Chapter 4

The Emergence of Scientific Reasoning

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1. Introduction

Scientific reasoning encompasses the reasoning and problem-solving skills involved in generating, testing and revising hypotheses or theories, and in the case of fully developed skills, reflecting on the process of knowledge acquisition and knowledge change that results from such inquiry activities. Science, as a cultural institution, represents a "hallmark intellectual achievement of the human species" and these achievements are driven by both individual reasoning and collaborative cognition (Feist, 2006, p. ix).

Our goal in this chapter is to describe how young children build from their natural curiosity about their world to having the skills for systematically observing, predicting, and understanding that world. We suggest that scientific reasoning is a specific type of intentional information seeking, one that shares basic reasoning mechanisms and motivation with other types of information seeking (Kuhn, 2011a). For example, curiosity is a critical motivational component that underlies information seeking (Jirout & Klahr, 2012), yet only in scientific reasoning is curiosity sated by deliberate data collection and formal analysis of evidence. In this way, scientific reasoning differs from other types of information seeking in that it requires additional cognitive resources as well as an integration of cultural tools. To that end, we provide an overview of how scientific reasoning emerges from the interaction between internal factors (e.g., cognitive and metacognitive development) and cultural and contextual factors.

The current state of empirical research on scientific reasoning presents seemingly contradictory conclusions. Young children are sometimes deemed "little scientists" because they appear to have abilities that are used in formal scientific reasoning (e.g., causal reasoning; Gopnik et al., 2004). At the same time, many studies show that older children (and sometimes adults) have difficulties with scientific reasoning. For example, children have difficulty in systematically designing controlled experiments, in drawing appropriate conclusions based on evidence, and in interpreting evidence (e.g., Croker, 2012; Chen & Klahr, 1999; Kuhn, 1989; Zimmerman, 2007).

In the following account, we suggest that despite the early emergence of many of the precursors of skilled scientific reasoning, its developmental trajectory is slow and requires instruction, support, and practice. In Section 2 of the chapter, we discuss cognitive and metacognitive factors. We focus on two mechanisms that play a critical role in all cognitive processes (i.e., encoding and strategy acquisition/selection). *Encoding* involves attention to relevant information; it is foundational in all reasoning. *Strategy use* involves intentional approaches to seeking new knowledge and synthesizing existing knowledge. These two mechanisms are key components for any type of intentional information seeking yet follow a slightly different development trajectory in the development of scientific reasoning skills. We then discuss the analogous development of metacognitive awareness of what is being encoded, and metastrategic skills for choosing and deploying hypothesis testing and inference strategies. In Section 3, we describe the role of contextual factors such as direct and scaffolded instruction, and the cultural tools that support the development of the cognitive and metacognitive skills required for the emergence of scientific thinking.

2. The development of scientific reasoning

Effective scientific reasoning requires both deductive and inductive skills. Individuals must understand how to assess what is currently known or believed, develop testable questions, test hypotheses, and draw appropriate conclusions by coordinating empirical evidence and theory. Such reasoning also requires the ability to attend to information systematically and draw reasonable inferences from patterns that are observed. Further, it requires the ability to assess one's reasoning at each stage in the process. Here, we describe some of the key issues in developing these cognitive and metacognitive scientific reasoning skills.

2.1. Cognitive processes and mechanisms

The main task for developmental researchers is to explain how children build on their intuitive curiosity about the world to become skilled scientific reasoners. *Curiosity*, defined as "the threshold of desired uncertainty in the environment that leads to exploratory behavior" (Jirout & Klahr, 2012, p. 150), will lead to information seeking. Information seeking activates a number of basic cognitive mechanisms that are used to extract (encode) information from the environment and then children (and adults) can act on this information in order to achieve a goal (i.e., use a strategy; Klahr, 2001; Kuhn, 2010). We turn our discussion to two such mechanisms and discuss how these mechanisms underlie the development of a specific type of information seeking: scientific reasoning.

A mechanistic account of the development of scientific reasoning includes information about the processes by which this change occurs, and how these processes lead to change over time (Klahr, 2001). Mechanisms can be described at varying levels (e.g., neurological, cognitive, interpersonal) and over different time scales. For example, neurological mechanisms (e.g., inhibition) operate at millisecond time scales (Burlea, Vidala, Tandonneta, & Hasbroucq, 2004) while learning mechanisms may operate over the course of minutes (e.g., inhibiting irrelevant information during problem solving; Becker, 2010). Many of the

cognitive processes and mechanisms that account for learning and for problem solving across a variety of domains are important to the development of scientific reasoning skills and science knowledge acquisition. Many cognitive mechanisms have been identified as underlying scientific reasoning and other high-level cognition (e.g., analogy, statistical learning, categorization, imitation, inhibition; Goswami, 2008). However, due to space limitations we focus on what we argue are the two most critical mechanisms – *encoding* and *strategy development* – to illustrate the importance of individual level cognitive abilities.

2.1.1. Encoding

Encoding is the process of representing information and its context in memory as a result of attention to stimuli (Chen, 2007; Siegler, 1989). As such, it is a central mechanism in scientific reasoning because we must represent information before we can reason about it, and the quality and process of representation can affect reasoning. Importantly, there are significant developmental changes in the ability to encode the relevant features that will lead to sound reasoning and problem solving (Siegler, 1983; 1985). Encoding abilities improve with the acquisition of *encoding strategies* and with increases in children's *domain knowledge* (Siegler, 1989). Young children often encode irrelevant features due to limited domain knowledge (Gentner, Loewenstein, & Thompson, 2003). For example, when solving problems to make predictions about the state of a two-arm balance beam (i.e., tip left, tip right, or balance), children often erroneously encode distance to the fulcrum and amount of weight as a single factor, decreasing the likelihood of producing a correct solution (which requires weight and distance to be encoded and considered separately as causal factors, while recognizing non-causal factors such as color; Amsel, Goodman, Savoie, & Clark, 1996; Siegler, 1983). Increased domain knowledge helps children assess more effectively what information is and is not necessary to encode. Further, children's encoding often improves with the acquisition of encoding strategies. For example, if a child is attempting to recall the location of an item in a complex environment, she may err in encoding only the features of the object itself without encoding its relative position. With experience, she may encode the relations between the target item and other objects (e.g., the star is in front of the box), a strategy known as cue learning. Encoding object position and relative position increases the likelihood of later recall and is an example of how encoding better information is more important than simply encoding more information (Chen, 2007; Newcombe & Huttenlocher, 2000).

Effective encoding is dependent on directing attention to *relevant* information, which in turn leads to accurate representations that can guide reasoning. Across a variety of tasks, experts are more likely to attend to critical elements in problem solving, and less likely to attend to irrelevant information, compared to novices (Gobet, 2005). *Domain knowledge* plays an important role in helping to guide attention to important features. Parents often direct a child's attention to critical problem features during problem solving. For example, a parent may keep track of which items have been counted in order to help a child organize counting (Saxe, Guberman, & Gearhart, 1987). Instructional interventions in which children were directed towards critical elements in problem solving improved their attention to these

features (Kloos & Van Orden, 2005). Although domain knowledge is helpful in directing attention to critical features, it may sometimes limit novel reasoning in a domain and limit the extent to which attention is paid to disconfirming evidence (Li & Klahr, 2006). Finally, *self-generated activity* improves encoding. Self-generation of information from memory, rather than passive attention, is associated with more effective encoding because it recruits greater attentional resources than passive encoding (Chi, 2009).

2.1.2. Strategy development

Strategies are sequences of procedural actions used to achieve a goal (Siegler, 1996). In the context of scientific reasoning, strategies are the steps that guide children from their initial state (e.g., a question about the effects of weight and distance in balancing a scale) to a goal state (e.g., understanding the nature of the relationship between variables). We will briefly examine two components of strategy development: *strategy acquisition* and *strategy selection*. Strategies are particularly important in the development of scientific reasoning. Children often actively explore objects in a manner that is like hypothesis testing; however, these exploration strategies are not systematic investigations in which variables are manipulated and controlled as in formal hypothesis-testing strategies (Klahr, 2000). The acquisition of increasingly optimal strategies for hypothesis testing, inference, and evidence evaluation leads to more effective scientific reasoning that allows children to construct more veridical knowledge.

New strategies are added to the repertoire of possible strategies through discovery, instruction, or other social interactions (Chen, 2007; Gauvain, 2001; Siegler, 1996). There is evidence that children can discover strategies on their own (Chen, 2007). Children often discover new strategies when they experience an insight into a new way of solving a familiar problem. For example, 10- and 11-year-olds discovered new strategies for evaluating causal relations between variables in a computerized task only after creating different cars (e.g., comparing the effects of engine size) and testing them (Schauble, 1990). Similarly, when asked to determine the cause of a chemical reaction, children discovered new experimentation strategies only after several weeks (Kuhn & Phelps, 1982). Over time, existing strategies may be modified to reduce time and complexity of implementation (e.g., eliminating redundant steps in a problem solving sequence; Klahr, 1984). For example, determining causal relations among variables requires more time when experimentation is unsystematic. In order to identify which variables resulted in the fastest car, children often constructed up to 25 cars, whereas an adult scientist identified the fastest car after constructing only seven cars (Schauble, 1990).

Children also gain new strategies through social interaction, by being explicitly taught a strategy, imitating a strategy, or by collaborating in problem solving (Gauvain, 2001). For example, when a parent asks a child questions about events in a photograph, the parent evokes memories of the event and helps to structure the child's understanding of the depicted event, a process called conversational remembering (Middleton, 1997). Conversational remembering improves children's recall of events and often leads to children spontaneously using this strategy. Parent conversations about event structures

improved children's memory for these structures; for example, questions about a child's day at school help to structure this event and improved recall (Nelson, 1996). Children also learn new strategies by solving problems cooperatively with adults. In a sorting task, preschool children were more likely to improve their classification strategies after working with their mothers (Freund, 1990). Further, children who worked with their parents on a hypothesis-testing task were more likely to identify causal variables than children who worked alone because parents helped children construct valid experiments, keep data records, and repeat experiments (Gleason & Schauble, 2000).

Children also acquire strategies by interacting with an adult modeling a novel strategy. Middle-school children acquired a reading comprehension strategy (e.g., anticipating the ending of a story) after seeing it modeled by their teacher (Palinscar, Brown, & Campione, 1993). Additionally, children can acquire new strategies from interactions with other children. Monitoring other children during problem solving improves a child's understanding of the task and appears to improve how they evaluate their own performance (Brownell & Carriger, 1991). Elementary school children who collaborated with other students to solve the balance-scale task outperformed students who worked alone (Pine & Messer, 1998). Ten-year-olds working in dyads were more likely to discuss their strategies than children working alone and these discussions were associated with generating better hypotheses than children working alone (Teasley, 1995).

More than one strategy may be useful for solving a problem, which requires a means to select among candidate strategies. One suggestion is that this process occurs by adaptive selection. In adaptive selection, strategies that match features of the problem are candidates for selection. One component of selection is that newer strategies tend to have a slightly higher priority for use when compared to older strategies (Siegler, 1996). Successful selection is made on the basis of the effectiveness of the strategy and its cost (e.g., speed), and children tend to choose the fastest, most accurate strategy available (i.e., the most adaptive strategy).

Cognitive mechanisms provide the basic investigation and inferential tools used in scientific reasoning. The ability to reason about knowledge and the means for obtaining and evaluating knowledge provide powerful tools that augment children's reasoning. *Metacognitive abilities* such as these may help explain some of the discrepancies between early scientific reasoning abilities and limitations in older children, as well as some of the developmental changes in encoding and strategy use.

2.2. Metacognitive and metastrategic processes

Sodian, Zaitchik, and Carey (1991) argue that two basic skills related to early metacognitive acquisitions are needed for scientific reasoning. First, children need to understand that inferences can be drawn from evidence. The theory of mind literature (e.g., Wellman, Cross, & Watson, 2001) suggests that it is not until the age of 4 that children understand that beliefs and knowledge are based on perceptual experience (i.e., evidence). As noted earlier, experimental work demonstrates that preschoolers can use evidence to make judgments

about simple causal relationships (Gopnik, Sobel, Schulz, & Glymour, 2001; Schulz & Bonawitz, 2007; Schulz & Gopnik, 2004; Schulz, Gopnik,& Glymour, 2007). Similarly, several classic studies show that children as young as 6 can succeed in simple scientific reasoning tasks. Children between 6 and 9 can discriminate between a conclusive and an inclusive test of a simple hypothesis (Sodian et al., 1991). Children as young as 5 can form a causal hypothesis based on a pattern of evidence, and even 4-year-olds seem to understand some of the principles of causal reasoning (Ruffman, Perner, Olson, & Doherty, 1993).

Second, according to Sodian et al. (1991), children need to understand that inference is itself a mechanism with which further knowledge can be acquired. Four-year-olds base their knowledge on perceptual experiences, whereas 6-year-olds understand that the testimony of others can also be used in making inferences (Sodian & Wimmer, 1987). Other research suggests that children younger than 6 can make inferences based on testimony, but in very limited circumstances (Koenig, Clément, & Harris, 2004). These findings may explain why, by the age of 6, children are able to succeed on *simple* causal reasoning, hypothesis testing, and evidence evaluation tasks.

Research with older children, however, has revealed that 8- to 12-year-olds have limitations in their abilities to (a) generate unconfounded experiments, (b) disconfirm hypotheses, (c) keep accurate and systematic records, and (d) evaluate evidence (Klahr, Fay, & Dunbar, 1993; Kuhn, Garcia-Mila, Zohar, & Andersen, 1995; Schauble, 1990, 1996; Zimmerman, Raghavan, & Sartoris, 2003). For example, Schauble (1990) presented children aged 9-11 with a computerized task in which they had to determine which of five factors affect the speed of racing cars. Children often varied several factors at once (only 22% of the experiments were classified as valid) and they often drew conclusions consistent with belief rather than the evidence generated. They used a positive test strategy, testing variables believed to influence speed (e.g., engine size) and not testing those believed to be non-causal (e.g., color). Some children recorded features without outcomes, or outcomes without features, but most wrote down nothing at all, relying on memory for details of experiments carried out over an eight-week period.

Although the performance differences between younger and older children may be interpreted as potentially contradictory, the differing cognitive and metacognitive demands of tasks used to study scientific reasoning at different ages may account for some of the disconnect in conclusions. Even though the simple tasks given to preschoolers and young children require them to understand evidence as a source of knowledge, such tasks require the cognitive abilities of induction and pattern recognition, but only limited metacognitive abilities. In contrast, the tasks used to study the development of scientific reasoning in older children (and adults) are more demanding and focused on hypothetico-deductive reasoning; they include more variables, involve more complex causal structures, require varying levels of domain knowledge, and are negotiated across much longer time scales. Moreover, the tasks given to older children and adults involve the acquisition, selection, and coordination of investigation strategies, combining background knowledge with empirical evidence. The results of investigation activities are then used in the acquisition, selection, and coordination

of evidence evaluation and inference strategies. With respect to encoding, increases in task complexity require attending to more information and making judgments about which features are relevant. This encoding happens in the context of prior knowledge and, in many cases, it is also necessary to inhibit prior knowledge (Zimmerman & Croker, in press).

Sodian and Bullock (2008) also argue that mature scientific reasoning involves the metastrategic process of being able to think explicitly about hypotheses and evidence, and that this skill is not fully mastered until adolescence at the very earliest. According to Amsel et al. (2008), metacognitive competence is important for hypothetical reasoning. These conclusions are consistent with Kuhn's (1989, 2005, 2011a) argument that the defining feature of scientific thinking is the set of cognitive and metacognitive skills involved in differentiating and coordinating theory and evidence. Kuhn argues that the effective coordination of theory and evidence depends on three metacognitive abilities: (a) The ability to encode and represent evidence and theory separately, so that relations between them can be recognized; (b) the ability to treat theories as independent objects of thought (i.e., rather than a representation of "the way things are"); and (c) the ability to recognize that theories can be false, setting aside the acceptance of a theory so evidence can be assessed to determine the veridicality of a theory. When we consider these cognitive and metacognitive abilities in the larger social context, it is clear that skills that are highly valued by the scientific community may be at odds with the cultural and intuitive views of the individual reasoner (Lemke, 2001). Thus, it often takes time for conceptual change to occur; evidence is not just evaluated in the context of the science investigation and science classroom, but within personal and community values. Conceptual change also takes place in the context of an individual's personal epistemology, which can undergo developmental transitions (e.g., Sandoval, 2005).

2.2.1. Encoding and strategy use

Returning to the encoding and retrieval of information relevant to scientific reasoning tasks, many studies demonstrate that both children and adults are not always aware of their memory limitations while engaged in investigation tasks (e.g., Carey, Evans, Honda, Jay, & Unger, 1989; Dunbar & Klahr, 1989; Garcia-Mila & Andersen, 2007; Gleason & Schauble, 2000; Siegler & Liebert, 1975; Trafton & Trickett, 2001). Kanari and Millar (2004) found that children differentially recorded the results of experiments, depending on familiarity or strength of prior beliefs. For example, 10- to 14-year-olds recorded more data points when experimenting with unfamiliar items (e.g., using a force-meter to determine the factors affecting the force produced by the weight and surface area of boxes) than with familiar items (e.g., using a stopwatch to experiment with pendulums). Overall, children are less likely than adults to record experimental designs and outcomes, or to review notes they do keep, despite task demands that clearly necessitate a reliance on external memory aids.

Children are often asked to judge their memory abilities, and memory plays an important role in scientific reasoning. Children's understanding of memory as a fallible process

develops over middle childhood (Jaswal & Dodson, 2009; Kreuzer, Leonard, & Flavell, 1975). Young children view all strategies on memory tasks as equally effective, whereas 8- to 10-year-olds start to discriminate between strategies, and 12-year-olds know which strategies work best (Justice, 1986; Schneider, 1986). The development of metamemory continues through adolescence (Schneider, 2008), so there may not be a particular age that memory and metamemory limitations are no longer a consideration for children and adolescents engaged in complex scientific reasoning tasks. However, it seems likely that metamemory limitations are more profound for children under 10-12 years.

Likewise, the acquisition of other metacognitive and metastrategic skills is a gradual process. Early strategies for coordinating theory and evidence are replaced with better ones, but there is not a stage-like change from using an older strategy to a newer one. Multiple strategies are concurrently available so the process of change is very much like Siegler's (1996) overlapping waves model (Kuhn et al., 1995). However, *metastrategic competence* does not appear to routinely develop in the absence of instruction. Kuhn and her colleagues have incorporated the use of specific practice opportunities and prompts to help children develop these types of competencies. For example, Kuhn, Black, Keselman, and Kaplan (2000) incorporated performance-level practice and metastrategic-level practice for sixth- to eighth-grade students. Performance-level exercise consisted of standard exploration of the task environment, whereas metalevel practice consisted of scenarios in which two individuals disagreed about the effect of a particular feature in a multivariable situation. Students then evaluated different strategies that could be used to resolve the disagreement. Such scenarios were provided twice a week during the course of ten weeks. Although no performance differences were found between the two types of practice with respect to the number of valid inferences, there were more sizeable differences in measures of understanding of task objectives and strategies (i.e., metastrategic understanding).

Similarly, Zohar and Peled (2008) focused instruction in the control-of-variables strategy (CVS) on metastrategic competence. Fifth-graders were given a computerized task in which they had to determine the effects of five variables on seed germination. Students in the control group were taught about seed germination, and students in the experimental group were given a metastrategic knowledge intervention over several sessions. The intervention consisted of describing CVS, discussing when it should be used, and discussing what features of a task indicate that CVS should be used. A second computerized task on potato growth was used to assess near transfer. A physical task in which participants had to determine which factors affect the distance a ball will roll was used to assess far transfer. The experimental group showed gains on both the strategic and the metastrategic level. The latter was measured by asking participants to explain what they had done. These gains were still apparent on the near and far transfer tasks when they were administered three months later. Moreover, low-academic achievers showed the largest gains. It is clear from these studies that although meta-level competencies may not develop routinely, they can certainly be learned via explicit instruction.

Metacognitive abilities are necessary precursors to sophisticated scientific thinking, and represent one of the ways in which children, adults, and professional scientists differ. In order for children's behavior to go beyond demonstrating the correctness of one's existing beliefs (e.g., Dunbar & Klahr, 1989) it is necessary for meta-level competencies to be developed and practiced (Kuhn, 2005). With metacognitive control over the processes involved, children (and adults) can change what they believe based on evidence and, in doing so, are aware not only that they are changing a belief, but also know *why* they are changing a belief. Thus, sophisticated reasoning involves both the use of various strategies involved in hypothesis testing, induction, inference, and evidence evaluation, and a meta-level awareness of when, how, and why one should engage in these strategies.

3. Scientific reasoning in context

Much of the existing laboratory work on the development of scientific thinking has not *overtly* acknowledged the role of contextual factors. Although internal cognitive and metacognitive processes have been a primary focus of past work, and have helped us learn tremendously about the processes of scientific thinking, we argue that many of these studies focused on individual cognition have, in fact, included both social factors (in the form of, for example, collaborations with other students, or scaffolds by parents or teachers) and cultural tools that support scientific reasoning.

3.1. Instructional and peer support: The role of others in supporting cognitive development

Our goal in this section is to re-examine our two focal mechanisms (i.e., encoding and strategy) and show how the development of these cognitive acquisitions and metastrategic control of them are facilitated by both the social and physical environment.

3.1.1. Encoding

Children must learn to encode effectively, by knowing what information is critical to pay attention to. They do so in part with the aid of their teachers, parents, and peers. Once school begins, teachers play a clear role in children's cognitive development. An ongoing debate in the field of science education concerns the relative value of having children learn and discover how the world works on their own (often called "discovery learning") and having an instructor guide the learning more directly (often called "direct instruction"). Different researchers interpret these labels in divergent ways, which adds fuel to the debate (see e.g., Bonawitz et al., 2011; Hmelo-Silver, Duncan, & Chinn, 2007; Kirshner, Sweller, & Clark, 2006; Klahr, 2010; Mayer, 2004; Schmidt, Loyens, van Gog, & Paas, 2007). Regardless of definitions, though, this issue illustrates the core idea that learning takes place in a social context, with guidance that varies from minimal to didactic.

Specifically, this debate is about the ideal role for adults in helping children to encode information. In direct instruction, there is a clear role for a teacher, often actively pointing out effective examples as compared to ineffective ones, or directly teaching a strategy to apply to new examples. And, indeed, there is evidence that more direct guidance to test variables systematically can help students in learning, particularly in the ability to apply their knowledge to new contexts (e.g., Klahr & Nigam, 2004; Lorch et al., 2010; Strand-Cary & Klahr, 2008). There is also evidence that scaffolded discovery learning can be effective (e.g., Alfieri, Brooks, Adrich, & Tenenbaum, 2011). Those who argue for discovery learning often do so because they note that pedagogical approaches commonly labeled as "discovery learning," such as problem-based learning and inquiry learning, are in fact highly scaffolded, providing students with a structure in which to explore (Alfieri et al., 2011; Hmelo-Silver et al., 2007; Schmidt et al., 2007). Even in microgenetic studies in which children are described as engaged in "self-directed learning," researchers ask participants questions along that way that serve as prompts, hints, dialogue, and scaffolds that facilitate learning (Klahr & Carver, 1995). What there appears to be little evidence for is "pure discovery learning" in which students are given little or no guidance and expected to discover rules of problem solving or other skills on their own (Alfieri et al., 2011; Mayer, 2004). Thus, it is clear that formal education includes a critical role for a teacher to scaffold children's scientific reasoning.

A common goal in science education is to correct the many misconceptions students bring to the classroom. Chinn and Malhotra (2002) examined the role of encoding evidence, interpreting evidence, generalization, and retention as possible impediments to correcting misconceptions. Over four experiments, they concluded that the key difficulty faced by children is in making accurate observations or properly encoding evidence that does not match prior beliefs. However, interventions involving an explanation of what scientists expected to happen (and why) were very effective in mediating conceptual change when encountering counterintuitive evidence. That is, with scaffolds, children made observations independent of theory, and changed their beliefs based on observed evidence. For example, the initial belief that a thermometer placed inside a sweater would display a higher temperature than a thermometer outside a sweater was revised after seeing evidence that disconfirmed this belief and hearing a scientist's explanation that the temperature would be the same unless there was something warm inside the sweater. Instructional supports can play a crucial role in improving the encoding and observational skills required for reasoning about science.

In laboratory studies of reasoning, there is direct evidence of the role of adult scaffolding. Butler and Markman (2012a) demonstrate that in complex tasks in which children need to find and use evidence, causal verbal framing (i.e., asking whether one event caused another) led young children to more effectively extract patterns from scenes they observed, which in turn led to more effective reasoning. In further work demonstrating the value of adult scaffolding in children's encoding, Butler and Markman (2012b) found that by age 4, children are much more likely to explore and make inductive inferences when adults intentionally try to teach something than when they are shown an "accidental" effect.

3.1.2. Strategy development and use

As discussed earlier in this chapter, learning which strategies are available and useful is a fundamental part of developing scientific thinking skills. Much research has looked at the role of adults in teaching strategies to children in both formal (i.e., school) and informal settings (e.g., museums, home; Fender & Crowley, 2007; Tenenbaum, Rappolt-Schlichtmann, & Zanger, 2004).

A central task in scientific reasoning involves the ability to design controlled experiments. Chen and Klahr (1999) found that directly instructing 7- to 10-year-old children in the strategies for designing unconfounded experiments led to learning in a short time frame. More impressively, the effectiveness of the training was shown seven months later, when older students given the strategy training were much better at correctly distinguishing confounded and unconfounded designs than those not explicitly trained in the strategy. In another study exploring the role of scaffolded strategy instruction, Kuhn and Dean (2005) worked with sixth graders on a task to evaluate the contribution of different factors to earthquake risk. All students given the suggestion to focus attention on just one variable were able to design unconfounded experiments, compared to only 11% in the control group given their typical science instruction. This ability to design unconfounded experiments increased the number of valid inferences in the intervention group, both immediately and three months later. Extended engagement alone resulted in minimal progress, confirming that even minor prompts and suggestions represent potentially powerful scaffolds. In yet another example, when taught to control variables either with or without metacognitive supports, 11-year-old children learned more when guided in thinking about how to approach each problem and evaluate the outcome (Dejonckheere, Van de Keere, & Tallir, 2011). Slightly younger children did not benefit from the same manipulation, but 4- to 6-year-olds given an adapted version of the metacognitive instruction were able to reason more effectively about simpler physical science tasks than those who had no metacognitive supports (Dejonckheere, Van de Keere, & Mestdagh, 2010).

3.2. Cultural tools that support scientific reasoning

Clearly, even with the number of studies that have focused on individual cognition, a picture is beginning to emerge to illustrate the importance of social and cultural factors in the development of scientific reasoning. Many of the studies we describe highlight that even "controlled laboratory studies" are actually scientific reasoning in context. To illustrate, early work by Siegler and Liebert (1975) includes both an instructional context (a control condition plus two types of instruction: *conceptual framework*, and *conceptual framework plus analogs*) and the role of cultural supports. In addition to traditional instruction about variables (factors, levels, tree diagrams), one type of instruction included practice with analogous problems. Moreover, 10- and 13-year-olds were provided with paper and pencil to keep track of their results. A key finding was that *record keeping* was an important mediating factor in success. Children who had the metacognitive awareness of memory limitations and therefore used the provided paper for record keeping were more successful

at producing all possible combinations necessary to manipulate and isolate variables to test hypotheses.

3.2.1. Cultural resources to facilitate encoding and strategy use

The sociocultural perspective highlights the role that language, speech, symbols, signs, number systems, objects, and tools play in individual cognitive development (Lemke, 2001). As highlighted in previous examples, adult and peer collaboration, dialogue, and other elements of the social environment are important mediators. In this section, we highlight some of the verbal, visual, and numerical elements of the physical context that support the emergence of scientific reasoning.

Most studies of scientific reasoning include some type of *verbal* and *pictorial representation* as an aid to reasoning. As encoding is the first step in solving problems and reasoning, the use of such supports reduces cognitive load. In studies of hypothesis testing strategies with children (e.g., Croker & Buchanan, 2011; Tschirgi, 1980), for example, multivariable situations are described both verbally and with the help of pictures that represent variables (e.g., type of beverage), levels of the variable (e.g., cola vs. milk), and hypothesis-testing strategies (see Figure 1, panel A). In classic work by Kuhn, Amsel, and O'Loughlin (1988), a picture is provided that includes the outcomes (children depicted as healthy or sick) along with the levels of four dichotomous variables (e.g., orange/apple, baked potato/French fries, see Kuhn et al., 1988, pp. 40-41). In fact, most studies that include children as participants provide pictorial supports (e.g., Ruffman et al., 1993; Koerber, Sodian, Thoermer, & Nett, 2005). Even at levels of increasing cognitive development and expertise, diagrams and visual aids are regularly used to support reasoning (e.g., Schunn & Dunbar, 1996; Trafton & Trickett, 2001; Veermans, van Joolingen, & de Jong, 2006).

(A) (B) (C)

Figure 1. Panel A illustrates the type of pictorial support that accompanies the verbal description of a hypothesis-testing task (from Croker & Buchanan, 2011). Panel B shows an example of a physical apparatus (from Triona & Klahr, 2007). Panel C shows a screenshot from an intelligent tutor designed to teach how to control variables in experimental design (Siler & Klahr, 2012; see http://tedserver.psy.cmu.edu/demo/ted4.html, for a demonstration of the tutor).

Various elements of *number and number systems* are extremely important in science. Sophisticated scientific reasoning requires an understanding of data and the evaluation of numerical data. Early work on evidence evaluation (e.g., Shaklee, Holt, Elek, & Hall, 1988) included 2 x 2 contingency tables to examine the types of strategies children and adults used (e.g., comparing numbers in particular cells, the "sums of diagonals" strategy). Masnick and Morris (2008) used data tables to present evidence to be evaluated, and varied features of the presentation (e.g., sample size, variability of data). When asked to make decisions without the use of statistical tools, even third- and sixth-graders had rudimentary skills in detecting trends, overlapping data points, and the magnitude of differences. By sixth grade, participants had developing ideas about the importance of variability and the presence of outliers for drawing conclusions from numerical data.

Although language, symbols, and number systems are used as canonical examples of cultural tools and resources within the socio-cultural tradition (Lemke, 2001), recent advances in *computing and computer simulation* are having a huge impact on the development and teaching of scientific reasoning. Although many studies have incorporated the use of physical systems (Figure 1, panel B) such as the canal task (Gleason & Schauble, 2000), the ramps task (e.g., Masnick & Klahr, 2003), mixing chemicals (Kuhn & Ho, 1980), and globes (Vosniadou, Skopeliti, & Ikospentaki, 2005), there is an increase in the use of interactive computer simulations (see Figure 1, panel C). Simulations have been developed for electric circuits (Schauble, Glaser, Raghavan, & Reiner, 1992), genetics (Echevarria, 2003), earthquakes (Azmitia & Crowley, 2001), flooding risk (Keselman, 2003), human memory (Schunn & Anderson, 1999), and visual search (Métrailler, Reijnen, Kneser, & Opwis, 2008). Non-traditional science domains have also been used to develop inquiry skills. Examples include factors that affect TV enjoyment (Kuhn et al., 1995), CD catalog sales (Dean & Kuhn, 2007), athletic performance (Lazonder, Wilhelm, & Van Lieburg, 2009), and shoe store sales (Lazonder, Hagemans, & de Jong, 2010).

Computer simulations allow visualization of phenomena that are not directly observable in the classroom (e.g., atomic structure, planetary motion). Other advantages include that they are less prone to measurement error in apparatus set up, and that they can be programmed to record all actions taken (and their latencies). Moreover, many systems include a scaffolded method for participants to keep and consult records and notes. Importantly, there is evidence that simulated environments provide the same advantages as isomorphic "hands on" apparatus (Klahr, Triona, & Williams, 2007; Triona & Klahr, 2007).

New lines of research are taking advantage of advances in computing and intelligent computer systems. Kuhn (2011b) recently examined how to facilitate reasoning about multivariable causality, and the problems associated with the visualization of outcomes resulting from multiple causes (e.g., the causes for different cancer rates by geographical area). Participants had access to software that produces a visual display of data points that represent main effects and their interactions. Similarly, Klahr and colleagues (Siler, Mowery, Magaro, Willows, & Klahr, 2010) have developed an intelligent tutor to teach experimentation

strategies (see Figure 1, panel C). The use of intelligent tutors provides the unique opportunity of personally tailored learning and feedback experiences, dependent on each student's pattern of errors. This immediate feedback can be particularly useful in helping develop metacognitive skills (e.g., Roll, Alaven, McLaren, & Koedinger, 2011) and facilitate effective student collaboration (Diziol, Walker, Rummel, & Koedinger, 2010).

Tweney, Doherty, and Mynatt (1981) noted some time ago that most tasks used to study scientific thinking were artificial because real investigations require *aided* cognition. However, as can be seen by several exemplars, even lab studies include support and assistance for many of the known cognitive limitations faced by both children and adults.

4. Summary and conclusions

Determining the developmental trajectory of scientific reasoning has been challenging, in part because *scientific reasoning* is not a unitary construct. Our goal was to outline how the investigation, evidence evaluation, and inference skills that constitute scientific reasoning emerge from intuitive information seeking via the interaction of individual and contextual factors. We describe the importance of (a) cognitive processes and mechanisms, (b) metacognitive and metastrategic skills, (c) the role of direct and scaffolded instruction, and (d) a context in which scientific activity is supported and which includes cultural tools (literacy, numeracy, technology) that facilitate the emergence of scientific reasoning. At the outset, we intended to keep section boundaries clean and neat. What was apparent to us, and may now be apparent to the reader, is that these elements are highly intertwined. It was difficult to discuss pure encoding in early childhood without noting the role that parents play. Likewise, it was difficult to discuss individual discovery of strategies, without noting such discovery takes place in the presence of peers, parents, and teachers. Similarly, discussing the teaching and learning of strategies is difficult without noting the role of cultural tools such as language, number, and symbol systems.

There is far more to a complete account of scientific reasoning than has been discussed here, including other cognitive mechanisms such as formal hypothesis testing, retrieval, and other reasoning processes. There are also relevant non-cognitive factors such as motivation, disposition, personality, argumentation skills, and personal epistemology, to name a few (see Feist, 2006). These additional considerations do not detract from our assertion that encoding and strategy use are critical to the development of scientific reasoning, and that we must consider cognitive and metacognitive skills within a social and physical context when seeking to understand the development of scientific reasoning. Scientific knowledge acquisition and, importantly, scientific knowledge *change* is the result of individual and social cognition that is mediated by education and cultural tools. The cultural institution of science has taken hundreds of years to develop. As individuals, we may start out with the curiosity and disposition to be little scientists, but it is a long journey from information seeking to skilled scientific reasoning, with the help of many scaffolds along the way.

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