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The Development of Causal Reasoning

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Abstract and Keywords

Research on the development of causal reasoning has broadly focused on accomplishing two goals: understanding the origins of causal reasoning, and examining how causal reasoning changes with development. This chapter reviews evidence and theory that aim to fulfill both of these objectives. In the first section, it focuses on the research that explores the possible precedents for recognizing causal events in the world, reviewing evidence for three distinct mechanisms in early causal reasoning: physical launching events, agents and their actions, and covariation information. The second portion of the chapter examines the question of how older children learn about specific causal relationships. It focuses on the role of patterns of statistical evidence in guiding learning about causal structure, suggesting that even very young children leverage strong inductive biases with patterns of data to inform their inferences about causal events, and discussing ways in which children's spontaneous play supports causal learning.

Keywords: development, causal reasoning, learning, induction, bias

Causality plays a fundamental role in human cognition, and has long been a topic of interest for many developmental researchers—causal reasoning has been proposed to be a central aspect of early learning in the physical (Baillargeon, 2004; Carey, 2009; Cohen, Amsel, Redford, & Casasola, 1998; Leslie, 1995; Spelke, 1990), psychological (Csibra & Gergely, 1998; Gopnik & Wellman, 1992; Meltzoff, 2007; White, 2014; Woodward, 2009), and biological world (Carey, 2009; Wellman & Gelman, 1992). Moreover, causal reasoning has been implicated in many theories of early social development, including developing notions of and theory of mind (Gopnik & Wellman, 2012) and morality (Cushman, 2008; Hamlin, 2013). Causal representations are also central to many linguistic theories of meaning (Jackendoff, 1990; Levin & Rappaport Hovav, 1995) and have been an area of interest in research on early language acquisition (Fisher, Hall, Rakowitz, & Gleitman, 1994; Naigles, 1990). Finally, researchers have studied the role of causal learning in the development of explanations (Legare, 2012; Rozenblit & Keil, 2002).

Research on the development of causal reasoning has broadly focused on accomplishing two goals: understanding the origins of causal reasoning, as well as how causal reasoning changes with development. Consequently, in this chapter, we review evidence and theory that aim to fulfill both of these objectives. In the first section, we focus on the research that explores the possible precedents for recognizing causal events in the world. How are early notions of possible causal relationship related to a broader abstract framework for recognizing events as causal? We review evidence for three distinct mechanisms in early causal reasoning—physical launching events, agents and their actions,[1] and covariation information—and discuss how these mechanisms might be integrated across development. In the second portion of the chapter, we focus on the question of how older children learn about specific causal relationships. Taking for granted that children recognize an event as involving a causal relation, how do (p. 678) children learn about the specific strengths and properties of causes and effects in a system? We focus on the role of patterns of statistical evidence in guiding learning about causal structure and point to evidence that shows that children integrate this evidence with their developing inductive biases.

Origins of Causal Reasoning

One of the hallmarks of mature causal reasoning is that adults can learn the causal structure of any kind of event in the world, ranging from how viruses cause disease to how human behavior influences global warming. In short, adult causal cognition is abstract and domain-general: there are no limits on the kinds of causal structures we can represent. Knowing that event A precedes event B warrants the potential conclusion that event A *caused* event B. What are the origins of such an ability? One might assume that this feature of mature causal reasoning is continuous throughout development—young children and perhaps even infants may also hold abstract, domain-general beliefs about causal relations in the world.

Yet, despite general agreement about the domain-generality of adult causal reasoning, developmental research suggests that there may be three potential early notions of causation in infancy: (1) the transfer of physical force between objects, (2) the outcomes of goal-directed actions produced by dispositional agents, and (3) the ability to track covariation relations between events. This research raises broad questions concerning the development of causal reasoning. How are these notions of causality related in early childhood development? Do infants integrate all three notions of causation across development? Alternatively, is one of these notions primary in development, and if so, does it serve as a starting point for the development of abstract causal reasoning?

Causal Reasoning Emerges from Representations of Motion Events

The majority of research investigating the development of causal reasoning has focused on infants' representations of caused motion events. These findings originated with systematic psychophysical investigations by Michotte (1963), and have been replicated by several other research groups in more recent years (Schlottmann, Ray, Mitchell, & Demetriou, 2006; Scholl & Nakayama, 2002, 2004; White, 1995, Chapter 14 in this volume). In the prototypical causal motion event, object A approaches and contacts object B, immediately after which object B begins to move. To adults, this event automatically gives rise to the impression that object A *caused* object B to move. In particular, research has shown that this impression depends upon the spatial and temporal features of the event. If object A stops short of object B before it moves (spatial gap), or if object B moves after a short delay from point of contact with object A (temporal gap), adults do not perceive the interaction as causal. These impressions are as automatic as many other illusions in vision research. Just as participants cannot help but see that one arrow is longer than the other in the Muller-Lyer illusion (Muller-Lyer, 1889), participants cannot help but view object A as the cause of object B's motion, even though both "objects" are really only colored discs on a computer screen and partake in no actual causal interaction.

Much of the early research on infant causal reasoning has similarly investigated the conditions under which infants perceive events as causal interactions between objects. Three general findings have emerged from this research. First, infants' perception of motion events is sensitive to the same spatial and temporal features that influence adult causal perception (Belanger & Desrochers, 2001; Cohen & Amsel, 1998; Cohen & Oakes, 1993; Leslie, 1982, 1984a; Leslie & Keeble, 1987; Mascalzoni, Regolin, Vallortigara, & Simion, 2013; Newman, Choi, Wynn, & Scholl, 2008; Oakes, 1994; Oakes & Cohen, 1990). For example, using a looking-time paradigm, Cohen and Amsel (1998) habituated 4-, 5.5-, and 6.25-month-old infants to either the prototypical causal motion event or to non-causal motion events that had either a spatial or temporal gap. Infants were then presented with all three events (causal motion event, spatial gap, temporal gap) at test. At 4 months of age, the youngest age tested, Cohen and Amsel (1998) found that infants preferred to look at the causal events, regardless of the event to which they were habituated. However, by 6.25 months of age, infants who were habituated to the prototypical motion event increased their looking time to both the gap and delayed motion events.

These findings suggest that 6-month-old infants were sensitive to the change in causality between the habituation and test phase. An alternative interpretation, however, is that infants simply detected changes in either the spatial or temporal features of a motion event. Support for the former interpretation came from infants who were habituated to either the spatial gap or temporal gap events—events that adults typically do not perceive as causal interactions. Cohen and Amsel (1998) found that infants in these conditions increased their looking time to (p. 679) the prototypical "causal" motion event, while maintaining decreased looking time to the other "non-causal" event to which they were not habituated (spatial or temporal gap). This looking-time pattern occurred despite the fact that switching between the non-causal events involved more featural changes than switching from a non-causal to a causal event. For example, the change from a spatial gap event to a temporal gap event involves both a spatial *and* temporal change; switching from the spatial or temporal gap to the causal event involves only one change (spatial or temporal change). Therefore, by around 6 months of age, infants appear able to categorically perceive motion events along causal dimensions in addition to spatial and temporal dimensions (see also Oakes, 1994, for similar results with 7-month-old infants).

Second, infants' causal representations support causal inference, in addition to causal perception (Ball, 1973; Kotovksy & Baillargeon, 1998, 2000; Muentener & Carey, 2010). For example, Kotovsky and Baillargeon (2000) have shown that infants as young as 7 months of age can infer causal violations between moving objects, even if they do not see the precise moment of contact between the objects. In these studies, infants viewed a scene in which one object stood at the top of the ramp; when released, the object would roll down the ramp toward a second object. For some infants (no contact condition), a solid wall stood at the bottom of the ramp, such that the first object could not hit the second object. For other infants (contact condition), the bottom portion of the wall was removed so that the first object could contact the second object. A black screen was then placed over the point of potential contact between the objects, and infants viewed one of two types of test events. In one test event, the first object rolled down the ramp, disappeared behind the wall, and the second object remained stationary. In the second test event, the first object rolled down the ramp, disappeared behind the wall, and the second object then began to move across the stage.

Infants' looking times were consistent with a causal interpretation of the scene. When the second object moved, infants looked longer in the no contact condition, in which the solid wall should have blocked the point of contact, than in the contact condition, in which the physical interaction should have occurred and caused the second object to move. When the second object remained stationary, however, infants looked longer in the contact condition, in which the second object should have been caused to move, than in the no contact condition, in which the inferred lack of contact between objects explained the lack of subsequent motion. Thus, discussions of infants' causal reasoning abilities are aptly named; infants not only directly perceive physical interactions between objects in a causal nature, they also can make inferences about potential causal interactions based on the spatial and temporal properties of events.

Finally, infants not only encode the spatial and temporal features of motion events that are relevant to causal reasoning and make successful inferences based on these features, they also represent motion events in terms of the situational causal roles (i.e., situational agent, situational patient) that individual objects play in a given interaction.[2] Leslie and Keeble (1987) presented infants with caused motion events until they habituated to the displays. Then, rather than switch the spatial and temporal features of the event as in the studies discussed previously, they showed infants the habituation display in reverse: object B now moved across the screen and contacted object A, after which it immediately began to move. Thus, although the spatial and temporal features of the event were the same, the causal representation of the event was altered: object B now appeared to cause object A's motion. In the comparison condition, infants were habituated to delayed events, in which a temporal gap was inserted at the point of contact between object A and object B, and were tested with reversals of the delayed event. The researchers found that infants dishabituated to reversals only in the causal condition, in which object A first appeared to cause object B's motion by direct contact. Infants in the delayed event condition did not similarly increase their looking time to the reversed test events. Belanger and Descrochers (2001) have replicated and extended these findings with non-causal events involving spatial gaps in addition to temporal gaps. Taken together, these findings suggest that infants are indeed representing these motion events in an abstract manner, assigning the conceptual roles of situational agent and situational patient to the events they perceive.

Thus, a long line of research has shown that adults automatically encode the interaction between moving objects in terms of their causal relations, and that by at least 6 months of age infants also represent the causal nature of motion events. One potential conclusion to draw from this research is that causal reasoning is continuous across development and has its roots in early causal perception. Despite not having conducted any developmental research, Michotte (1963) in fact explicitly hypothesized (p. 680) that causal perception of motion events formed the origin of mature adult causal reasoning of events outside the domain of motion. The fact that adults use spatial language to describe many instances of non-spatial causal events ("he pushed me over the edge," "he turned me into a monster") was among the speculative evidence to Michotte that motion events formed the origin of adults' most abstract causal representations.

That motion events form the origin of mature causal reasoning is also implicit in the developmental research on causal reasoning of motion events. First, infants' representations of motion events were the primary focus of causal reasoning research in infancy for over 25 years. Other researchers, although not explicitly stating that abstract causal reasoning was derived from reasoning about caused motion events, framed their research as addressing the early developing causal representations that at least precede mature causal reasoning. Finally, some researchers have offered formal computational models describing the potential development of causal reasoning, placing the spatial and temporal features of spatial contact and delay time as the inputs to causal reasoning from which abstract causal representations are derived (Cohen, Chaput, & Cashon, 2002).

Causal Reasoning Emerges from Representation of Agents and Their Actions

Among the many developmental changes children undergo within the first year of life is their increasing ability to act upon the world around them, as well as reason about other agents' actions. By around 6 months of age, infants begin to physically interact with objects, providing them with endless opportunities to engage causally with their environment. By 6 months of age, infants also encode the goals of intentional, human action as object-directed (Woodward, 1998). When infants are habituated to a person repeatedly reaching for one of two objects, they dishabituate when the person subsequently reaches for the new object. Moreover, the ability to engage in reaching actions and the ability to encode other agents' actions appear to be intertwined—infants' reasoning about the goal-directedness of others' actions seems to follow the developmental trajectory of their own motor milestones (Cashon, Ha, Allen, & Barna, 2013; Cicchino & Rakison, 2008; Sommerville, Woodward, & Needham, 2005), and improving infants' motor repertoire in early development enhances their ability to represent both the objects and the people around them (Libertus & Needham, 2010, 2011; Needham, Barrett, & Peterman, 2002; Sommerville et. al., 2005). These findings lead to the possibility that abstract causal representations may also emerge from the close tie between agent action (the infant's own actions as well as those of other people) and causal events.

The hypothesis that causal reasoning may emerge from representations of agents and their actions is most closely associated with Piaget (1954). Piaget believed that causal reasoning emerges slowly over the first few years of life, with children first learning how his or her own actions produce effects in the environment (e.g., that moving a rattle is followed by a specific noise), much like animals can learn causal relationships between their own actions and outcomes in operant conditioning (see Schloegl & Fischer, Chapter 34 in this volume, for further discussion on comparative approaches). The child then gradually extends this egocentric causal representation to other intentional agents in his or her environment. Finally, children extend their causal reasoning to non-agentive entities, such as objects, and eventually to the abstract causal events represented in adulthood. More recently, White (1995, 2014, Chapter 14 in this volume) has made similar arguments that causal reasoning emerges from action representations early in infancy.

As reviewed earlier, however, infants appear to reason causally about object motion within the first year of life. Infants are able to represent the causal relations between objects that are separate from their own action at about the same age at which successful reaching behaviors first emerge in infancy. These findings suggest that Piaget may have placed the developmental milestones at the wrong time course in development. However, there are several pieces of evidence which suggest that while Piaget may have been wrong about the timing of developmental change, he may have been correct in identifying the importance of infants' actions and representations of other agents and their actions in early causal reasoning.

First, infants' representations of motion events are affected by whether the individuals in the event are dispositional agents (Leslie, 1984b; Luo, Kaufman, & Baillargeon, 2009; Woodward, Phillips, & Spelke, 1993). In an early finding, for example, Woodward, Phillips, and Spelke (1993) showed that while 7-month-old infants expected one object to contact a second object before it moved, they did not hold such an expectation for two moving people. The (p. 681) researchers inferred that infants reasoned that people were capable of self-generated motion, and thus, contact between the individuals was not necessary for the second person to move (see also Kosugi & Fujita, 2002). In a second example, Luo, Kaufman, and Baillargeon (2009) have shown that although infants expect objects to move upon contact, they do not expect self-moving objects to move upon contact. Moreover, infants dishabituate only when an inert object, but not a self-propelled object, appears to resist the force of an external cause. Thus, despite the spatial and temporal features that elicit infants to represent one object as causing another object to move, these expectations do not seem to apply when the entities involved are dispositional agents.

Second, infants seem to infer that objects are caused to move by other agents, not by other objects. Saxe and colleagues have shown in a series of studies that when infants see an object launched from off-stage, they infer the location of the "launcher" and have expectations about what kind of individuals can fill the "launcher" role (Saxe, Tenenbaum, & Carey, 2005; Saxe, Tzelnic, & Carey, 2007; see also Kosugi, Ishida, & Fujita, 2003). Infants expect causers to be at the origin of motion (rather than the end point of motion) and represent human hands or novel, self-moving puppets with eyes as more likely causes of object motion than prototypical objects such as toy trains. Although infants in these studies do not see the entire Michottian features argued as necessary for causal perception, if representations of caused motion events served as the origin of causal reasoning, one might expect infants to infer that any individual could cause its motion given the appropriate point of origin. However, this does not appear to be the case.

Third, infants' causal perception develops alongside infants' increasing motor abilities (Sommerville et. al., 2005). In these studies, 12-month-old infants were shown means–end sequences in which an experimenter pulled a cloth to retrieve an object. Following habituation to the means–end sequences, infants were shown test events that were consistent or inconsistent with the causal structure presented during the habituation phase. In the inconsistent test trials, the experimenter moved the object off the cloth; however, when she pulled the cloth, the object still moved toward her, seeming as if the cloth caused the object to move at a distance. In contrast, in the consistent test trials, the object did not move when the experimenter pulled it. Infants' attention was drawn more toward the inconsistent test events than the consistent test events, suggesting that they detected the violation in causal structure. Ten-month-old infants similarly detected causal violations in means–end sequences that involved pulling platforms, rather than cloths. Interestingly, infants' looking times were correlated with their own ability to engage successfully in the means–end sequences presented during the study. Infants who engaged in more planful actions in a separate reaching task were more likely to detect the causal violations than infants with more immature means-end reaching abilities.

These findings provide evidence that the spatial and temporal features that consistently give rise to causal perception of motion events cannot be the sole origin of mature causal reasoning. Infants' representations of agents influence their causal reasoning well within the first year of life and near the same age at which we first have evidence for infants' representing object-caused motion. Whether causal reasoning is tied to representations of agents *in general* (i.e., themselves or other agents) or only initially to infants' own actions, the studies reviewed in the preceding suggest that causal reasoning may emerge from representation of agents and their actions. Findings that the development of children's motor abilities is related to developmental changes in causal reasoning also provides a potential mechanism responsible for developmental change. As children learn to act on objects, they might begin to identify the outcomes that followed their actions and gradually begin to detect more complex causal relations in the world. Once they determine that actions are particularly relevant to causal reasoning, they might focus on other people's actions. Such a process could then rapidly expand the child's acquisition of causal knowledge. Still, even if developmental change in causal reasoning does not depend specifically on motor development, infants' initial concepts of causality may still derive from reasoning about agents and their actions.

Causal Reasoning from Covariation Information

The previous two sections provide evidence for domain-specific origins for the development of causal reasoning (caused motion interactions between two objects and infants' representations of their own and other agent's actions on the environment) and suggest that causal cognition becomes more abstract and domain-general over the course of development. A third line of research, in contrast, suggests that causal reasoning may be (p. 682) domain-general, even in very young infants. Here, the focus is on children's ability to form causal representations based on the covariation information they receive in their environment. In the most fundamental sense, a causal representation is a covariation relation between two events: when event A occurs, event B follows; when event A does not occur, event B also does not occur. Research has shown that children are sensitive to statistical information in their environment from a very early age (Saffran, Aslin, & Newport, 1996; Wu, Gopnik, Richardson, & Kirkham, 2011), and that this might inform their language learning (Smith & Yu, 2008; Xu & Tenenbaum, 2007a, 2007b) and even social preferences (Kushnir, Xu, & Wellman, 2010; Ma & Xu, 2011). Therefore, young children may be sensitive to statistical information in their environment to represent causal structure.

The majority of evidence for causal reasoning being a domain-general process comes from research focused on causal reasoning in the preschool years, which we review at length in the following. Research with younger populations suggests, however, that even very young infants are sensitive to the covariation relations between events (Sobel & Kirkham, 2006, 2007). For example, Sobel and Kirkham (2006) presented 8-month-old infants with covariation information in which the appearance of two objects (A & B) predicted the appearance of another object at location C. A fourth event (D) is not predicted by the two objects (A & B). Over the course of familiarization to the events, because A and B occurred together, it was unclear whether A or B caused the appearance at location C. However, during test events, Kirkham and Sobel asked whether infants were capable of inferring the correct cause. In one condition (backwards blocking), infants saw that object B predicted the appearance at location C (thus explaining away A as a potential cause for C). In a second condition (indirect screening off), infants saw B predict the appearance at D (thus providing evidence that A must have been the cause of C). To adults, this evidence leads to distinct causal interpretations (Le Pelley, Griffiths, & Beesley, Chapter 2 in this volume). Adults infer that A is the cause of the appearance at C in the indirect screening-off condition, but not in the backwards blocking condition. Infants' subsequent looking patterns supported a similar causal interpretation. When they viewed A appear on the screen, they spent more time looking at location C in the indirect screening off condition than the backwards blocking condition.

Thus, infants are capable of tracking statistical information in causal situations to predict events. These findings provide a clear picture for the development of causal reasoning. If causal reasoning emerged from the ability to track covariation information without constraints on the types of events (e.g., motion), features (e.g., temporal or spatial), and individuals (e.g., objects or agents), then infants and young children would have a domain-general and abstract causal reasoning system set up to acquire a wealth of causal information across development.

Reconciling the Different Accounts

Thus, there are three distinct proposals for the origins, mechanism, and development of causal reasoning across infancy and early childhood. After nearly three decades of research on infants' folk physics, it might be of little surprise that causal reasoning emerges from early physical reasoning systems. Given infants' increasing physical and social interactions over the first year of life, and the importance of these experiences to infants' reasoning about objects and people, it also seems plausible that infants' early causal reasoning may be tied to their representations of agents and actions. Finally, research has shown that children are sensitive to the statistical information in their environment from early in infancy; given that covariation relations define a causal relation, they may also entail infants' earliest causal representations.

How then might one reconcile these distinct views on early causal reasoning? One possibility is to accept all three views as providing distinct origins for causal reasoning, much in the same way that multiple origins for agency can be seen in the innate ability to detect face-like stimuli, the early developing ability to pay attention to eyes, and imprinting in animals (see Carey, 2009, for extended discussion; Saxe & Carey, 2006). Yet, how do these distinct causal concepts interact (or not) across development and how do they become integrated across development? Moreover, why do we use the same causal language to describe physical and social causation (e.g., "he made the child cry," "he made the block move") if causal reasoning emerges from distinct representational systems? Finally, if there are distinct origins, why is covariation information a part of representations of both caused object motion and the causal consequences of agent action?

A second option might be to simply assert that infants start with no causal representations and are simply sensitive to all the statistical information (p. 683) in their environment. Since their own actions are likely the most salient in their environment and the outcomes they notice would likely occur following contact, the early causal notions focused on spatial features of an event and agents' actions could simply be a product of early causal learning based on covariation information. Similarly, as infants begin to act on the world around them, they typically (although not always) involve moving objects. Thus, children may learn about caused motion events early in development. However, in most studies of early causal reasoning, infants' attention is always clearly drawn to a highly predictable relation between events, but infants seem to represent only some of them as causal relations. If tracking covariation information is the sole mechanism behind infants developing causal reasoning abilities, then one might expect infants to be most successful when experiments narrow the hypothesis space for the infant.

Finally, a third way to reconcile these differences is to suggest that causal reasoning about motion events is not an independent origin for mature causal reasoning. For example, Scholl and colleagues have proposed that causal perception of motion events is a modular process distinct from the abstract causal reasoning seen in adults (Newman et al., 2008; Scholl & Tremoulet, 2000). Alternatively, White (2009, 2014, Chapter 14 in this volume) has argued that representations of agency may in fact underlie our ability to represent caused motion events involving objects. If infants view the causal agent in a caused motion event as an abstract dispositional agent, then there may only be a singular origin for causal reasoning, one that derives from representations of agents and their actions.

Thus, although there is extensive research documenting causal reasoning in early childhood, emerging well within the first year of life, and there are multiple proposals to explain the emergence and development of causal reasoning across the life span, researchers have yet to reach a consensus explanation for the development of causal reasoning in the first few years of life. More recently, researchers have attempted to reconcile these approaches by directly testing predictions from each research tradition using highly similar paradigms, with varied dependent measures, across a range of ages.

Muentener and Carey (2010) first investigated 8.5-month-old infants' causal representation of occluded causal events, which included three important changes from past research on infant causal reasoning. First, the studies investigated causal reasoning of novel state change events such as a box breaking into pieces or lighting up and playing music, moving the investigation of causal reasoning outside the domain of canonical motion events. Second, the study manipulated the kind of candidate agents (dispositional agents vs. objects) within these events. Third, the predictive relations within the events were kept constant.

In these studies, infants were shown predictive events in which one entity (e.g., a human hand) was the potential cause of an outcome. For instance, infants saw a candidate causal agent travel behind an occluder toward a box, a short time after which the box would break apart into several pieces. Note that since the infants never saw what occurred behind the occluder, they had no visual evidence of a causal relation between the candidate agent and the outcome. The research question was whether infants inferred that the candidate agent was the cause of the box's breaking.

Muentener and Carey (2010) tested for this in two ways. In all subsequent test events, infants then were shown the unoccluded test events in which the agent either contacted or stopped short of the box. For half of the infants, the outcome occurred and the box broke; for the other half of the infants, the outcome did not occur and the box remained solid. If infants represented the agent as the cause of the outcome, then they should look longer when (1) the candidate agent contacts the box and the outcome doesn't occur, and (2) when the candidate agent stops short of the box and the outcome still occurs.

Note that covariation presented initially to the infants was fully consistent with a causal interaction—the candidate agents' approach always preceded the subsequent outcome that occurs. Thus, if infants rely solely on covariation information to establish causal representations, they should have inferred that a causal interaction had occurred because the candidate agent's action always preceded and predicted the outcome. However, infants only inferred a causal interaction for change of state events when a dispositional agent was the candidate cause. When a human hand (or a self-propelled puppet) was the candidate agent, infants looked longer during the test events when the agent stopped short of the box and the outcome occurred and when the agent contacted the box and the outcome did not occur. In contrast, when the candidate agent was a toy train (a typically inert object), infants' looking times did not differ across conditions.

(p. 684) The findings that infants reason differently about equivalent predictive relations based on the kind of individual in the event suggests that infants' causal reasoning is unlikely to be a domain-general process across development; infants should have succeeded across all conditions if that were the case. Moreover, that infants are able to reason about causal interactions outside the domain of caused motion at nearly the earliest ages at which researchers have evidence for causal reasoning in infancy suggests that mature causal reasoning is unlikely to emerge solely from causal perception (or inference) of motion events. These results extend prior findings (Leslie, 1984b; Saxe et al., 2005, 2007) that infants infer dispositional agents, such as a human hand, as the cause of object motion. They also suggest that infants may represent caused motion events in terms of dispositional agent–patient relations, rather than simply situational agent–patient relations, akin to arguments made by White (1995, 2014, Chapter 14 in this volume). Thus, there may be a bias toward reasoning about agents and their actions in infants' early causal reasoning.

Follow-up research suggests that this agency bias continues through toddlerhood. In a series of studies, Bonawitz and colleagues found that 2-year-old toddlers fail to represent predictive events as causal events unless they are initiated by an agent's action (Bonawitz et al., 2010). The researchers presented toddlers with predictive chains in which a block (A) slid toward and contacted another block (B), after which a small toy airplane (C), connected to B by a wire, began to spin. Between conditions, they manipulated whether A began to move on its own toward B or whether the experimenter moved A. Toddlers readily learned the predictive relation between A and B's contact and C's activation, and there was no difference between conditions. The researchers then asked a simple question: Do toddlers infer that A *caused* C to activate? If so, then toddlers should be more likely to push A into contact with B *and* look toward C upon contact—that is, they should expect that their action should cause the airplane to spin. Bonawitz et al. found that this was the case when A's motion was agent-initiated, but that toddlers failed to make predictive looks when it engaged in self-initiated motion. This failure was not due to a lack of interest in or fear of the self-moving block, as all toddlers played with the block and eventually placed A into contact with B. Rather, toddlers simply did not believe that their action would cause the outcome to occur.

Intervening on the block (A) is a fairly low-cost action, and in fact, all children eventually interacted with the block and placed the two blocks in contact with each other. Thus, the difference between the agent and non-agent conditions was not a matter of motivation or imitation. The failure to make a predictive look toward the airplane, thus, seems to be a true failure to represent it as even a *potential* cause of the airplane's motion. Again, to pass this task, children are not required to infer that the block is the definitive cause of the outcome, but rather a *plausible* cause of the outcome. That they fail to look toward the outcome following their action strongly suggests that toddlers did not even entertain this possibility. Toddlers, similar to infants, were biased to represent only predictive relations involving agents as potential causal interactions.

In fact, a visible agent is not even necessary to show such an effect. Using a modified looking-time method with toddlers, Muentener, Bonawitz, Horowitz, and Schulz (2012) asked whether toddlers would infer the presence of an agent when they see an object emerge in sight already in motion (as seen in Saxe et al., 2005) *and* whether this invisible agent could facilitate toddlers' causal inferences. In one condition, toddlers viewed the block (A) initiate its own motion toward the base object (B), after which the airplane (C) began to spin. In the second condition, toddlers viewed A emerge from offstage already in motion; it moved toward B, after which C began to spin. In contrast to Bonawitz et al., toddlers viewed occluded causal interactions, similar to the looking time paradigm used in Muentener and Carey (2010) described earlier—that is, toddlers needed to infer whether or not A contacted B behind a screen. During the test, toddlers' causal interpretations were tested by varying the spatial relation between A and B alongside the presence or absence of C's spinning, between conditions.

When A's motion was self-initiated, an analysis of toddlers' looking times provided a conceptual replication of Bonawitz et al. (2010). Toddlers looked longer when C spun than when it didn't, but they were insensitive to the spatial relations between A and B—they did not seem to infer that A was the cause of C's spinning. In contrast, when A appeared onstage already in motion, they appeared to engage in causal inference. When C spun during the test, they looked longer when A stopped short of B than when it contacted B. When C did not spin during the test, they looked longer when A contacted B than when it stopped short of B. Follow-up conditions confirmed that toddlers inferred the (p. 685) presence of a hidden agent. When a hidden hand was revealed behind an occluder at the impetus of A's motion, infants looked longer when A initiated its own motion onstage than when A appeared onstage already in motion. Thus, across two different ages and two different measures, children's causal reasoning appears biased toward dispositional agents. Despite equivalent predictive relations between events, infants and toddlers seem to preferentially represent only those events initiated by dispositional agents as causal interactions.

These findings have implications for a complete understanding of the origins of causal reasoning. First, these findings suggest that abstract causal reasoning does not emerge solely from representations of caused motion events triggered by spatial and temporal features. As has been found in prior research, infants and toddlers are capable of representing causal structure in non-Michottian events, even when the precise spatial interaction is occluded. Second, these findings suggest that early causal reasoning is not simply the result of tracking covariation information in the world, as infants and toddlers failed to represent predictive events as causal relations when they did not include a dispositional agent. While it is possible that infants and toddlers have already acquired an expectation that dispositional agents are more likely causal agents than are objects, toddlers did not engage in causal exploration even when the cost of intervening was very low (i.e., simply looking up toward the outcome). This suggests that the link between agents and causation is either established via tracking covariation information and insensitive to new evidence or that there are early biases on the types of predictive relations that infants and toddlers track when engaged in causal reasoning. Infants may be particularly attuned to attending to the actions of dispositional agents and the outcomes that follow them. This close relation between agents and causation may provide a starting point for the abstract, domain-general causal representations that emerge across development.

Learning Specific Causal Relationships in Early Childhood

We have focused on three mechanisms that might support infants' early recognition of causal events, suggesting that domain-specific knowledge plays an important role in identifying events as causal. Of course, causal reasoning extends beyond initial recognition that events are causal—it involves reasoning about more specific causal relationships, including the identification of which objects or agents in a scene are responsible for effects, assessing the relative strengths of generative and inhibitive causal entities, and understanding how causes and effects stand in relation to each other. How might children understand these more specific causal relationships once events are identified as causal?

Domain-Specific Mechanism Information

Consistent with the idea that infants use very early developing or innate knowledge of physical forces and agents' actions to identify causal events, one way that older children might learn causal relations is through prior causal knowledge expressed in domain-specific beliefs (Bullock, Gelman, & Baillargeon, 1982; Leslie & Keeble, 1987; Meltzoff, 1995; Shultz, 1982a; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Wellman, Hickling, & Schult, 1997; Woodward, 1998; Spelke, Phillips, & Woodward, 1995). For example, domain boundaries (such as boundaries between psychological and biological events) might help early learners identify which kinds of entities in the world are candidate causes for observed events in specific domains. Indeed, research shows that older children's causal inferences respect domain boundaries. Specifically, preschoolers are hesitant to say that a psychological event, such as being embarrassed, can cause a biological event, such as blushing (Notaro, Gelman, & Zimmerman, 2001).

A second way in which domain-specific knowledge could facilitate causal reasoning is in identifying the kinds of causal mechanisms that might link a potential cause and effect. Young children believe that there are domain-specific differences in the kinds of forces that lead to causal transmission from one event to another, with physical events linked by transmission of energy and social events linked by psychological mechanisms such as intention (Schultz, 1982b). Children can also use this domain-specific knowledge to draw inferences about new causal events (Shultz, 1982a).

The idea that distinct mechanisms (e.g., between physical and psychological domains) underpin children's causal understanding is consistent with Piaget (1954), and prevalent in contemporary theories of causal reasoning (e.g., Ahn, Kalish, Medin, & Gelman, 1995; Bullock et al., 1982; Schlottmann, 2001). However, many causal inferences that we draw do not have an obvious mechanism, and learners need not understand a specific process of transmission in order to draw causal conclusions. Indeed, given that our causal mechanism knowledge (p. 686) is quite impoverished (Keil, 2006), children must also rely on other sources of information to reason causally. We turn our attention to a domain-general mechanism—statistical learning—and discuss how this mechanism has informed our understanding of children's causal reasoning.

Statistical Learning

How might young learners begin to identify the potential causal relationships among events? Although domain-specific knowledge may help to constrain the space of possible causes, along with their strength and relationship to other events, additional information must drive causal inference and is necessary for learning. As with learning in other domains, sensitivity to patterns of statistical evidence certainly plays an important part in causal reasoning (see Perales, Catena, Cándido, & Maldonado, Chapter 3 in this volume, for further discussion).

Perhaps the simplest statistical machinery is an association detector—a mechanism by which the covariation of spatiotemporally related events are learned. Causes and their effects will be correlated, so these simple association detectors might get reasoning off the ground, without any need for a notion of "cause" (Hume, 1748/1999). In this way, covariation information could be sufficient for drawing inferences about causal strength (Mackintosh, 1975; Rescorla & Wagner, 1972). In more sophisticated models of statistical covariation learning, information about effects happening in the presence and absence of potential causes inform causal inferences (e.g., **Δ**P: Allan, 1980; Jenkins & Ward, 1965;

Shanks, 1995). Other models suggest ways in which the strength (or generative power) of a cause on its effect might be measured by taking into account all potential causes on the effect and considering the unique additional difference of a particular cause (e.g., power PC: Cheng, 1997, 2000; see also Cheng & Lu, Chapter 5 in this volume). These models predict the degree to which an effect should occur given a cause and some background noise, and provide a theoretical story for how young learners might draw causal inferences from statistical data, assuming they can track probability information of this kind.

Are children able to track probability information in the service of causal reasoning? Indeed, even 4-year-old children can use covariation information to infer causal strength; children who see a block activate a machine 2 out of 6 times believe it to be less effective than a block that activates a machine the same number of times (2 activations) but in fewer trials (4 total trials). This evidence suggests that children are tracking the *proportion* of activation (e.g., Kushnir & Gopnik, 2005).

An appeal of adopting these covariation approaches to understand early causal reasoning is that they do not depend on specialized causal learning mechanisms, but instead could be adapted from domain-general statistical learning mechanisms. However, more specialized causal learning mechanisms might better describe preschool-aged children's causal learning. Specifically, learners could attend to the conditional probability of variables, as with causal power models, but this statistical information may then be used to construct or identify the best "causal graph"—an abstract representation of the causal variables and the relationship between them (Glymour, 2001; Gopnik, 2000; Gopnik & Glymour, 2002; Pearl, 1988, 2000; Steyvers, Tenenbaum, Wagenmakers, & Blum, 2003; Tenenbaum & Griffiths, 2003; Spirtes, Glymour, & Scheines, 1993; see Rottman, Chapter 6 in this volume, for detailed discussion).

Causal graphs are a generative model, representing the patterns of dependencies between variables, and affording a causal-specific framework for reasoning beyond covariation information about the relationship between variables (Glymour, 2001; Pearl, 1988, 2000; Spirtes et al., 1993). Causal graphs may be a critical component of children's early intuitive theories, because—necessary for theories—they are an abstract representation that supports prediction, explanation, and intervention (Carey, 1985; Gopnik & Meltzoff, 1997; Wellman & Gelman 1992). Graphs support predictions because a learner with such a representation can "run the model" in their mind to generate possible outcomes. Graphs support explanations in that observed outcomes can be traced back within the graph to the likely causes that explain their presence or absence. Inferring causal structures is also intimately tied to an interventionist account of causal learning (Woodward, 2003, 2007); knowing that there is a causal link between two variables, as expressed in a graph, means that intervening to change the probability of the cause will change the probability of the effect. Given that these causal structure representations may underlie intuitive, potentially domain-specific reasoning, it becomes important to ask whether this structure account captures children's causal reasoning more generally.

There is evidence that the causal structure account underlies children's causal representations (p. 687) in multiple domains, and that causal inference in general depends on this more sophisticated learning account. To start, research has shown that children can use indirect evidence to draw causal inferences that would not be supported under the simpler associative models (Gopnik, Sobel, Schulz, & Glymour, 2001; Schulz, Kushnir, & Gopnik, 2007). For example, Sobel, Tenenbaum, and Gopnik (2004) investigated whether young children could use rules of conditional dependence to draw inferences about likely causes. Children were introduced to possible "blickets" and a "blicket detector machine" that activated when blickets were placed on the machine (see also Gopnik & Sobel, 2000). In one backwards blocking condition, children observed two blocks placed on the machine simultaneously (A and B), and the machine activated. On the next trial, only block A was placed on the machine, and the machine activated. Children were asked whether blocks A and B were blickets. Unsurprisingly, children correctly inferred that block A was a blicket. However, 4-year-olds were less likely to endorse B as a blicket (3-year-olds' responses were less clear). Simpler associative models cannot explain this pattern of responding (though see also Dickinson & Burke, 1996; Larkin et al., 1998; McClelland & Thompson 2007; Le Pelley et al., Chapter 2 in this volume), however, the structure learning accounts can explain this pattern. Specifically, Sobel et al.'s (2004) structure learning account considers two models (one in which both A and B are blickets, and one in which only A is a blicket). Assuming that blickets are rare, the "only-A" model is more likely under that structure learning account, and qualitatively matching preschoolers' preference.

A second, but related, set of evidence derives from preschoolers' use of base-rate information to draw inferences about potential causes. The structure learning account depends on not only the probability of observing patterns of data given different possible causal structures, but also the base-rate probabilities of these structures. To directly test the prediction that base-rate information influences children's causal structure inferences, Griffiths, Sobel, Tenenbaum, and Gopnik (2011) manipulated the base-rate information of blickets and gave them the same backwards blocking task described earlier. Consistent with the predictions of the structure learning account, when blickets were rare, children endorsed only A as the cause following this pattern of data, but when blickets were common, children also endorsed B (Griffiths, Sobel, Tenenbaum, & Gopnik, 2011).

A third line of evidence in support of structure learning accounts pertains to children's use of intervention information to draw causal inferences. The adage "correlation does not imply causation" derives from the pervasive issue of using covariation to inform our causal understanding. Knowing that A and B are correlated does not tell us whether A causes B, B causes A, or some unobserved variable C causes both. However, as with careful scientific experiment, intervention information can resolve the ambiguity among causal structures. Structure learning frameworks afford a privileged place for interventions, because they can account for causal direction in a way that associationist or causal power accounts cannot. Like scientists, children also combine intervention information with covariation information to draw inferences about the most likely causal structure, such as whether A caused B, or B caused A, and also to draw inferences about unobserved variables (Gopnik et al., 2004). Children can also decide between more complicated causal structures using both covariation and intervention information (Schulz, Gopnik, & Glymour, 2007); for example, following evidence about a toy with two gears spinning, preschoolers accurately inferred whether patterns of data were caused by one of four structures including causal chains (e.g., A → B → C) and common cause structures (e.g., A → B and A→ C).

Of course, a causal graphical model does not capture all possible information about the structure of causal events. Additional information, such as causal form and the number of ontological kinds (categories) in the observed set could depend on “higher order” causal knowledge. Research with preschoolers suggests that children make causal inferences that extend to this higher order knowledge. For example, causal form can vary across different event types: a causal event might occur when at least any single activator is present; the event might require that two activators be present at the same time; or the event might only occur when exactly one activator is present, and so on. Recent research suggests that children are not only able to learn these different causal forms from limited evidence, but they may be more likely to be able to learn more unusual causal forms than adults (Lucas, Bridgers, Griffiths, & Gopnik, 2014).

Causal reasoning also depends on a joint inference between categories and causal relations. For example, imagine playing with a set of objects that includes magnets, metals, and inert (e.g., plastic) objects for the first time. Drawing inferences from (p. 688) patterns of exploration depends on three things. First, the learner must be able to learn that there are exactly three causal “kinds,” the categories of “metal,” “magnet,” and “inert.” Then, causal inference about any particular object depends on both the correct categorization of these objects (which objects are magnets? which are metals? etc.), as well as inferring the causal relations between them (magnets react with other magnets and also with metals, but metals do not react with themselves, and inert objects do not react with anything). Preschool-aged children can jointly infer causal structure and category information like this—discovering how many categories exist, which objects should be assigned to these categories, and the causal laws that guide the relationship between these categories (Bonawitz, Ullman, Gopnik, & Tenenbaum, 2012; Bonawitz, Ullman, Gopnik, & Tenenbaum, in revision*;* see also Schulz, Goodman, Tenenbaum, & Jenkins, 2008). These results are consistent with hierarchical computational learning accounts that start with logical grammars; these grammars serve as a broad “language of thought” for how more specific kinds of causal structures could be represented and discovered (Goodman, Ullman, & Tenenbaum, 2011; Kemp, Perfors, & Tenenbaum, 2007). Thus, it appears as though children are employing statistical learning strategies that go beyond naïve associative accounts. Causal structure accounts suggest a means by which learners can draw inferences about causal events, from relatively limited data. By at least as early as preschool age, children's sophistical causal inferences are well explained by this framework.

Reconciling Statistical and Domain-Specific Approaches

The research on children's causal reasoning described in the preceding suggests that by at least 4 years of age, children are representing causal structures and using these representations to guide their causal inferences. However, children's causal inferences are supported by more than statistical learning principles—statistical learning is not likely to be able to account for the speed or accuracy in which even very young children draw inferences from ambiguous, noisy data. In contrast, consider that domain-specific mechanisms support rapid learning, but do not necessarily capture the flexibility of data-driven approaches. Might children be able to harness the power of both domain-specific knowledge and statistical learning accounts?

Children's causal inferences clearly include both domain-specific mechanism information and statistical learning. For example, following covariation information, 3-year-old children are more likely to extend causal efficacy based on an object's internal properties when the mechanism is psychological (an "agent" likes the block) than when it is physical (a machine activates it), adding support to the claim that domain-specific mechanistic knowledge can support causal inferences (Sobel & Munro, 2009). Additionally, given identical covariation evidence, children are more likely to endorse a cause that is domain consistent (e.g., a switch activating a machine) than domain violating (e.g., asking the machine to go); however, given overwhelming evidence, children are willing to endorse causes that cross domain boundaries (Schulz & Gopnik, 2004).

These studies of children's causal reasoning using mechanism information and statistical learning might lead one to believe that children follow an "either-or" approach. Perhaps children choose to stick with either domain knowledge or evidence, depending on the strength of their beliefs and the evidence. However, children seem able to integrate domain knowledge with evidence in a more graded way. Schulz, Bonawitz, and Griffiths (2007) provided 3-, 3.5-, and 4-year-old children with ambiguous, but statistically compelling evidence about possible causes (e.g., A & B→E; A & C→E; A & D→E, etc.), and were asked at the end of the book what caused E. In one condition, the recurring variable A crossed domain boundaries (e.g., "worrying"—a psychological domain covaried with "stomach ache—a biological domain), and in another the variables were all within domain boundaries (e.g., plants causing itchy spots, both biological). While the youngest children had difficulty learning from evidence in either condition, 3.5-year-olds were able to learn from the evidence when all variables were within domain, and 4-year-olds were able to learn from both within and cross-domain conditions. However, 4-year-olds also showed sensitivity to their prior belief in domain boundaries—they were less likely to endorse A as the causal variable when it crossed domain boundaries than when it was within. A follow-up training study with 3.5-year-olds suggested that younger children's failures to learn were due both to stronger prior belief in domain boundaries and a fragile ability to reason from ambiguous evidence presented in these tasks (Bonawitz, Fischer, & Schulz, 2012).

Thus, children may rely on domain-specific information early in life, and especially when statistical evidence is probabilistic. However, by 4 years of age, children seem able to integrate these beliefs (p. 689) with patterns of evidence to inform their causal judgements including drawing inferences about (Seiver, Gopnik, & Goodman, 2013) and from (Kushnir, Vredenburgh, & Schneider, 2013) other people. This research suggests the important role for both domain-specific beliefs and statistical learning in early causal reasoning.

Inductive Constraints Beyond Domain Knowledge

In addition to a belief in domain boundaries, children likely employ numerous inductive constraints to guide their causal inferences, and importantly integrate these constraints with probability information. Such constraints may take many forms. For example, they could include causal-specific principles—such as beliefs in determinism or biases to favor information that comes from one's own interventions or that has salient spatiotemporal cues. Constraints could also include more general inductive biases that shape children's preference for certain explanations (such as a preference for simpler explanations) and that shape their interpretation of evidence in different contexts (such as when evidence is generated purposefully/accidentally by a knowledgeable/ignorant agent). Is there evidence that children have and use these inductive constraints in the service of causal reasoning?

Recent research suggests that preschoolers do indeed bring numerous causal inductive biases to bear on their interpretation of causal events. Preschool-aged children infer the presence of unobserved (inhibitory) causes (or absent generative causes) when observed causes appear stochastic (probabilistic), suggesting that children are causal "determinists" (Schulz & Sommerville, 2006). A bias for determinism can provide a powerful basis for inferring the existence of unobserved variables and can help guide exploration in search of these potential hidden causes (Schulz, Hooppell, & Jenkins, 2008; for evidence from toddlers, see Muentener & Schulz, 2014). Children also demonstrate a bias for evidence observed from their own interventions (Kushnir, Wellman, & Gelman, 2009), but they can ignore this bias when their interventions are confounded, such as when an alternate known cause (flipping a switch) is produced at the same time as the intervention (Kushnir & Gopnik, 2005). Furthermore, children use spatiotemporal information (e.g., whether there is contact between a block and a machine) to guide their causal inferences; however, probability information can overturn this bias (Kushnir & Gopnik, 2007). Thus, children seem ready to bring causal-specific biases to bear in reasoning from evidence, though it is unknown whether or not these biases are learned from experience.

More general biases may also help learners constrain and reason from causal information. Lombrozo (2007) hypothesized that a bias for "simplicity" might inform inference to the best explanation (see Lombrozo & Vasilyeva, Chapter 22 in this volume). Lombrozo (2007) found that, controlling for the probability of events, adults preferred explanations that were simpler—in that they appealed to fewer causes. Bonawitz and Lombrozo (2012) extended this investigation to preschoolers, to see whether young children rely solely on probability information to select candidate causes, or whether, like adults, children preferred explanations with fewer causes (controlling for probability information). Children were shown a toy that could light up (when a red chip was placed in an activator bin), spin (when a green chip was placed in the bin), or that could do both simultaneously (when a blue chip was placed in the bin, or when both a red and a green chip were placed in the bin). Children were shown information about the prevalence of red, green, and blue chips. Then a bag with all three chips was accidentally spilled into the bin. Both the fan and light activated, and children were asked what fell into the bin. Children were sensitive to the probability information and began to favor the "red and green chip" explanation as its probability increased across conditions. However, children also showed a strong preference for the simpler, one-chip explanation—even when the complex explanation was twice as likely as the one-chip explanation. These results suggest that children may rely on a principle of parsimony as an inductive constraint to draw inferences about causal events, and that they integrate this constraint with probability information.

In addition to integrating inductive biases with data, children could also leverage social information to guide their causal reasoning. In particular, if children were sensitive to the process of how data were generated, that could lead to stronger causal inferences from limited data. Consider watching a person walk over to a wall and flip a light switch, but nothing happens. Although the covariation evidence provides cues that the switch is not related to a light, inferences about a person's actions ("there must have been a reason that she tried to flip it") can inform causal inferences.

(p. 690) Recent research suggests that children are indeed sensitive to the social cues, and use these cues about how data were generated to draw causal conclusions (Kushnir, Wellman, & Gelman, 2008). For example, Gweon, Tenenbaum, and Schulz (2010) found that 15-month-old infants attend to whether objects were drawn purposefully or randomly from a box in order to make inferences about the extension of a causal property to novel objects. Sixteen-month-old infants also track whether probabilistic causal outcomes co-occur with an individual (i.e., person A always makes it go, but person B fails) or object (i.e., the object fails occasionally independent of the user) to decide whether a failed event with the same object is due to their own inability or the object's inconsistency (Gweon & Schulz, 2011). Other work shows that preschool children use information about whether an experimenter was knowledgeable or ignorant when deciding whether to switch responses in response to neutral question about a causal event (Gonzalez, Shafto, Bonawitz, & Gopnik, 2012; Bonawitz et al., in review).

Thus, from very early on, children seem to understand that people are part of the generative process; children used information about the other people's goals and knowledge to draw stronger causal inferences from data. Pedagogy is a special case of leveraging social information, because the learner can infer not only that data were drawn with intent, but also that data were drawn in order to be maximally efficient for teaching (Shafto, Goodman, & Griffiths, 2014). For example, pedagogical inferences seem to drive children to "over-imitate" causal action sequences; children are more likely to generate longer strings of actions to cause an outcome when those strings are demonstrated by a teacher than when strings are demonstrated by an ignorant actor (Buchsbaum, Gopnik, Griffiths, & Shafto, 2011).

The teaching assumption yields a special additional constraint for causal inference. Although lack of evidence does not always entail evidence of a lack, when a teacher chooses the data, lack of a demonstration provides such support for evidence of a lack. For example, Bonawitz, Shafto, et al. (2011) showed children a novel toy with many interesting pieces (knobs, tubes, buttons) that might afford an interesting event (perhaps squeaking, lighting up, or making music). In one condition, children were given strong pedagogical cues and were told, "this is how my toy works," as the demonstrator pulled a tube out and caused the toy to squeak. The experimenter did not demonstrate additional properties of the toy. Here, lack of evidence provides evidence of a lack: had there been additional causal affordances, then the teacher should have demonstrated them. We can contrast this inference to a non-pedagogical condition: children were shown the same outcome (the tube causing the toy to squeak), but the event happened accidentally by an experimenter who was "ignorant" about how the toy worked. In this case, the child need not draw the inference that squeaking is the only causal function of the toy. In the accidental condition, children explored the toy broadly, suggesting that they believed the toy was likely to have additional properties. In contrast, children in the pedagogical condition constrained their exploration to the pedagogically demonstrated function; this less variable play suggests that children believed that there was likely only one causal property (the demonstrated squeaking event). Furthermore, children use this pedagogical assumption to evaluate whether teachers are accurate, following causal demonstrations. For example, if children discover additional properties of a toy following a narrow pedagogical demonstration, children rate those informants lower and are less likely to constrain search following subsequent pedagogical demonstrations from the same informant (Gweon, Pelton, Konopka, & Schulz, 2014).

Discussion of Children's Causal Reasoning

Taken together, these results suggest that even very young children leverage strong inductive biases with patterns of data to inform their inferences about causal events. Given that children seem to form sophisticated causal theories about the world by the first few years of life, it is perhaps not surprising that multiple constraints inform their inferences from data. Rapid learning from minimal data requires that there be inductive biases to limit the myriad possible causal structures that could have produced the data. Importantly, these multiple constraints point to ways in which we might expect causal inferences to reflect important developmental differences in learning about cause. Namely, if, as we have suggested, causal reasoning is driven by the interaction of data and these inductive constraints, then changes in these inductive constraints will change the resulting causal inferences. Thus, one can begin to explore developmental changes in domain beliefs, inductive constraints, and social (p. 691) inference more broadly as a possible explanation for observed developmental differences in causal reasoning.

Causal Exploration and Discovery

Being able to identify causal scenes in the world is certainly important, but of course it differs from the ability to seek out and discover the causal structure of the world. Although we now know that gravity causes apples to fall from trees, there is nothing in the visual percept that identifies the gravitational pull that eventually connects an apple to the ground beneath a tree. Rather, if we want to understand how the apple falls from the tree and believe that the apple is a prototypical object that does not have the ability to move on its own, then we must infer and posit the existence of an unknown causal source for the motion. Only then are we in a position to discover new causal structure in the world around us.

This is the root of scientific exploration: positing new theories, creating new hypotheses, and designing experiments to test those hypotheses. In the previous section, we suggested that the structure learning account alone provided a privileged role for interventions of these kinds, and we pointed to evidence that children can use intervention information to draw accurate causal inferences. But, to what extent do children spontaneously engage in causal hypothesis testing in their exploratory play? Are children only able to identify the causal structure of fully transparent predictive relations provided for them? Or, do they seek out causal structure in their everyday play? Recent studies suggest that children are engaged in this type of behavior from at least the second year of life (for a review, see Schulz, 2012).

One way that play could facilitate causal reasoning is if actions in play serve as new evidence. If one were biased to explore events where evidence has not yet disambiguated between potential causal structures, then play could generate the necessary disambiguating evidence from which to learn. Are children motivated to explore when causal information is ambiguous? Schulz and Bonawitz (2007) investigated this question with preschoolers, using a jack-in-the-box with two levers. When the levers were depressed, two toys popped up. The location of the toys were both in the center of the box, so there was no information that could guide inference as to which lever might cause which toy. In one condition, children observed confounded evidence in which the levers were always depressed simultaneously. Because the levers were depressed simultaneously, the evidence does not disambiguate the potential causal structures. (Either the right lever could cause toy A, or the left, or the toy levers combined could cause one, etc.). Another group of children were introduced to the same box, but observed disambiguating evidence, where one lever was depressed at a time. For all children, the toy was removed and then returned, along with a novel toy, and children were allowed to play freely for 60 seconds. Unsurprisingly, children in the unconfounded condition showed a strong preference to play with the new toy. However, in the confounded condition, the pattern of play reversed: children overcame the novelty preference and played more with the familiar (confounded evidence) toy and even spontaneously generated evidence that resolved the confounding. Indeed, other studies have found that when given confounded evidence, children are more likely to produce variable exploration, which provides evidence to support causal learning (Cook, Goodman, & Schulz, 2011; Gweon & Schulz, 2008). These findings suggest that children are motivated to explore, following uncertainty about causal structure.

Other studies have shown that children's play is guided by the interaction of their strong prior beliefs and the evidence they observe (Bonawitz, van Schijndel, Friel, & Schulz, 2012; Legare, 2012; van Schijndel et al, 2015). For example, Bonawitz, van Schijndel, Friel, and Schulz (2012) looked at children's exploratory play in the domain of balance. As initially found by Karmiloff-Smith and Inhelder's (1975) influential study, children initially entertain a "center theory" of balance, believing that regardless of the center of mass, an object should be balanced at its geometric center; gradually, children learn a "mass theory"—that blocks balance over their center of mass. Bonawitz, van Schijndel, Friel, and Schulz (2012) first tested children on a set of blocks to determine their beliefs about balance. Then children were shown one of two events. In one event, an unevenly weighted L-shaped block balanced at its center of mass (toward the heavy side). Another group of children saw the L-shaped block "balance" at its geometric center. Note that to mass theorists the block balancing at its geometric center is surprising and causes a conflict with their prior beliefs; however, center theorists observing the same evidence have no conflict. In contrast, mass theorists seeing the block balance at its center of mass do not experience conflict, but this same evidence is surprising to center theorists. Neither children's beliefs or the evidence alone predicted children's pattern of play. Critically, it was the interaction of (p. 692) children's beliefs and the evidence that led to significant differences. Children who observed belief-consistent evidence showed a standard preference for the novel toy. However, when evidence was surprising with respect to the children’s beliefs, they overcame a preference for the novel toy and spent more time continuing to explore the block.

Children’s explanations on the Bonawitz, van Schijndel, Friel, and Schulz (2012) task also suggested that they were seeking out potential causal explanations during play: Why might the block balance the way it does? In fact, there was a magnet at the balance point of the blocks and the stand. However, although all children discovered the magnet during the course of free play, and the magnet is a reasonable explanation for the block’s balancing in all conditions, children were significantly more likely to appeal to the magnet as an explanatory variable when evidence conflicted with their beliefs than when it confirmed their beliefs. In a follow-up condition, when no magnets were present and thus could not explain away the surprising evidence, center theory children were significantly more likely to revise their beliefs about balance following play. These results show the important combined role of evidence and children’s prior beliefs in guiding play. Given evidence that is surprising with respect to their beliefs, children are more likely to explore, and thus consequently either they discover causal variables to explain away the evidence, or they generate new evidence from their own interventions that leads to belief revision.

These results suggest that children’s desire to learn about causal outcomes is reflected in their play. Other researchers have suggested that the link between play and causal learning extends beyond generating evidence to resolve immediate, tangible causal outcomes; instead, it could support reasoning through imaginary, possible worlds. Thus, children’s pretend play may guide their understanding of causal events. In particular, it has been suggested that pretend play may facilitate causal counterfactual reasoning, much as thought experiments support reasoning in science (Buchsbaum, Bridgers, Weisberg, & Gopnik, 2012; Gopnik & Walker, 2013; Harris, 2000; Walker & Gopnik, 2013; Weisberg & Gopnik, 2013). Some initial recent evidence supports a link between pretend play and causal reasoning. For example, children’s performance in causal counterfactual reasoning tasks and their engagement in pretend play correlate with each other (Buchbaum et al., 2012). However, many open questions between pretense and causal reasoning remain, and additional empirical evidence is still in progress.

We have suggested that play and causal inference are tightly coupled. Although the particular actions children take in the course of play might not be systematic, children’s exploratory play might nonetheless be driven by opportunities to learn about causal structure. When evidence is ambiguous or surprising with respect to the children’s beliefs, they explore more and more variably, producing opportunities for causal learning. Furthermore, children’s pretend play may be an early mechanism that supports the development of causal counterfactual reasoning.

General Conclusions and Open Questions

We have reviewed research on the development of causal reasoning in infancy, toddlerhood, and the preschool years with the broad goals of (1) understanding the origin of our mature causal reasoning abilities, and (2) discussing how the process of causal reasoning and discovery may change throughout early childhood. Research on causal reasoning in infancy and toddlerhood provides evidence for both domain-specific (object motion, agent action) as well as domain-general (covariation information) roots to causal reasoning. More recent research suggests that representations of agent's actions may play a particularly important role in the development of causal reasoning. However, independent from the precise origin of causal reasoning, our review on studies with preschool-aged children leads to the conclusion that by about 4 years of age, children are integrating domain-general covariation information with domain-specific prior knowledge, as well as with causal inductive constraints and more general inductive biases, to rapidly and effectively represent causal structure.

Yet, despite a large body of research focused on the development of causal reasoning, several open questions remain. With regard to the origins of causal reasoning, how do early notions of causality, such as caused motion and agent action, become integrated across development? One possibility is that causal representations serve to integrate object and agent representations as children come to form event representations. Alternatively, there may be multiple representations of cause that are part of infants' core knowledge of objects and agents (Carey, 2009; Spelke & Kinzler, 2007). While the answers to these question inform our understanding of the development of causal reasoning, they also have important implications for a fuller understanding of our early conceptual system. If infants have several (p. 693) domain-specific representations of causality, then how do we come to integrate these representations over development? How do early non-linguistic representations of causality map onto emerging causal language in early childhood? The fact that adults (as well as children; see Callanan & Oakes, 1992; Hickling & Wellman, 2001; Muentener & Lakusta, 2011) can use similar language to identify the broad range of causal relations suggests that somehow this does occur over development. However, what role might language play in helping young children identify and learn about specific causal relations in their everyday life (Muentener & Schulz, 2012)?

A second, related question concerns the belief that there is in fact a unified abstract of representation in adult higher cognition. Although adults use similar causal language across domains, the distinction between reasons (e.g., social causation) and causes (e.g., physical causation) in adult causal reasoning suggests a continued distinction within causal reasoning across development. What is the relation between physical and psychological causation early in development? Although there is recent research suggesting that children use similar processes to reason about causes in the social world (Seiver et al., 2013), future research is needed to understand whether younger infants and toddlers reason in similar ways.

The review of research on preschool causal reasoning suggests that children are sophisticated intuitive causal reasoners. However, this finding is in tension with research on children's causal scientific reasoning abilities. One the one hand, children can successfully use causal information to categorize events and objects (Nazzi & Gopnik, 2003; Schulz, Standing, & Bonawitz, 2008), can understand the relationship between internal parts and causal properties (Sobel, Yoachim, Gopnik, Meltzoff, & Blumenthal, 2007), can use counterfactuals to reason causally (Harris, German, & Mills, 1996), and even can design appropriate interventions on causal systems (Cook et al., 2011; Gopnik, Sobel, Schulz & Glymour, 2001; Gweon & Schulz, 2008). On the other hand, children have difficulty in explicit, scientific reasoning studies. In particular, children have a weak explicit understanding of how patterns of data support or falsify possible hypotheses, and they do not isolate variables to produce informative experiments (Klahr, 2000; Kuhn, 1989; Schauble, 1990, 1996). This pattern of results suggests an important divide between the metacognitive processes that support explicit scientific reasoning and the intuitive mechanisms for causal inference in day-to-day experience. Here we have focused on the intuitive mechanisms that might support children's developing causal reasoning abilities, but understanding the way in which metacognitive reasoning might connect to intuitive reasoning remains an important challenge to the field.

A second ongoing challenge for studies that demonstrate young children's rapid and accurate causal inferences pertains to the problem of search. How does a learner find the structure that accurately carves up the world into causes and events, with the relationship and causal weights correctly specified? Consider that the number of possible causal structures that could capture any particular pattern of statistical evidence is vast at best, and often infinite. We have pointed to the role of domain-specific knowledge, inductive constraints, and play-generated interventions as potential tools to deal with this problem of information and search. However, if following a truly rational model of learning—one that considers all possible causal models and selects the best model given the data—then additional constraints only offer a modest narrowing of the space of possibilities; the search problem and computational demands on the learner remain immense. How could children—who, in particular, face even stronger working memory, attentional, and executive function limitations than adults—possibly hope to solve this search problem?

Recently, researchers have suggested that—rather than considering all possible causal structures—children might "sample" causal hypotheses from a probability distribution (Bonawitz, Denison, Griffiths, & Gopnik, 2014). For example, in a paradigm close to Bonawitz and Lombrozo's simplicity experiment (2012), children were shown a box full of red and blue chips in different proportions and were asked to predict which chip was most likely to have fallen out of a "spilled" bag to activate a machine (Denison, Bonawitz, Gopnik, & Griffiths, 2013). Children's responses were variable—the same child would sometimes say "red" and sometimes say "blue." But they also closely tracked the probability of the relevant hypotheses—children said "red" more often when that was more likely to be the correct answer. In follow-up work, Bonawitz et al. (2011, 2014) proposed different specific sampling rules, such as a win-stay, lose-sample strategy that greatly reduces the computational demands of causal structure search; they showed that in simple causal learning paradigms, children and adults' behavior matched well with the predictions of this algorithm. Although these algorithmic approaches (p. 694) offer a promising potential solution to the search problem, we have only just begun to explore which algorithms best capture young learners' causal learning. Future work is needed to understand the degree to which these algorithms solve the search problem and capture causal learning behavior more generally.

A potential limitation of our claims is that the focus of the research discussed here comes primarily from "WEIRD" populations (Western Educated Industrialized Rich Democratic). Indeed, many studies show important cultural differences in causal, categorical inferences (e.g., Coley, 2000; Lopez et al., 1997; Ross et al., 2003). Other studies have demonstrated cultural and developmental differences in identifying causes, such as "scientific" versus "magical" mechanisms (Subbotsky, 2001; Subbotsky & Quinteros, 2002). However, the differences in causal inductive inferences found in these studies are almost certainly driven by cultural differences in the *content* of knowledge. It is less clear the degree to which experience shapes the *form* of causal learning. That is, we have suggested that causal reasoning is driven by the interaction of data and inductive constraints, and it is unlikely that this process is radically different across cultures. However, if some inductive constraints are learned, this could explain additional cross-cultural differences in causal learning (see Bender, Beller, & Medin, Chapter 35 in this volume, for further discussion).

In sum, understanding the development of causal reasoning can have both near- and far-reaching implications. On the near side, understanding the origins of causal reasoning and how it changes over the course of development can help us to better understand the process by which we continue to discover and learn about causal structure throughout adulthood. On the far side, given the ubiquity of causal reasoning in higher-order cognition, understanding causal reasoning early in development can have implications for our understanding of the origins and development of our conceptual system more broadly.

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Notes:

(1.) The term "agents" can refer to three distinct kinds of individuals. The common, general use of "agents" in developmental research refers to intentional beings, such as people. We use the abstract term "agents," rather than a more specific terms such as "people," since studies have shown that infants and adults alike are able to engage in social reasoning about individuals that behave like people (e.g., an object that appears to move on its own and change direction) despite not looking like a person. "Dispositional agents" refer to individuals that are capable of intentional and causal actions—these are enduring properties of the individual. In contrast, "situational agents" are the causes of an outcome in a given situation, but do not necessarily have enduring causal powers outside of that situation (e.g., a billiard ball can cause another ball to move, but is not independently capable of causing motion). We refer to all three notions of agency throughout this chapter and specify the specific notion of agency throughout ("agents," "dispositional agents," "situational agents").

(2.) As discussed earlier, the term "situational agent" refers to an individual that causes an outcome in a given situation, without specifying whether the ability to cause an outcome is an enduring property of the individual. Similarly, the term "situational patient" refers to an individual that undergoes a change in a given causal event, without specifying whether the individual is incapable of causing another event to occur. "Patient" is used instead of "effect" to distinguish between the individual that undergoes a change ("patient") and the change itself ("effect").

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