless of explanation type and age, children touched each kind of object an equal number of times, and were equally likely to engage with the light box, to place all objects on at least one of the light boxes, and to touch the inconsistent object first.

Importantly, there were differences in the kind of play and patterns of hypothesis-testing behavior based on the kind of explanation children provided. An Age Group (2-, 3-, 4-, 5-, 6-year-olds) × Explanation Type (causal function = 1, causal action = 2, category switch = 3, noncausal = 4)

Table 1

Percentage and Proportion of Total Explanations for Inconsistent Outcomes by Age Group

Age group	Explanation type			
	Causal function	Causal action	Category switch	Noncausal
2	50% (8/16)	6% (1/16)	6% (1/16)	38% (6/16)
3	44% (7/16)	6% (1/16)	19% (3/16)	31% (5/16)
4	50% (8/16)	19% (3/16)	31% (5/16)	0% (0/16)
5	25% (4/16)	6% (1/16)	38% (6/16)	31% (5/16)
6	31% (5/16)	19% (3/16)	31% (5/16)	19% (3/16)

Table 2
Summary of Key Findings About the Relation Between the Kind of Causal Explanation Provided for Inconsistent Outcomes and the Amount and Kind of Exploratory Behavior

Dependent measure	Relation between the kind of causal explanation provided for inconsistent outcomes and dependent measure
Length of play time	Children giving causal function explanations played for a longer time, $p = .002$
Opening inconsistent object	Children were more likely to open inconsistent objects after providing causal function explanations, $p = .006$
Variability in exploratory behavior and engagement in hypothesis-testing strategies	Children giving causal function explanations engaged in more variable play (i.e., multiple hypothesis-testing strategies), $p = .03$
Sorting by kind	Children giving category switch explanations were more likely to sort objects by kind, overriding perceptual appearances, $p = .004$
Evidence evaluation statements	Children giving causal function explanations gave a greater number of evidence evaluation statements during play, $p = .05$

univariate ANOVA with age group and explanation type as between-subjects factors, and whether children spontaneously opened the inconsistent object as the dependent variable produced a main effect for the kind of explanation provided, $F(3, 61) = 4.57$, $p = .006$, partial $\eta^2 = .18$ (see Table 2). Children were more likely to open inconsistent objects when they provided causal function explanations (as opposed to other kinds of causal explanations), $p = .006$. Thirty-one percent of 2-year-olds ($SD = 0.48$), 30% of 3-year-olds ($SD = 0.48$), 43% of 4-year-olds ($SD = 0.53$), 33% of 5-year-olds ($SD = 0.52$), and 56% of 6-year-olds ($SD = 0.52$) spontaneously opened the inconsistent object. Notably, all of the children who opened the object had provided causal function explanations; none of the children giving other kinds of explanations ever opened the inconsistent object. This suggests that causal function explanations in particular were associated with exploration oriented toward uncovering internal mechanisms. This finding also provides evidence that in addition to predicting the amount of play children engage in, children's explanations for inconsistent outcomes differentially predict the *kind* of exploratory behavior children engage in. There was no significant age group or Age Group × Explanation Type interaction.

The same pattern of results was found for variability and potential hypothesis-testing strategies in exploratory behavior. Variability in play was calculated by creating a summary score of the number of hypothesis-testing strategies children engaged in such as stacking or combining a "broken" object with a functioning object, trying out different combinations of objects on the light boxes, experimenting with object placement and orientation,

switching or substituting the locations of an object pair with each other, engaging with more than one light box, and opening the inconsistent object. An Age Group (2-, 3-, 4-, 5-, 6-year-olds) × Explanation Type (causal function = 1, causal action = 2, category switch = 3, noncausal = 4) univariate ANOVA with age group and explanation type as between-subjects factors and variability in play as the dependent variable produced a main effect for the kind of explanation provided, $F(3, 60) = 3.21$, $p = .03$, partial $\eta^2 = .14$ (see Table 2). Post hoc tests indicated that children giving causal function explanations engaged in more variable play (i.e., used a larger number of hypothesis-testing strategies) than those providing category switch explanations, $p = .03$ (see Table 2). Table 3 shows that this was true across age groups; overall, the mean number of hypothesis-testing strategies used during exploration of inconsistent outcomes was highest for

Table 3
Mean Number of Hypothesis-Testing Strategies Used During Exploration of Inconsistent Outcomes by Age Group and Explanation Type

Age group	Explanation type			
	Causal function	Causal action	Category switch	Noncausal
2	3.69 (1.54)	0 (0)	3.0 (0)	2.5 (2.12)
3	3.1 (1.60)	3.0 (0)	0.5 (0.71)	2.33 (1.5)
4	4.4 (3.69)	2.67 (3.79)	2.8 (1.64)	1.0 (0)
5	4.5 (3.14)	6.0 (0)	3.8 (1.3)	2.0 (0.82)
6	5.89 (3.78)	5.0 (2.82)	4.25 (1.5)	0 (0)
Total	4.22 (2.78)	3.86 (2.85)	3.18 (1.70)	1.91 (1.3)

Note. Standard deviations are in parentheses.

children providing causal function explanations at each age group. Additionally, of the six children that spontaneously asked the experimenter for additional objects to explore, presumably as additional sources of information, all of these children had provided causal function explanations (and all requests occurred in the inconsistent condition). There was no significant age group or Age Group × Explanation Type interaction.

Spontaneous sorting by kind (i.e., blickets vs. nonblickets) was analyzed as a function of explanation type. For inconsistent outcomes, the blicket group consisted of only one object (active consistent) and the nonblicket group consisted of three objects (two inactive-consistent objects and one active-inconsistent object). An Age Group (2-, 3-, 4-, 5-, 6-year-olds) × Explanation Type (causal function = 1, causal action = 2, category switch = 3, noncausal = 4) univariate ANOVA with age group and explanation type as between-subjects factors, and sorting of objects as the dependent variable produced a main effect for kind of explanation provided on whether children spontaneously sorted objects by kind based on function, $F(3, 60) = 3.49$, $p = .02$, partial $\eta^2 = .15$. Post hoc tests indicated that children who gave category switch explanations were more likely to sort objects by kind than were children who gave causal function explanations, $p = .004$, and noncausal or no explanations, $p = .012$ (see Table 2). Twenty percent of 3-year-olds ($SD = 0.45$), 60% of 4-year-olds ($SD = 0.55$), 17% of 5-year-olds ($SD = 0.41$), and 40% of 6-year-olds ($SD = 0.55$) giving category switch explanations spontaneously sorted by kind. Notably, sorting by kind never occurred when children provided explanations other than category switch explanations. There was no significant age group or Age Group × Explanation Type interaction.

Spontaneous evidence evaluation statements during the course of exploratory play were analyzed based on the kind of initial explanation provided. An Age Group (2-, 3-, 4-, 5-, 6-year-olds) × Explanation Type (causal function = 1, causal action = 2, category switch = 3, noncausal = 4) univariate ANOVA with age group and explanation type as between-subjects factors, and the number of evidence evaluation statements as the dependent variable produced a main effect for the kind of explanation provided, $F(3, 60) = 3.36$, $p = .03$, partial $\eta^2 = .14$. Table 4 shows the mean number of evidence evaluation statements for inconsistent outcomes by age group and explanation type. When the same analysis was run with the number of times exploratory play followed an evidence evaluation statement as the dependent variable, there was also a significant main effect for the kind of explanation provided, $F(3, 60) = 6.84$, $p = .001$, partial $\eta^2 = .26$. Table 5 shows the proportion of time exploratory play followed evidence evaluation statements for inconsistent outcomes by age group and explanation type. Post hoc tests indicated that children giving causal function explanations gave a greater number of evidence evaluation statements during play than children giving category switch or noncausal explanations, $ps < .05$, and exploratory behavior was more likely to follow evidence evaluation statements for children providing a causal function than a category switch explanation, $p = .05$. Exploratory behavior was more likely to follow all kinds of causal explanations than noncausal explanations, $ps < .05$ (see Table 2). There was no significant age group or Age Group × Explanation Type interaction for either analysis.

Table 4

Mean Number of Evidence Evaluation Statements for Inconsistent Outcomes by Age Group and Explanation Type

Age group	Explanation type			
	Causal function	Causal action	Category switch	Noncausal
2	2.63 (2.07)	2.00 (0)	1.00 (0)	1.26 (1.20)
3	2.71 (2.36)	0 (0)	0.33 (0.58)	1.0 (2.24)
4	1.14 (0.38)	3.33 (4.04)	0.80 (1.30)	0 (0)
5	2.25 (3.3)	1.0 (0)	0.67 (0.82)	1.00 (1.0)
6	3.8 (2.68)	4.67 (3.06)	3.0 (2.12)	0 (0)
Total	2.45 (2.21)	3.00 (3.04)	1.25 (1.62)	0.80 (1.36)

Note. Standard deviations are in parentheses.

Table 5

Proportion of Time Exploratory Play Followed Evidence Evaluation Statements for Inconsistent Outcomes by Age Group and Explanation Type

Age group	Explanation type			
	Causal function	Causal action	Category switch	Noncausal
2	0.88 (0.35)	1.00 (0)	1.00 (0)	0.50 (0.55)
3	1.0 (0)	0 (0)	0.33 (0.58)	0.20 (0.45)
4	1.0 (0)	1.0 (1.0)	0.40 (0.58)	0 (0)
5	0.25 (0.5)	1.0 (0)	0.33 (0.52)	0.60 (0.55)
6	1.0 (0)	1.0 (0)	0.80 (0.45)	0 (0)
Total	0.87 (0.34)	0.89 (0.33)	0.50 (0.51)	0.35 (0.49)

Note. Standard deviations are in parentheses.

Discussion

There is mounting evidence that engaging in explanation facilitates causal knowledge acquisition and promotes causal learning (De Leeuw & Chi, 2003; Lombrozo, 2006). However, less is known about how explanation informs this process. This study provides support for the proposal that one mechanism by which explanation may enhance causal knowledge acquisition is by informing the process of exploring inconsistent outcomes and revealing underlying causal relations and properties.

The data provide support for the two primary predictions based on this proposal. The kind of explanation provided for inconsistent outcomes differentially predicted the kind of exploratory behavior children engaged in (as opposed to consistent outcomes). Focally, the results provide insight into the relation between inconsistency, explanation, and exploration. The data support a mediating role of explanation in the relation between inconsistency with prior knowledge and exploratory behavior oriented toward discovering underlying causal mechanisms and relations.

For inconsistent outcomes only, children's exploratory behavior was informed by the kind of causal explanation they provided, demonstrating that exploratory behavior was driven by an interest in testing, and in some cases confirming, explanatory hypotheses. The kind of causal explanation children provided differentially informed (and predicted) both the amount and kind of exploratory play children engaged in. For example, causal function explanations were associated with the most play and the most variable play. Children providing causal function explanations engaged in a greater number of hypothesis-testing strategies such as playing with more than one light box, stacking or combining a ''broken'' object with a functioning object, trying out different combinations of objects, experimenting with multiple orientations of objects, and opening the inconsistent object. This kind of exploratory behavior is consistent with an attempt to discover the source of a problematic outcome. Causal function explanations also predicted behavior consistent with a search for an internal mechanism; children only spontaneously opened inconsistent objects following a causal function explanation.

The kind of explanation children provided also influenced the extent to which children engaged in spontaneous hypothesis-testing and modified existing explanatory hypotheses in the face of disconfirming evidence. For example, the majority of children providing causal function explanations spontaneously tested multiple different hypotheses when faced with disconfirming evidence and in the process of doing so produced multiple spontaneous evidence evaluation statements, modified their exploratory behavior to accommodate inconsistent information, and generated new explanatory hypotheses. Importantly, young children spontaneously generated and tested explanatory hypotheses for inconsistent outcomes in the context of unstructured free play.

Notably, there were no substantive age-related changes in the kind of exploratory behavior children engaged in during this experimental task. Although on the one hand this indicates that the results are robust across age groups, and that even 2-year-olds can engage in spontaneous hypothesis-testing behavior in sufficiently constrained tasks, on the other hand, it is likely that the relatively straightforward and simple experimental paradigm made developmental differences difficult to detect. In future work, more complex tasks could be designed in order to investigate developmental improvements in hypotheses-testing strategies.

It is worth emphasizing that exploratory behavior is not exclusively a reflection of children's explanatory hypotheses and, instead, that causal explanation and exploratory behavior operate in tandem as hypothesis-generating and hypothesis-testing mechanisms. As Karmiloff-Smith and Inhelder (1978, p. 207) note, ''Action sequences are not merely a reflection of the child's implicit theories. The very organization and reorganization of the actions themselves, the lengthening of their sequences, their repetition and generalized application to new situations give rise to discoveries that will regulate the theories, just as the theories have a regulating effect on the action sequences.'' Isolating the unique contributions of explanation, exploration, and observation on learning would thus be an informative direction for future research.

An additional implication of these data is that the kind of explanation children construct can be both advantageous and disadvantageous from the perspective of acquiring new information (Kuhn, 2009). Indeed, explanation may at times be conducive to theory-preserving strategies such as misinterpreting evidence as more consistent than it actually is. In addition to influencing the kind of exploratory behavior they engaged in, the kind of explanation children provided influenced the extent to which they perceived evidence as inconsistent or not. For example, category switch explanations were associated with the least overall play and a

specific kind of sorting behavior in which children spontaneously sorted by kind. One potential explanation for this kind of behavior is that children giving category switch explanations had decided that kind membership was based on function instead of perceptual appearance, and upon verifying category membership, had little interest in exploring the underlying causal mechanism further. In fact, it is possible that children giving category switch explanations did not interpret the object that violated expectations as inconsistent per se and instead engaged almost exclusively in behavior that would confirm their explanatory hypothesis.

In sum, this study provides empirical evidence that one mechanism by which explaining inconsistency promotes discovery is by guiding exploratory, hypothesis-testing behavior, and is consistent with the possibility that explanation serves as a mechanism for generating hypotheses and exploration serves as a mechanism for testing explanatory hypotheses. Indeed, the relation between causal explanation and exploratory behavior provides information about how inconsistency with prior knowledge triggers the process of knowledge acquisition and supports the role of explanation in discovery. Evidence that explanation serves a mediating role in the relation between inconsistency with prior knowledge and exploration took several forms. For inconsistent outcomes only, the kind of explanation provided by children predicted the kind of exploratory behavior they engaged in; children played considerably longer and engaged in more sophisticated exploratory play when an inconsistent versus a consistent event was present, and when faced with inconsistent outcomes children modified their hypotheses by engaging in different kinds of exploratory behavior. Although the present experiments do not directly assess learning, they provide a promising empirical basis for investigating the interplay of explanation, exploration, and learning in ongoing and future research.

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