The Contributions of Explanation and Exploration to Children’s Scientific Reasoning

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Word count: 2,791
Abstract

There is substantial evidence that explanation and exploration can both foster causal learning, yet the mechanisms underlying these effects are largely unknown, especially in early childhood. The objective of this paper is to provide an overview of new research on the relationship between explanation, exploration, and the development of scientific reasoning. I propose that explaining and exploring operate in tandem as hypothesis-generating and hypothesis-testing mechanisms. I review evidence in support of this claim by demonstrating that inconsistency with prior knowledge selectively motivates children to construct explanations, guides discovery-oriented behavior, and drives the early developing capacity to reason scientifically. I conclude with a discussion of the educational applications of research on the development of children’s scientific reasoning in informal learning settings.

Keywords: CAUSAL REASONING, CHILDREN’S MUSEUMS; COGNITIVE DEVELOPMENT; EARLY CHILDHOOD; EARLY SCIENCE LEARNING; EXPLANATION; EXPLORATION; GENERALIZATION; INFORMAL LEARNING; SCIENCE MUSEUMS; SCIENTIFIC REASONING; SELF-EXPLANATION
The Contributions of Explanation and Exploration to Children’s Scientific Reasoning

Young children are characteristically curious; they explain unexpected phenomena (Legare, Gelman, & Wellman, 2010), and explore causal connections through play (Legare, 2012; Schulz & Bonawitz, 2007). Explaining and exploring are crucial components of the scientific process and thus determining how young children engage in early scientific reasoning is critical for teaching science at any level of education (Gelman, Brenneman, Macdonald, & Roman, 2010).

Despite the often unstructured and unsystematic appearance of children’s explanations and exploration, a large literature supports the proposal that these behaviors facilitate learning (Amsterlaw & Wellman, 2006; Crowley & Siegler, 1999; Nicolopoulou, 2010; Rittle-Johnson, Saylor, & Swygert, 2007; Siegler, 1995; Singer, Golinkoff, & Hirsh-Pasek, 2006). For example, there is evidence that generating explanations can improve causal learning and promote generalization (Lombrozo, 2006; Wellman, 2011). Research on children’s play also provides evidence that children can effectively learn from spontaneous exploration (Baldwin, Markman, & Melartin, 1993; Bonawitz, van Schijndel, Friel, & Schulz, 2012). Children’s exploration helps to generate evidence relevant to disambiguating different causal variables (Cook, Goodman, & Schulz, 2011; Schulz & Bonawitz, 2007), and appears to be most effective when directed towards explaining inconsistent outcomes as opposed to confirming previous observations (Legare, 2012).

Although there is strong evidence that explanation and exploration can both confer learning benefits, the mechanisms underlying these effects are largely unknown, especially in early childhood. The objective of this paper is to provide an overview of new research on the relationship between explanation, exploration, and scientific reasoning. First, I will discuss
evidence that generating explanations and engaging in exploration may uniquely and selectively benefit causal learning. Second, I will provide evidence for the proposal that explaining and exploring are not mutually exclusive in spontaneous conversation and play but instead that they may operate in tandem as hypothesis-generating and hypothesis-testing mechanisms. Finally, I will motivate the need for future research on the relationship between explanation, exploration, and causal learning and will review the educational applications of research on the development of scientific reasoning in informal learning settings.

**Explanation and Causal Learning**

Relatively little is known about the ways in which engaging in the process of explanation is unique in its effects on learning (i.e., the ways in which they differ from other processes) and the ways in which they are selective (i.e., whether and how their effects are targeted to particular kinds of learning) in early childhood. In the context of this review, I define explanation as an attempt to understand a causal relationship by identifying relevant functional or mechanistic information (Kelemen, 1999; Legare et al., 2010; Lombrozo, 2009; Lombrozo & Carey, 2006). There is growing interest in the extent to which the learning benefits of self-explanation are unique compared to other cognitive processes (e.g., observation or description) (see Lombrozo, 2012). Could self-explanation— that is, explaining to oneself or another person – exert effects by increasing general attention or engagement rather than recruiting mechanisms specific to the construction or evaluation of explanation (Chi, 2009)? New work supports the proposal that the effects of explanation are in fact unique. For example, there is evidence from recent developmental research demonstrating that the learning benefits of explanation may be unique from comparison activities that require similar amounts of times and effort (McEldoon, Durkin,
What might be responsible for these unique effects? One possibility is that the process of engaging in explanation constrains children to selectively focus on identifying causal mechanisms (Keil, 2006; Legare, 2012) and making broad generalizations (Williams & Lombrozo, 2010). Recent work also demonstrates that a prompt to explain can lead even young children to posit unobserved causes, internal mechanisms, and causal functions (Legare et al., 2010; Legare, Wellman, & Gelman, 2009) and favor generalizations that account for more observations (Walker, Williams, Lombrozo, & Gopnik, 2012), suggesting that prompts to explain might guide children towards underlying causal patterns (Walker, Lombrozo, Legare, & Gopnik, 2013).

In recent work, Legare and Lombrozo (2011) have studied how and why explanation influences learning in young children, by investigating the unique and selective effects of explanation compared to other tasks that require equivalent cognitive engagement. In particular, they have examined how explanation differs from the spontaneous processing of information that occurs during observation, and from other processes that require constructive engagement, such as description. This work aimed to address two questions. First, does explanation provide unique leverage in learning about a causal system? Second, to what extent does explanation result in general benefits for learning as opposed to highly selective benefits, or even potential costs?

To examine these questions, preschool-aged children were presented with a novel mechanical toy involving visible interlocking gears and their learning was examined using a variety of measures. The measures assessed learning about the toy’s functional-mechanical relationships, learning about the toy’s non-functional properties (such as color), and generalizing
the toy’s function and mechanism in constructing a novel toy. In Study 1, learning was assessed as a function of two between-subjects conditions in which the kind of behavior children engaged in was experimentally manipulated (explain only, observe only). In Study 2, learning was assessed as a function of type of verbal response, with children’s spontaneous utterances coded for the presence of explanations. Dependent measures included the extent to which children (a) understood the machine’s functional-mechanical relationships, (b) remembered perceptual features of the machine, (c) successfully reconstructed the machine, and, for Study 2 only, (d) generalized the function of the machine in constructing a novel machine.

The results of this research provide evidence that explanation is especially useful for learning causal mechanisms and supporting generalization, but does not improve memory for functionally irrelevant, perceptual details. An additional contribution of this work is that it demonstrates that self-explanations facilitate children’s learning in the absence of explanatory feedback from others. In previous studies on self-explanations, children are asked to explain the feedback of others such as why an answer is correct, or why a strategy is effective (Crowley & Siegler, 1999; Rittle-Johnson et al., 2008).

There is converging support from research with older children and adults that the effects of explanation are selective. There is some evidence that explanation can foster analogical transfer at the expense of memory for previous problems (Needham & Begg, 1991), and may lead to overgeneralization errors by privileging (a) patterns over individual examples (Williams, Lombrozo, & Rehder, 2013) and (b) consistency with data in justifying causal judgments (Berthold, Roder, Knorzer, Kessler, & Renkl, 2011; Kuhn & Katz, 2009). When adults are asked to explain an event, they often seek information about causal mechanisms (Keil, 2006), and prompting adults to explain can foster the discovery and generalization of broad patterns
(Williams & Lombrozo, 2010, 2013) at the expense of individual examples (Williams, Lombrozo, & Rehder, 2013).

Exploration and Causal Learning

As with explanation, relatively little is known about the ways in which the process of exploration may have unique and selective learning benefits in early childhood. This is surprising given that exploration is considered crucial for cognitive development in early childhood (Singer et al., 2006). Evidence does suggest that both infants and preschoolers can effectively learn from spontaneous exploration (Baldwin et al., 1993; Bonawitz et al., 2012; Needham, 2009; Schulz & Bonawitz, 2007) and that they learn more from their own intervention on a causal system than from those of others (Kushnir, Wellman, & Gelman, 2009).

Yet despite evidence for the relationship between children’s exploratory behavior and scientific reasoning (Gelman et al., 2010; Hirsh-Pasek, Golinkoff, Berk, & Singer, 2009; Singer et al., 2006), research in science education with older children has found that children and adults have difficulty designing informative, controlled interventions and are poor at anticipating the type of evidence that would support or undermine causal hypotheses (Masnick & Klahr, 2003). There is much about formal science learning, however, that is unlike exploratory learning in early childhood (Bonawitz, et al., 2012). Although the ability to engage in some of the precursors of scientific reasoning emerges in early childhood (Gopnik & Schulz, 2007), some aspects of scientific thinking require extensive formal science education and remain difficult even in adulthood. Unlike many of the tasks that are used in science education research, which typically require suspending prior beliefs and reasoning from statistical data, everyday causal reasoning often requires integrating prior beliefs and evidence. There is now a large body of research demonstrating that even preschool children are capable of integrating prior knowledge with
statistical information to make accurate causal judgments (Gopnik & Schulz, 2007). An important topic for future research is to examine the relationship between children’s early developing and untutored proclivities for explanation and exploration, and the development of scientific skills that require formal education and training.

**Explanation and Exploration Work in Tandem**

I propose that explanation and exploration operate synergistically: explanation serves as a mechanism for generating, constraining, and evaluating hypotheses, and exploration serves as a mechanism for testing them. Recent research suggests that these two key components of scientific reasoning are connected in the context of causal learning settings (Bonawitz et al., 2012; Legare, 2012). One possibility is that explanation and exploration are especially powerful in early childhood because they serve as mechanisms by which children succeed in going beyond concrete appearances to recognize abstract structure, such as causal relationships.

Despite the evidence that anomalous or inconsistent information motivates both explanation (Legare, et al., 2010, Legare, 2012) and exploration (Schulz & Bonawitz, 2007), the way in which the two processes may jointly facilitate or drive causal knowledge acquisition remains underspecified. Additionally, little is known about the extent to which children spontaneously generate and test hypotheses in the context of free play (Legare, 2012). 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 synergistically as hypothesis-generating and hypothesis-testing mechanisms? Is this process associated with tangible learning outcomes?

I propose that encouraging children to explain inconsistency confronts children with the inconsistent evidence most likely to foster theory revision, guides the hypothesis-testing process,
and promotes learning. These explanatory intuitions may constrain learners to focus on some aspects of what they are trying to understand over others. Young children readily form expectations for causal regularities based on prior knowledge (even when sparse) (Gopnik & Schulz, 2007), and thus children may be highly motivated to attend to irregular or discordant information. Information that is inconsistent with how they expect things to happen is especially informative because it indicates that their prior knowledge about a causal relationship or outcome is incomplete or inaccurate. Therefore, children may be vigilantly attentive to, and more likely to attempt to explain, disconfirmatory outcomes. Engaging in explanation allows children the opportunity to examine and reconcile inconsistent information in the context of prior beliefs through a dynamic process of hypothesis-testing and hypothesis-revision.

There is increasing empirical support for this proposal. Children learn better when their exploration uncovers new knowledge as opposed to confirming information they have already observed (Legare, 2012; Sobel & Sommerville, 2009). Children explore more when shown ambiguous data (Schulz & Bonawitz, 2007) and explore in systematic ways to resolve ambiguity (Cook, Goodman, & Schulz, 2011), seemingly trying to discover explanations for unusual or unexpected events (Legare et al., 2010). There is also evidence that explaining inconsistency informs the knowledge acquisition process by guiding exploratory behavior; for inconsistent outcomes only, the kind of explanation children generate differentially predicts the kind of exploratory behavior children engage in. The kind of explanation children provide also predicts the rate of spontaneous, hypothesis-testing exploratory behavior and the tendency to modify existing explanatory hypotheses in the face of disconfirming evidence (Legare, 2012).

There are a number of ways in which explanation and exploration may operate in tandem. One possibility is that children iterate back and forth between exploration and explanation in the
service of testing the truth-value of their explanatory hypotheses and thus that explanation and exploration are complementary processes. For example, generating explanations may lead to more targeted subsequent exploration and thus may produce the kind of feedback necessary for hypothesis-revision (Legare, 2012). Prior knowledge and learning goals likely play important roles in how information is interpreted and how conclusions are drawn as well as influencing the optimal temporal sequence of these behaviors, such as “explain first, then explore”. Thus, examining the reciprocal and complementary contributions of explanation and exploration to the development of scientific reasoning requires understanding what motivates children to engage in the discovery process, what their background knowledge is, and what the desired learning outcomes are. An important topic for future research is to examine the conditions under which direct instruction can be integrated with discovery learning in educationally optimal ways. Under certain conditions, there is evidence that children benefit from direct instruction to a similar extent as both self-explanation (Crowley & Sigler, 1999) and self-discovery (Dean & Kuhn, 2007; Klahr & Nigam, 2004). Another fruitful topic for future research is to examine the extent to which exploration and explanation may operate differently across different domains. For example, the kind of evidence children have access to through direct exploration may be different for physical versus biological or psychological processes.

**Explanation and Exploration in Early Science Learning Environments**

There is evidence from laboratory-based studies that young children have sophisticated capacities to both explain and explore, however, the extent to which these capacities translate to formal or informal learning environments is understudied. The literature examining children’s scientific reasoning suggests that preschoolers do not consistently engage in systematic hypothesis testing, nor do they demonstrate consistent understanding of the relation between data
and conclusions or how to design unconfounded tests of causal relations (Dean & Kuhn, 2007; Klahr & Nigam, 2004). The learning objectives of informal science learning environments include the development of intuitive understanding of science content knowledge – concepts, explanations, models, and facts – through an increased store of firsthand experience. There is much to be gained by examining how to use explanation and exploration to structure engagement with learning environments to optimize learning, reasoning, and problem solving. I propose that explanation provides a means to practice reasoning scientifically, thinking logically, and connecting new ideas to prior knowledge. Explanation elucidates relationships by constraining and guiding exploration, and provides opportunities for making predictions and formulating new hypotheses (Legare, 2012; Legare, et al., 2010). Conducting research in children’s science museums also allows researchers to examine the extent to which the use of explanation in the context of informal learning increases intuitive understanding of basic natural science and engineering concepts.

Given the proposed interaction between explanation and exploration, the informal learning environments of children’s museums provide an ideal setting for research on this topic. Children’s museums are designed to promote exploration (Gaskins, 2008) and parent-child conversations (Callanan & Jipson, 2001). Research in informal learning environments allows scientists to study the interaction between children’s cognition and the social context of family interactions and conversations (Benjamin, Haden, & Wilkerson, 2010; Callanan & Oakes, 1992; Callanan & Jipson, 2001; Gaskins, 2008; Frazier, Gelman, & Wellman, 2009). Museums also provide opportunities to investigate diversity in children’s social learning experiences, providing information needed to advance our understanding of how to broaden participation in science learning.
Working with children’s science museums has the potential to make both basic contributions to our understanding of causal learning and scientific reasoning and applied contributions to our understanding of how to use explanation and exploration to maximize engagement in informal learning contexts. A compelling direction for future research is to link the social nature of exploration and explanation with measures of children’s conceptual understanding by focusing on family interaction. Another interesting direction for future research would be to examine how explanation and exploration interact in informal settings and how they relate to children’s learning using principles of design-based research (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003).

**Summary**

The way in which evidence is gathered through exploration and understood through explanation provides unique insight into the development of scientific reasoning. Recent developmental research sheds light on the cognitive processes by which explanation and exploration work in tandem to lead to novel understanding. There is evidence that inconsistency with prior knowledge selectively motivates children to construct explanations (Legare & Gelman, 2014; Legare et al., 2010), guides discovery-oriented behavior, and constrains the early developing capacity to reason scientifically (Legare, 2012). Although many questions remain for future research, new findings help lay the foundation for a more comprehensive understanding of the contributions of explanation and exploration to the development of scientific reasoning, and inform design-based research on how to harness the potential of each process for more effective early science education. This research has potential applications in informal learning environments such as children’s museums and should be informed by examining the occurrence of explanation and exploration in children’s learning across a variety of sociocultural settings.
References


