Chapter 9

The Development and Application of Scientific Reasoning

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What is Scientific Reasoning?

Scientific reasoning is by definition a broad term, and encompasses the mental activities that are involved when people attempt to make systematic and empirical-based discoveries about the world. The goal of the scientific reasoning process, as highlighted by Zimmerman (2000), is to extend our world knowledge, thus allowing us to gain a more detailed and conceptually richer understanding of the domain of inquiry. Throughout this scientific reasoning process, people make use of several domain-general cognitive processes that are employed across different situations to facilitate the discovery process. It has been argued that these domain-general cognitive processes, such as causal reasoning, deductive reasoning, analogical reasoning, hypothesis testing, and problem solving, are the same cognitive tools that humans use in everyday nonscientific contexts (see Dunbar & Fugelsang, 2005, for broad coverage of these and other domain-general cognitive tools). In the current chapter, we will discuss how these domain-general cognitive processes, together with domain-specific knowledge, are used to support the scientific discovery process. We will focus the majority of this review on the use of causal reasoning, deductive reasoning, and analogical reasoning in scientific thinking, as they have received much empirical attention over the last several decades. In addition, throughout this review, we will concentrate much of our coverage on neuroimaging evidence, as it provides a means of assessing whether the same functional brain systems are active in

Educational Neuroscience, First Edition. Edited by Denis Mareschal, Brian Butterworth and Andy Tolmie.

adults and children of different ages, and importantly to establish any links that exist between physiological and behavioral changes with age. Several laboratories over the past decade have begun to explore the neural basis of reasoning, focusing on deductive reasoning, causal reasoning, and relational or analogical reasoning, predominantly in adults. In reviewing some of this work, we will make links between research conducted with children and adults to gain insights into how these competencies develop and change over time.

Before we discuss each of these domain-general reasoning processes, we will first provide a brief description of how domain-general cognitive processes are proposed to work together with conceptual representations (i.e., domain-specific knowledge) to support scientific thinking. In addition, we will briefly discuss how the two types of reasoning process have been examined historically. This overview will be necessarily brief, however, as an in-depth discussion of the historical approaches to such investigations is far beyond the scope of this chapter. The interested reader should refer to the comprehensive reviews and syntheses of this work by Corinne Zimmerman (2000, 2005, 2007), which significantly informed our synopsis below.

Historical Approaches to the Study of Domain-General and Domain-Specific Scientific Reasoning

As noted above, the process of scientific reasoning makes use of domain-general problem solving and reasoning skills coupled with domain-specific knowledge of the specific area under study. The process of scientific investigation, as exemplified by proficient adults, includes a broad range of procedural and conceptual activities, including, but by no means limited to, formulating hypotheses, designing experiments, making predictions, and collecting data (or making observations) (Klahr, Zimmerman, & Jirout, 2011; Zimmerman, 2005). In addition, once all of the data have been collected, one needs to carefully examine the data (often performing statistical analyses), which then leads to the evaluation and coordination of these new data with pre-existing theory. This latter stage is often complicated by the presence of contradictory data (i.e., data inconsistent with theory). Here, the reasoner may need to revise and update existing theories or models in order to accommodate the new data (Dunbar & Fugelsang, 2005; Fugelsang, Stein, Green, & Dunbar, 2004; Koslowski, 1996), or develop an entirely new theory altogether. These processes rely on a synergist interplay between domain-general reasoning skills (such as those alluded to above) and domain-specific content knowledge. As the coordination of domain-general and domain-specific activities is a highly complex process, researchers studying these processes in children and adults have traditionally attempted to focus their research programs on *either* the conceptual (i.e., domain-specific) *or* the procedural (i.e., domain-general) aspects of the scientific reasoning process in isolation (Zimmerman, 2005). As we will see below, however, this is not always possible.

Concerning the conceptual (i.e., domain-specific) approach, researchers following this research tradition have focused on investigating the nature of the *concepts* that individuals have about various phenomena in a variety of content domains (Zimmerman, 2000). Following this approach, the goal is often to describe and uncover the cognitive mechanisms underlying conceptual development or conceptual *change* as a function of new learning (which may require a radical shift in current ways of thinking) within a specific domain of study (Carey, 1985, 2000). Here, researchers are interested in children's and adults' level of understanding, the nature of their knowledge representations, and how their conceptual understanding (or knowledge representation) develops and changes about specific phenomena in a variety of scientific content areas, such as biology (e.g., Carey, 1985), climatology (Dunbar, Fugelsang, & Stein, 2007), and physics (McCloskey, 1983). Often, the research emphasis is concentrated on indexing the degree to which new conceptual knowledge changes (or overwrites) previously held naïve views, or whether both previously held naïve and new worldviews coexist in the mind (Dunbar et al., 2007; Shtulman & Valcarcel, 2012). These cognitive operations are highly relevant to scientific reasoning, as it is likely very rare that individuals would be faced with a situation that would require them to reason and make decisions in situations where they have no prior knowledge, experience, or conceptual representations. We will see in later sections of this chapter that domain-specific content influences reasoning processes (and subsequent brain recruitment) in significant ways.

Concerning the procedural approach, researchers have focused on understanding the development and application of domain-general skills, which are thought to be applied across multiple content domains in a relatively similar fashion (Zimmerman, 2005). Such empirical investigations have followed from the Piagetian research tradition (see, e.g., Inhelder & Piaget, 1958), whereby children are asked to scientifically reason (i.e., formulate and test hypotheses) while performing tasks that are thought to be relatively free from the influence of any domain-specific content knowledge that could impact performance (e.g., the balance-scale task; Siegler, 1976). The primary objective with this approach is to eliminate (or at least reduce) the potential impact of conceptual knowledge about specific content domains in order to observe how domain-general reasoning strategies are applied in a relatively knowledge-free manner (Zimmerman, 2005). It should be noted, however, that even with these relatively knowledge-free tasks children and adults often possess naïve views about their operation, and these naïve views can be very resilient to change (see, e.g., Pine &

Messer, 2000). Indeed, others have noted that many of the experimental tasks that have been used following this research tradition are arguably quite conceptually rich in nature (Zimmerman, 2005, 2007). Taken together, however, these early empirical approaches laid the foundation for later work looking at the integration of both domain-general and domain-specific reasoning processes.

In the following sections of this chapter, we will mainly focus on the latter scientific reasoning skills that underlie thinking processes in a scientific domain. As discussed above, these are thought to be domain-general skills and should be viewed as interacting with the domain-specific "conceptual" knowledge that is specific to any domain of inquiry. We focus first on causal reasoning, then deductive reasoning, and finally analogical reasoning. The main reason for focusing on these domains is that they are three of the key reasoning areas that underlie much of scientific reasoning (Dunbar & Fugelsang, 2005). In addition, and based on this importance, they are also some of the main domains of reasoning in which the methods of cognitive neuroscience have been applied to elucidate the neural systems and mechanisms that underlie largely adult performance, but also children's performance too. Within our coverage of each of these domain-general reasoning skills, we will discuss work that examines how domain-specific knowledge about problem content impacts these processes behaviorally and neurophysiologically.

Causal Reasoning

A central goal of many scientific investigations is the discovery of causal relations between key variables. Indeed, isolating causal relations is often the crucial first step in identifying underlying mechanisms governing relations, and eventually being able to control outcomes experimentally. For example, much of scientific theory development involves the construction of comprehensive causal models, which often requires the isolation and modeling of causal relations between variables of interest (Dunbar & Fugelsang, 2005). There are many examples of the primary role of causal reasoning in scientific theory development. For example, scientists have spent decades examining whether there is a causal relation between human activities on earth, greenhouse gases, and global warming (see Figure 9.1), and whether smoking causes cancer. In order to effectively develop causal models, scientists develop techniques that allow them to maximally discriminate between the causal candidates of theoretical interest, and extraneous variables that are also present in the environment.

In this section, we will discuss the types of cognitive operation that govern how one evaluates causal relations. We will begin by discussing evidence for two levels of causal reasoning, one involving perceptually based processes, and one

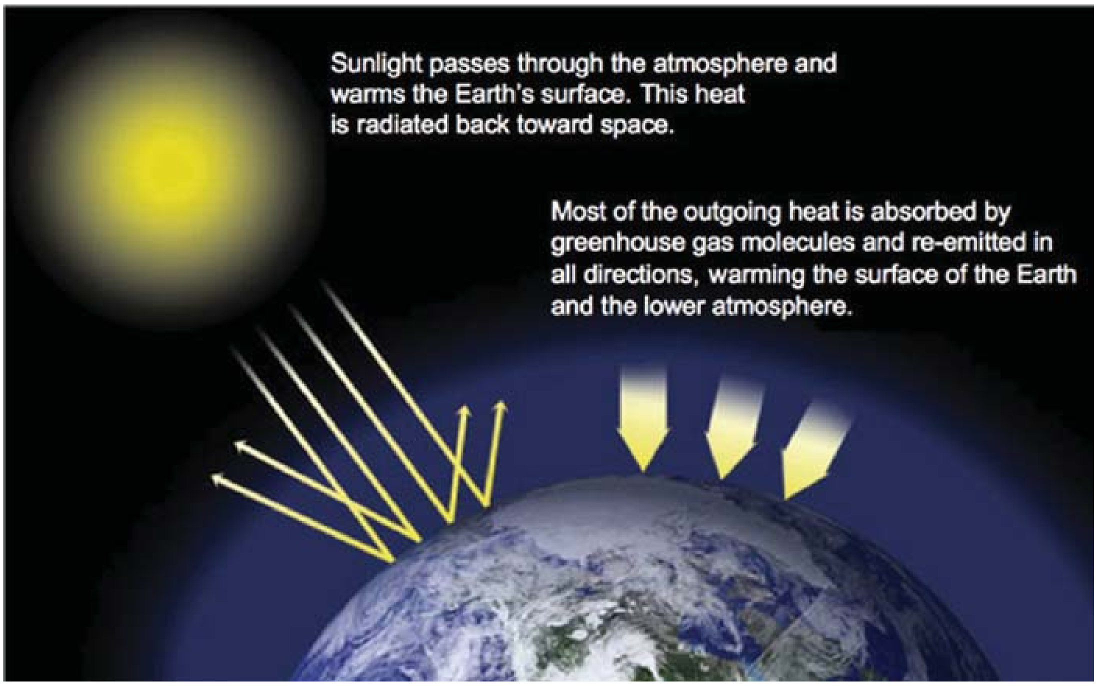


Figure 9.1 A contemporary example of causal reasoning in science is the work devoted to studying the possibility of complex causal relations between human activities on Earth and the greenhouse effect, which is thought to be resulting in global warming. Courtesy NASA's Global Climate Change Website.

involving inferential-based processes. We will then focus predominantly on inferential processes in causal reasoning, specifically covering the types of information (i.e., data, evidence, etc.) that children and adults alike use to make causal inferences in probabilistic environments. Finally, we will review experiments that have investigated how people deal with causal evidence that is inconsistent with their conceptual understanding (i.e., their expectations).

Countless studies have examined how people determine the degree to which specific variables are causally related through the use of various causal cues (e.g., covariation information, knowledge of causal mechanisms, temporal and spatial contiguity; for an extensive review of multiple causal cues in adults see Young, 1995, or in children see Shultz, 1982; for a recent Bayesian perspective on causal learning see Pearl, 2009). When thinking about causal reasoning, it is important to differentiate between causal perception, in which the perceptual system "directly" attributes causality to an event such as when viewing physical collision events (see, e.g., Michotte, 1963), and causal inference, which draws on a more "cognitive" level of understanding of cause and effect (e.g., learning that flipping a switch turns a light on). Indeed, there is substantial evidence that different neural systems underlie these two forms of causal competence, with causal perception and causal inference proceeding relatively independently and relying on dissociable

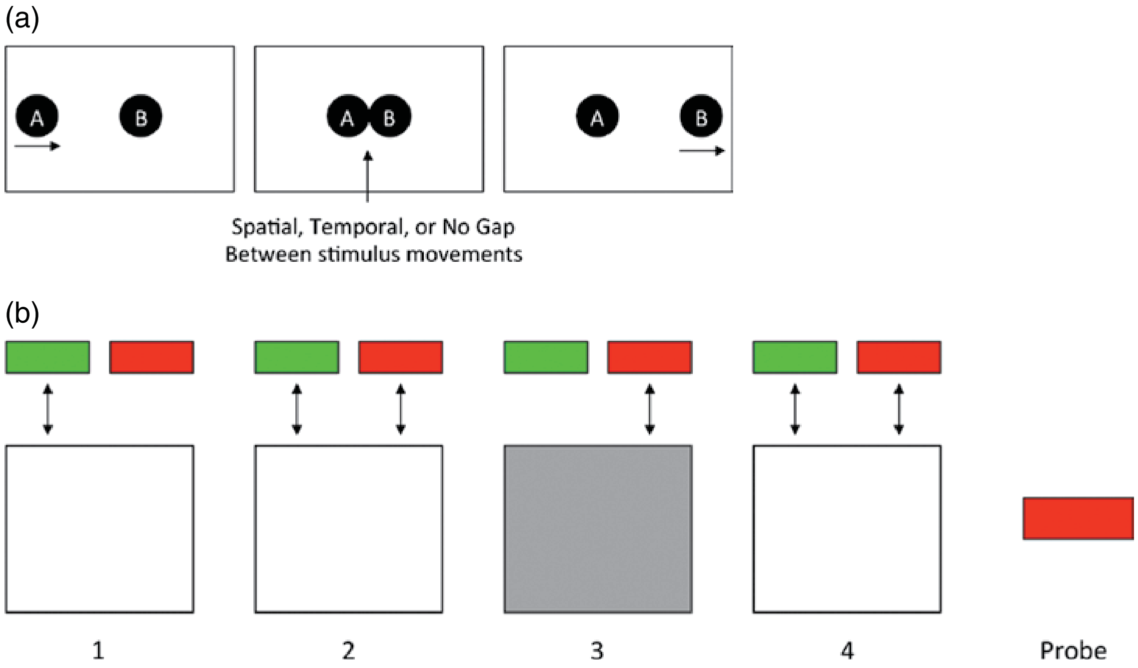


Figure 9.2 Example stimuli used by Roser et al. (2005). (a) A graphical illustration of the causal collision animations used in the causal-perception task. The three panels depict the motion of a ball A towards a second ball B, and the subsequent motion of ball B. Note that the movement of the second ball (B) was preceded by either a temporal delay, a spatial gap, or no gap. (b) A graphical illustration of the animated causal-inference task. The sequential presentation of four stimulus interactions and a response probe is shown, representing one trial. Arrows indicate the movement of one or both of the colored "switches" on each presentation. Adapted from Roser, M., Fugelsang, J., Dunbar, K., Corballis, P., & Gazzaniga, M. (2005). Dissociating processes supporting causal perception and causal inference in the brain. *Neuropsychology*, *19*, pages 593 (a) and 597 (b) with permission from APA.

neural architectures. One of the most striking examples of the independence of these two processes comes from a series of studies led by Matthew Roser (Roser, Fugelsang, Dunbar, Corballis, & Gazzaniga, 2005) with two patients who had undergone callosotomy surgery (J.W. and V.P.): a surgery that severs the corpus callosum, thus severely limiting the communication between the two cerebral hemispheres (see Fugelsang and Dunbar, 2009, for further discussion of this experiment in the context of multiple representations of causality). The two patients were presented with causal collision events (i.e., one object appearing to hit [or not hit] another object, causing it to move) using the standard Michotte paradigm (see Figure 9.2(a); Michotte, 1963), and a task hypothesized to tap into causal inference (adapted from the "blicket detector" task of Gopnik, Sobel, Schulz, & Glymour, 2001). This task consisted of a series of four dynamic stimulus interactions between two "switches" (green or red), and a "lightbox" that changed colors in response to the movement of one of the switches (see Figure 9.2(b)). The participants' task was simply to judge which switch caused the lightbox to change colors. Note here that there was no physical interaction between the stimuli in this condition (i.e., no contact), thus participants would need to *infer* the existence of a causal relation based on the observed patterns of relations in the absence of the ability to directly perceive one. Critically, the stimuli were presented to each hemisphere of the divided brain in isolation using an eye tracker coupled with a mirror deflector system that stabilized the dynamic displays on the retina of the participant.

For the Michotte task, the right hemispheres of J.W. and V.P. performed similarly to control participants with intact corpora callosa; however, the left hemispheres of the same patients performed at chance level on this task. Conversely, for the causal inference task, the left hemispheres of J.W. and V.P. performed similarly to those of control participants, whereas the right hemispheres of the same patients performed at chance level. This clear double dissociation between the causal task (perception versus inference), and cerebral hemisphere supporting that task, lends support to the hypothesis that the ability to draw causal inferences based on statistical associations and the ability to directly "perceive" causality based on physical contact interactions are supported by different hemispheres of the divided brain, and thus anatomically and functionally dissociable. It is important to note here that it is entirely possible that the two tasks noted above may become less independent with time. For example, given experience with colliding events, one may develop theories underlying their interaction, and this may in turn influence the judgment of these events in a top-down manner. Nevertheless, this study provided compelling evidence that humans have independent abilities to directly perceive and to infer causality. The extent to which either process is recruited would depend on the nature of the stimuli being judged.

What cognitive processes might underlie this dissociation? Perhaps the most recognized and empirically supported hemispheric asymmetry in the human brain is that between linguistic and visual–spatial processing. Countless studies of preserved cognitive functioning in patients with focal brain lesions and more recent functional brain imaging studies (using positron emission tomography and functional magnetic resonance imaging, fMRI) have shown that the left hemisphere has a distinct advantage for linguistic processing (Milner, 1962), whereas the right hemisphere has a processing advantage for visual–spatial information (Corballis, 2003; Corballis, Funnell, & Gazzaniga, 2002). Note that this dissociation is true for most (but not all) right-handed individuals, and fewer left-handed individuals. Here, it has been argued (e.g., Roser et al., 2005; Fugelsang, Roser, Corballis, Gazzaniga, & Dunbar, 2005; Fugelsang & Dunbar, 2009) that causal perception may rely on similar underlying neural architectures to those which are involved in visual–spatial processes, whereas causal inference may rely on similar underlying neural architectures to those involved in linguistic processing. These findings are likely to have important developmental implications for understanding the transition from a perceptual to an abstract and productive mind. Here, one may hypothesize that the ability to make causal inferences of the kind described above may be scaffolded onto the same neural architecture that supports linguistic processing. It is also important to note here that the processes described with reference to the causal-inference task may be very different (and rely on different neural architecture) from those that are involved in associative learning of causal relations (see, e.g., Corlett et al., 2004; Fletcher et al., 2001; Turner et al., 2004), which may rely on tacit awareness of associative strength in the absence of any conscious inferential processes.

Fewer studies have focused on the underlying brain correlates of more complex causal reasoning (as opposed to causal perception), which reflects the kind of causal scientific reasoning individuals might undertake in a more ecologically valid context. When we speak of complex causal reasoning in the present context, we are referring to the inferential processes associated with evaluating new observations (i.e., empirical data) to test an existing theory. In an attempt to empirically examine the brain correlates of complex scientific reasoning of this kind, Fugelsang and Dunbar (2005) opted to examine the degree to which individuals reason about covariation-based data that may be consistent or inconsistent with a causal model containing a plausible or implausible mechanism of action. The focus on these two cues (i.e., covariation information and causal mechanisms) is due to the assumption that they nicely map onto the types of cue people use in the real world when making scientific discoveries (see Fugelsang & Dunbar, 2009, for further discussion of this study within the broader context of research on causality). Here, evidence is gathered to test specific hypotheses about the world. These specific hypotheses often involve mechanistic information detailing how certain variables are thought to *produce* changes in other variables. Furthermore, the data collected often come in the form of repeated trial-by-trial observations. Importantly, the data collected (i.e., the cause-and-effect trial observations) may turn out to be either consistent or inconsistent with the theory being tested.

To test these processes in a controlled experimental setting, Fugelsang and Dunbar (2005) presented participants with a reasoning task that required them to reason with covariation-based data that were either consistent or inconsistent with a causal theory. The causal theories could be either plausible or implausible. Theory plausibility was manipulated by presenting participants with introductory cover stories that contained information about a causal mechanism specifying how a specific drug impacted mood in a group of fictitious patients (see Fugelsang & Dunbar, 2005, for a list of the stimuli). For plausible causal theories, the drug cover stories were modeled after known antidepressants (which contained a direct plausible mechanism to affect mood); for implausible theories, the cover stories were modeled after known antibiotics (which did not contain a direct plausible mechanism to affect mood). After participants read over the cover story, covariation-based data were then presented in a sequential trial-by-trial format, where they viewed multiple cause–effect observations that were associated with each causal theory. Importantly, the trials cumulatively contained evidence (i.e., covariation-based data) that was either consistent or inconsistent with the theory provided in the cover story. That is, under some conditions, the theory would set up the participant to believe that a causal relation existed, and the data were consistent with that theory (strong covariation) or inconsistent with that theory (weak covariation). Under other conditions, the theory would set up the participant to believe that a causal relation does *not* exist. Here, strong covariation would be consistent with the theory presented, but inconsistent with what one might expect to observe given that the theory would set one up to believe that no relation should exist. The presence of weak covariation-based data following an implausible theory, however, would be inconsistent with the theory presented, but consistent with what one might expect to observe.

Concerning the behavioral data first, participants' causal responses reflected an interaction between theory plausibility and data strength such that the covariation-based data were weighted more heavily for plausible theories than for implausible theories. This finding was consistent with prior behavioral work (i.e., Fugelsang & Thompson, 2000, 2003; Fugelsang et al., 2004) that has shown that people are biased by their expectations (i.e., beliefs) in their interpretation of covariation-based data when inferring causal relations. That is, there is a bias towards assessing data that are relevant to existing beliefs. Put another way, these findings imply that people may have difficulties with assessing data corresponding to alternative theories – something that both children and adults have been demonstrated to have problems with (see Howe, Tolmie, & Sofroniou, 1999). One could argue that these behavioral findings may reflect a sensible strategy for everyday reasoning, in that they protect individuals from prematurely changing their worldviews based on anomalous observations (i.e., type 1 errors). However, it is obviously not a suitable strategy for scientific thinking in general, as scientists may be inclined to prematurely disregard anomalous observations. Indeed, as an astute reviewer of this chapter noted, paradigm shifts in the history of science often, by definition, involve a radical change in what counts as a plausible theory (see Kuhn, 1962). In addition, it should be noted here that researchers have found that the degree to which prior beliefs impacts the evaluation of covariation-based data also depends on the reliability of that data (Perales, Catena, Maldonado, Cándido, 2007).

Critically, the brain imaging data provided information about a possible neural mechanism underlying this behavioral bias. Here, the consistency between theory plausibility and the covariation-based empirical data (i.e., whether the data were consistent with or conflicted with what one would expect to see given the presented causal theory) influenced the degree to which dissociable neural

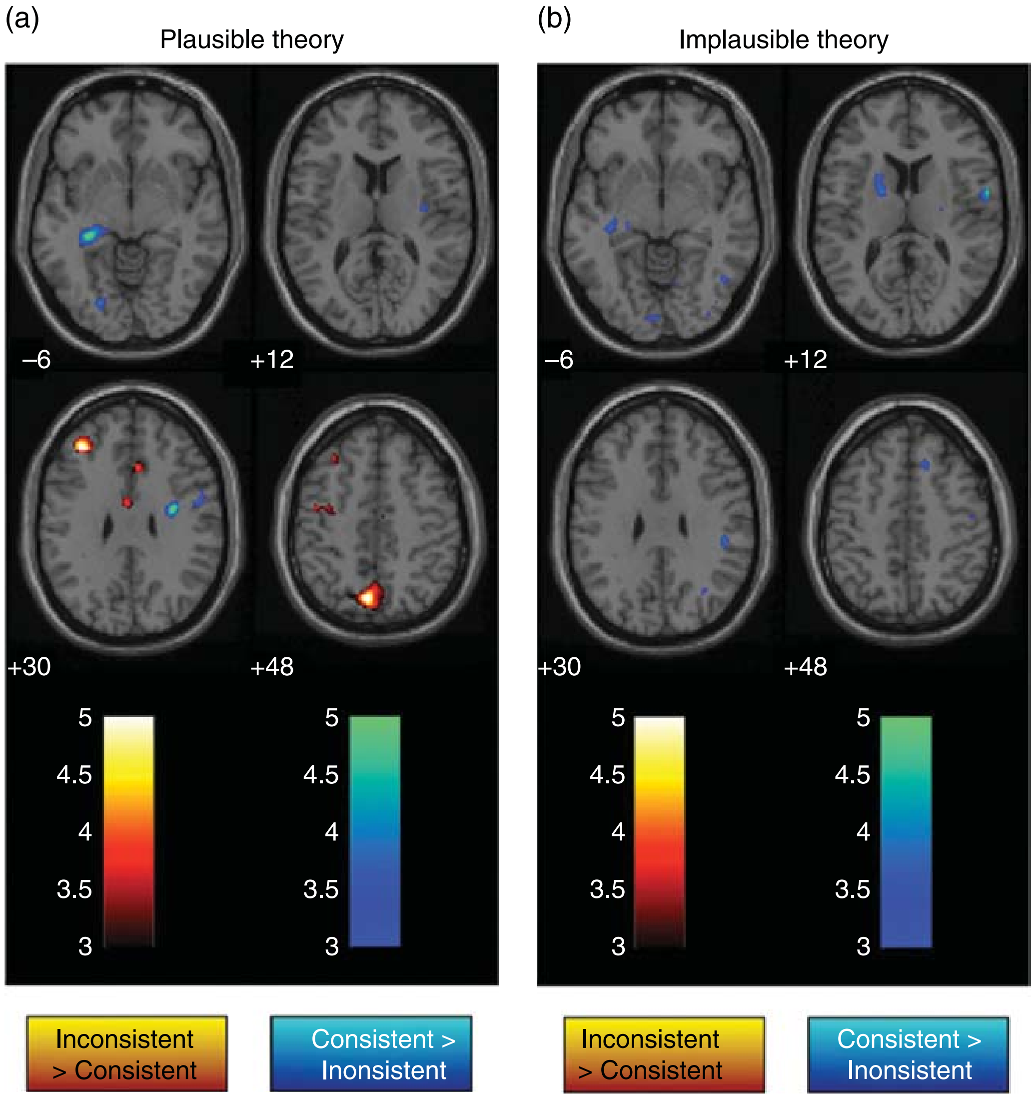


Figure 9.3 Average brain activation patterns occurring when participants viewed data *inconsistent* versus *consistent* with a plausible theory (a) and an implausible theory (b). Note that the activations denoted by red to yellow are for the conditions in which the provided theory and data are *inconsistent* and the activations denoted by blue to green are for the conditions in which the theory and data are *consistent*. Adapted from Fugelsang, J. A., & Dunbar, K. N. (2005). Brain-based mechanisms underlying complex causal thinking. *Neuropsychologia*, *43*, page 1208, with permission from Elsevier.

networks were recruited. Specifically, when covariation-based data were consistent with what one would expect to see given the causal theory (i.e., strong covariation-based data for plausible theories, and weak covariation-based data for implausible theories), regions in the caudate and parahippocampal gyrus were selectively activated; whereas, when the covariation-based data conflicted with the causal theory, the anterior cingulate (ACC) and precuneus were selectively activated. Fugelsang and Dunbar (2005, 2009) hypothesized that these behavior–brain associations likely reflected the preferential recruitment of learning mechanisms for data that were consistent with what one would expect to observe given the presented theory (see Kelley et al., 1998; McDermott et al., 1999) and conflict monitoring/error detection mechanisms for data inconsistent with what one would expect to observe given the presented theory (see Botvinick, Braver, Barch, Carter, & Cohen, 2001; van Veen & Carter, 2002; Yeung, Botvinick, & Cohen, 2004).

A further interesting finding was discovered when they analyzed the effects of data consistency (i.e., whether the data matched the theory) separately for plausible and implausible theories (see Figure 9.3). Here, when participants evaluated data that were inconsistent (i.e., in conflict) with a *plausible* theory, additional activations were observed in the left dorsal lateral prefrontal cortex (DLPFC) in concert with activations in ACC and precuneus. Of course, there are many possible interpretations of these activation patterns. These interpretations hinge in part on how the presence of conflicting data (i.e., the degree to which theory and data are inconsistent) is presumed to be processed. For example, does this conflict processing result in the active (conscious) inhibition of data inconsistent with one's expectations, or is it more a passive (potentially unconscious) process, where attention is simply shifted to consistent data? Fugelsang and Dunbar (2005) preferred the interpretation that the combined recruitment of the DLPFC and the ACC in this condition may be due to the active *inhibition* of processing the conflicting data. These findings (and interpretation) are consistent with those of Goel and Dolan (2003) and Stollstorff, Vartanian, and Goel (2012) in a deductive reasoning task. Specifically, they found increased recruitment of regions within the DLPFC under conditions in which the believability of a conclusion conflicted with the logical structure of a problem and thus required the *inhibition* of a behavioral response. We will discuss these findings further below when we cover deductive reasoning in more detail.

More recently, others have examined complex causal reasoning in other domains. For example, Parris, Kuhn, Mizon, Bennattayallah, and Hodgson (2009) extended the work of Fugelsang and Dunbar (2005) by teasing apart the neural responses to surprising events, and those that violated well established and "deterministic" causal beliefs. This is in contrast to the work of Fugelsang and Dunbar (2005), who focused on causal events that were probabilistic. To do this, they empirically examined the perception of magic tricks in order to investigate violations of causal relations that are long established. For example, participants viewed videos containing several magic tricks such as disappearing acts and levitation. Note that these types of event are similar in many ways to those of causal perception (e.g., using the standard Michotte paradigm) in that they involve observable physical stimulus interactions. Here, an unexpected finding would presumably violate one's worldview in a similar manner as a temporal or spatial gap would when viewing collision events. When magic-trick perception (which included a violation of a known deterministic causal relation) was contrasted with situations in which expected causal relations are observed, they found that the former recruited greater activations in regions in the left DLPFC and ACC than the latter. The authors also included further control conditions to determine the degree to which these activations were selective to causal events, or common for other surprising events. Critically, the left DLPFC was selectively more active when viewing magic tricks than surprising events. However, the same region in the DLPFC was *not* more active when viewing surprising than nonsurprising causal control events. This latter finding is important, as it provides support for the hypothesis that the DLPFC plays a key role in the higher-order aspects (i.e., causality) of the perception of expectancy violations. These data nicely extend the work of Fugelsang and Dunbar (2005) by showing that information that violates expected causal relations (whether they are probabilistic or deterministic in nature) activates regions in the brain known to be associated with conflict processing (van Veen & Carter, 2002). The degree to which this conflict processing is active or passive is up for debate, and an important avenue for future research.

Taken together, the work of Fugelsang and Dunbar (2005) and Parris et al. (2009) provides insights into the development of causal scientific thinking skills. As noted above, much of scientific thinking involves the testing and establishment of causal relations between variables of interest. Based on the literature reviewed, it appears that the human brain seems to be especially tuned to detect and process information that contradicts and challenges established conceptual knowledge about such relations. As noted by Parris et al., in the context of complex causal thinking, the ACC and DLPFC may play a central role in the establishment of *disbelief*. Here, the development and maturation of this neural architecture may result in a shift from primarily perceptually driven to more inferentially driven reasoning processes, supporting our ability to question and learn from observations that conflict with existing knowledge. As noted above, however, individuals often remain biased when reasoning with causal relations despite this detection of conflict.

The above idea regarding the development of the ability to reason about conflict is also at the heart of Houdé's (2000, 2007) proposal that the *key* cognitive developmental factor across childhood is the improving ability to inhibit pre-potent perceptually based responses, and allow slower reflective processes to act. Consistent with this view, he and his colleagues have found that training on inhibition tasks, but not logical reasoning tasks, led young adolescents to reduce the frequency of logical reasoning errors. This change in behavior was also associated with a shift in activation from posterior cortical regions (involved in early perceptual processing) to anterior cortical regions involved in executive control (Houdé et al., 2000, 2001). The suggestion that such inferential mechanisms tend to exert a dominant influence on judgments once they reach a certain state of organization is also supported by a recent electroencephalography (EEG) study with adults reported by Kallai and Reiner (2010). They employed a trajectory task based on McCloskey's (1983) work on naïve physics, in which participants viewed animations of an object exiting either straight or circular tubes, with either normal parabolic or circular motion. Behavioral judgments (via key press) of whether the displayed motion was accurate or not showed an effect of tube type (more correct responses were made for the straight tube), in line with McCloskey's results. However, event-related potential data gathered from the same trials showed a negative activation peak at 400 ms (associated with semantic violations in previous research) for displays of circular motion from *both* tube types. This suggests that participants held an accurate implicit expectation about the trajectory shape that was overruled by the behavioral judgment in the case of the circular tube. However, a further positive activation peak at 600 ms (associated with syntactic violations) was found in participants incorrectly accepting a circular trajectory from the *straight* tube, but not when correctly accepting a circular trajectory from the circular tube. This suggests that the dominant consideration for decisionmaking was whether trajectories corresponded to rule-based expectations rather than perceptual experience. Importantly, these findings reveal that this ability to detect conflicts between our expectations and our perceptual experience when reasoning can sometimes lead us astray in that they can override an accurate perceptual input. That is, at least some of the time the influence of higher-order inferential processes can impede performance, as the perceptual responses are in fact accurate, and the considered responses are inaccurate (see also Howe, 1998; Howe, Tavares, & Devine, 2012). This point is important given the prevalence of misconceptions of students up to and including the undergraduate level.

Deductive Reasoning

Alongside causal reasoning, deductive reasoning processes, which are thought to be one of the hallmark processes indexing rational thought (Evans, 2008), underlie much of scientific thinking. This involves reasoning processes that assess the degree to which a conclusion logically follows from stated information (i.e., premises). Deductive reasoning is useful in the scientific enterprise as much of scientific thinking involves reasoning from known (i.e., previously established) information (Dunbar & Fugelsang, 2005). That is, scientists and laypeople alike assume that events in our world unfold due to the operation of stable and predictable rules, and they reason from these known and established rules to draw new conclusions based on new observations, using the tools offered through deductive reasoning.

Deductive reasoning is a key component of scientific thinking, as it underlies much of how scientists make inferences about new discoveries. A contemporary example of deductive reasoning in scientific thinking was provided by Dunbar and Fugelsang (2005), with regard to the discovery of new planets in our solar system, and other solar systems. Here, some scientists speculate that there exists another planet in our solar system (not including Pluto) beyond the orbit of Neptune (referred to as "Planet X"). This is due to the significant orbital perturbations of the planets Uranus and Neptune (note that Neptune was discovered in a similar fashion due to perturbations in the orbit of Uranus). Given that it is generally assumed that only very large objects possessing a strong gravitational pull can cause significant orbital perturbations (discounting Pluto as a possible candidate), and given further that Uranus and Neptune do have notable perturbations in their orbits, it follows logically from these premises that a large planetary body is influencing Uranus and Neptune's orbital patterns. This process of deductive reasoning also extends to the discovery of new planets in other solar systems (see Figure 9.4).

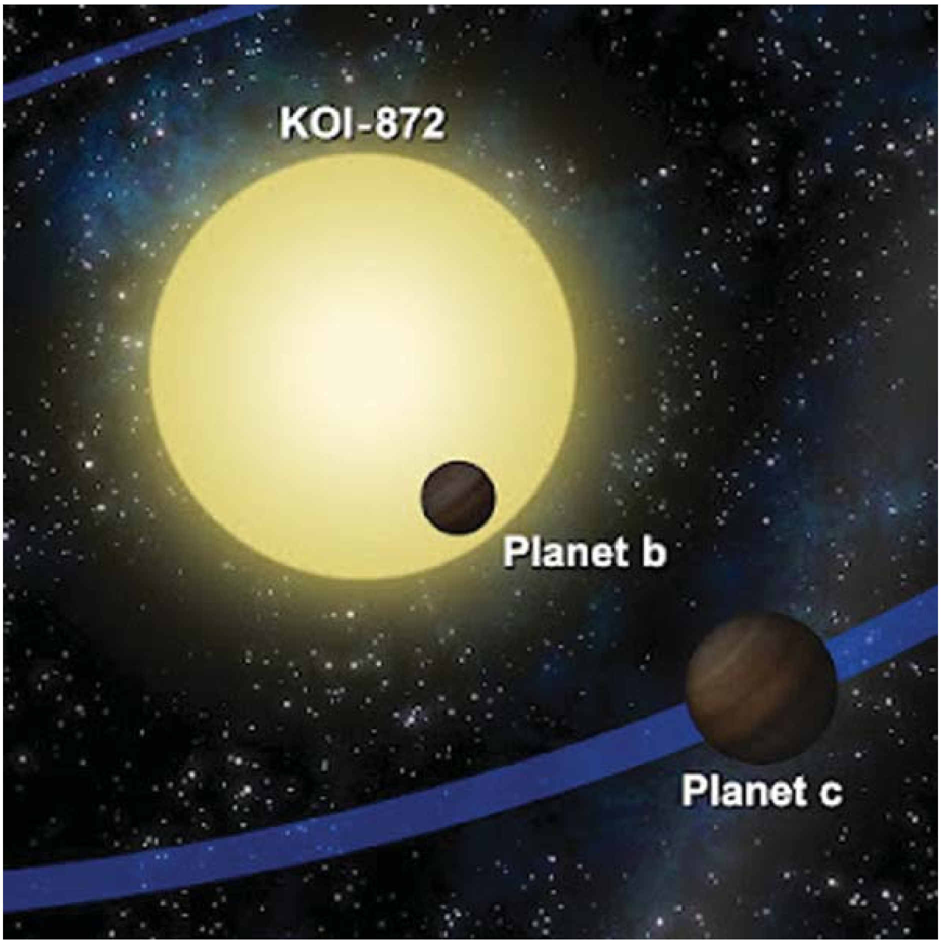
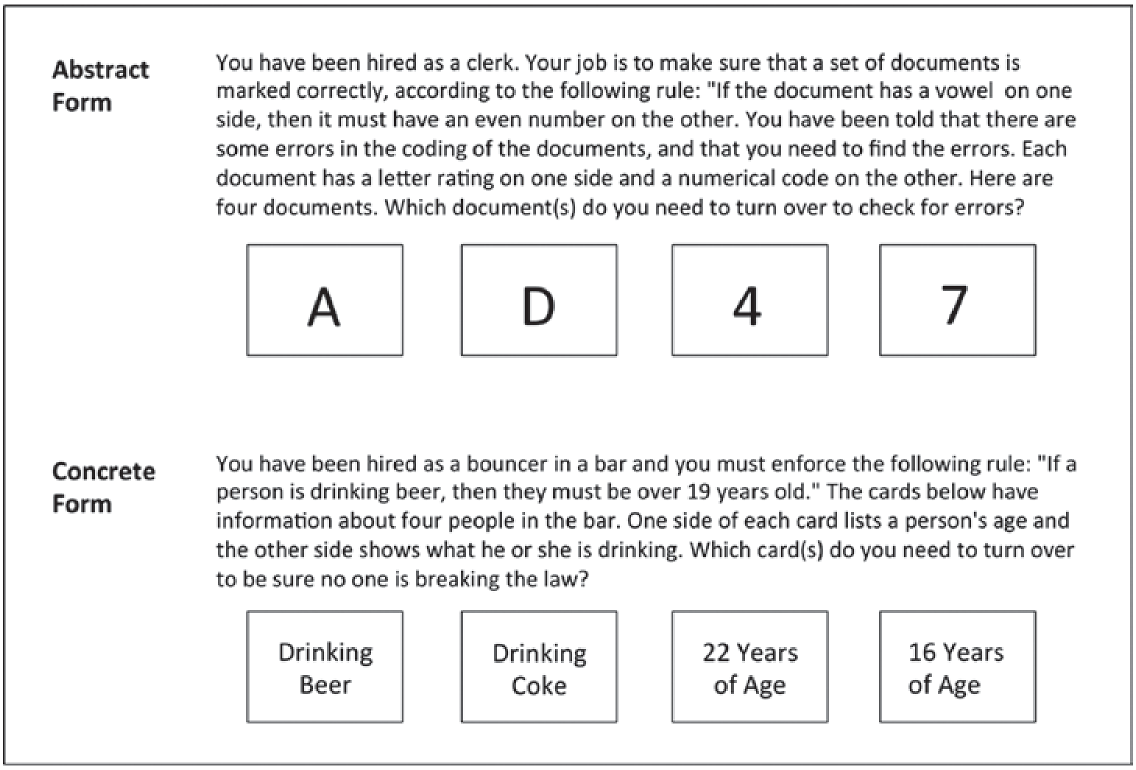


Figure 9.4 A famous (and still widely used) example of deductive reasoning is the use of gravitational perturbation theory to predict the presence of new planets in solar systems. A recent example is the discovery of a second planet, "Planet C," orbiting the distant star KOI-872. Based on the discovery of orbital perturbations of "Planet B," and the premise that only large objects possess a strong enough gravitational force to cause such perturbations, the conclusion that there exists a second planet, "Planet C," logically follows. Courtesy Southwest Research Institute.



Abstract Form

You have been hired as a clerk. Your job is to make sure that a set of documents is marked correctly, according to the following rule: "If the document has a vowel on one side, then it must have an even number on the other. You have been told that there are some errors in the coding of the documents, and that you need to find the errors. Each document has a letter rating on one side and a numerical code on the other. Here are four documents. Which document(s) do you need to turn over to check for errors?

Concrete Form

You have been hired as a bouncer in a bar and you must enforce the following rule: "If a person is drinking beer, then they must be over 19 years old." The cards below have information about four people in the bar. One side of each card lists a person's age and the other side shows what he or she is drinking. Which card(s) do you need to turn over to be sure no one is breaking the law?

Figure 9.5 The Wason four-card selection task in abstract and concrete forms. The logically correct response is the card showing a vowel (or drinking beer in the concrete form), and the card showing a number that is not even (the person 16 years of age in the concrete example).

In this section, we will discuss how both children and adults use deduction to make scientific discoveries. Furthermore, we will look at common errors people make when reasoning deductively. Specifically, we will focus on research looking at the degree to which the content (i.e., reflecting domain-specific conceptual knowledge) of information in the premises and conclusions impact the deductive reasoning process (i.e., the application of the domain-general reasoning process).

Decades of research have shown that adults often fall far short of optimal rational behavior when reasoning with standard deductive reasoning tasks. For example, researchers have consistently found that only around 10% of adult participants correctly solve the abstract version of the Wason selection task (Wason, 1968). However, when abstract content is replaced with thematic content (e.g., the drinking age problem; see Figure 9.5), performance increases dramatically to around 75% correct (Griggs & Cox, 1982). There are several explanations and theoretical accounts of this facilitation in performance, which we will not get into here. For our purposes, it is important simply as an example of how deductive reasoning is profoundly affected by the content with which one is reasoning. That is, the content of a problem greatly influences the degree to which adults reason in a logical manner. This again is an example of how domain-general reasoning processes (in this case

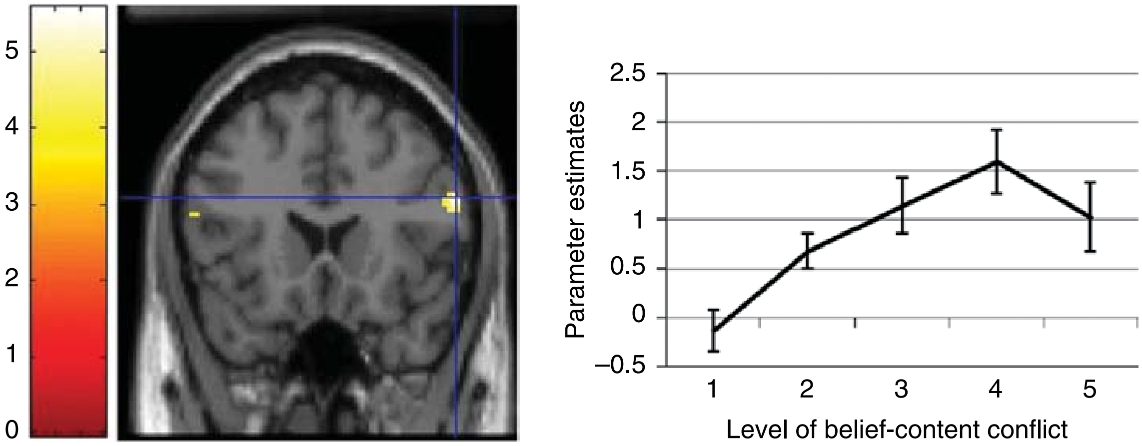


Figure 9.6 Parametric modulation of lateral prefrontal cortex as a function of conflict between belief and logic. Reprinted from Stollstorff, M., Vartanian, O., & Goel, V. (2012). Levels of conflict in reasoning modulate right lateral prefrontal cortex. *Brain Research*, *1428*, page 29, with permission from Elsevier.

deductive reasoning) are significantly influenced by domain-specific knowledge. This is similar to what we discussed above with regard to causal reasoning where participants' beliefs and expectations altered the degree to which they evaluated covariation-based evidence. Related to the content effects discussed above is the "belief-bias effect." Here, people are more likely to judge a conclusion as valid if it is believable, regardless of whether or not the conclusion follows necessarily from the information contained in the premises (Evans, Barston, & Pollard, 1983). Like causal reasoning, one's knowledge can override the acceptance of logically valid conclusions that are unbelievable. Of course, this often results in faulty reasoning whereby valid arguments are prematurely dismissed as invalid.

Research by Vinod Goel and his colleagues has used fMRI extensively to uncover the neural mechanisms underlying how people reason deductively with believable and unbelievable content. In a series of studies (e.g., Goel & Dolan, 2003; Stollstorff et al., 2012), they found that regions within the lateral prefrontal cortex were selectively activated when participants effectively reasoned logically when beliefs conflicted with valid conclusions (i.e., unbelievable but valid conclusions). In addition, they found that the activation in regions in the lateral prefrontal cortex increased parametrically with the amount of conflict present between the believability of the content and the logical structure of the conclusion (see Figure 9.6). This is an important finding, as it demonstrates the sensitivity of this neural region to conflict processing. These findings were taken to support the hypothesis that regions within the lateral prefrontal cortex initiate cognitive control to mediate the successful resolution of belief–logic conflicts during deductive reasoning. This is consistent with the general suggestion that regions of the lateral prefrontal cortex are involved in conflict-resolution tasks that require inhibitory control (see, e.g., Aron, Robbins, & Poldrack, 2004; Carter & van Veen, 2007). In addition, these findings converge with those discussed above regarding causal reasoning (another domain-general cognitive process), in that when reasoning with content (i.e., reflecting domain-specific knowledge) of which the reasoner has personal knowledge, which is often the case in scientific reasoning, effective inhibition of that knowledge is often imperative for successful performance. More generally, this work fits with the growing body of literature on inductive reasoning (e.g., Goel & Dolan, 2000, 2004; Seger et al., 2000) and deductive reasoning (Goel, Gold, Kapur, & Houle, 1998; Osherson et al., 1998; Parsons & Osherson, 2001) that have converged on the dominant role of the DLPFC in high-level reasoning tasks that involve the integration of prior world knowledge with the current logical demands of a given task (Baird & Fugelsang, 2004).

These findings also resonate with the developmental finding of improved reasoning performance in familiar domains by young children. For example, children generally succeed at classic Piagetian tasks if these are contextualized within familiar domains (Donaldson, 1978) or will show evidence of analogical reasoning (to be discussed in the next section) from as early as 3 years of age when tested in familiar domains (Goswami & Brown, 1990). In fact, both unschooled children and unschooled adults will generally succeed on logical reasoning tasks in familiar domains, but do so on the basis of knowledge-based inference rather than applying the rules of formal logic. Only once they have gone to school are they able to overcome this "empirical bias" and reason abstractly and counterfactually (Harris, 2000; Dias, Roazzi, & Harris, 2005). Of course, based on the literature reviewed above, it is clear that this ability to reason abstractly using the rules of logic is not always applied even after much schooling.

More recent research has also provided important new insights into the precise role of multiple brain regions in the prefrontal and parietal cortices, along with the timecourse of their recruitment, during the stages of deductive reasoning. Specifically, using event-related fMRI, Rodriguez-Moreno and Hirsch (2009) have found that areas in the frontal and parietal cortices are differentially recruited at different times in the deductive reasoning process as the participant steps through a syllogistic reasoning problem. Here, by presenting each premise, conclusion, and response phase sequentially, the authors were able to isolate the different brain regions that come online during the three proposed phases of the deductive reasoning process (i.e., premise encoding, premise integration, and conclusion validation). They found evidence for a frontal–parietal–caudate brain network that spanned both the premise integration and conclusion phases of reasoning. Furthermore, they were able to isolate areas of the brain that were primarily engaged during processing of the second premise, where premise integration and conclusion generation is thought to occur, including areas in the left middle and superior frontal gyrus and left superior and inferior parietal cortices. Areas in the medial and left inferior frontal cortex and bilateral inferior parietal and bilateral regions in the caudate nucleus were most active during the conclusion phase, presumably when conclusion validation occurs. Here, the activation of these latter inferior frontal regions suggests that the active conflict-resolution mechanisms associated with deductive reasoning with content likely do not come online until the conclusion-validation phase.

As with all research on higher-level cognition, it is important to be careful when inferring the operation of distinct cognitive processes based on observed patterns of brain activation (see Poldrack, 2006, for a discussion on the "reverse inference" problem, and Shallice and Cooper, 2011, for further discussions on the difficulty of interpreting imaging data in higher-level cognition). In addition, the degree to which these reasoning brain networks are scaffolded onto existing language areas (Hickok & Poeppel, 2004), working memory/executive processing networks, or visual–spatial networks (see Cabeza & Nyberg, 2000, for review of overlapping networks) is an important point of consideration. Indeed, in addition to the work on the impact of domain-specific knowledge (i.e., content) on deductive reasoning, much of the cognitive and neuroscience research on deductive reasoning has been focused on adjudicating between visual–spatial and linguistic theories of reasoning (see Goel, 2003, 2007, for reviews). In general, neuroimaging studies have provided support for the view that both language-based and visual–spatial modes are engaged during logical reasoning. As argued by Goel (2007), rather than having a unitary reasoning system, "the evidence points to a fractionated system that is dynamically configured in response to certain task and environmental cues" (p. 440). Here, the degree to which language-based or visual–spatial modes are recruited can depend on many factors, including, but by no means limited to, the type of logical relation to be reasoned with (e.g., categorical versus conditional), and the content of the problem (e.g., concrete versus abstract).

The findings above are also consistent with the emerging consensus in cognitive neuroscience suggesting that executive control can be separated into "evaluative" and "executive" processing components: one involving the ACC and the other involving the DLPFC (see Carter & van Veen, 2007). Broadly speaking, concerning the respective roles of the ACC and the DLPFC, as noted above, the ACC has been proposed to monitor the presence of conflict in a cognitive task, and the DLPFC is alerted to resolve the conflict. This conclusion mirrors the importance attributed to conflict monitoring in classic theories of reasoning development (e.g., Piaget's reflective abstraction, Karmiloff-Smith, 1992) and the relatively late maturing of the DLPFC across development (Zelazo, Carlson & Kesek, 2008). This could explain the relatively prolonged development of the ability to resolve inconsistencies between prior beliefs and new evidence in scientific learning and discovery. However, it should be noted that these regions have also been associated with a multitude of roles in other reasoning and decisionmaking situations (e.g., executive processing, working memory, attention, etc.). Indeed, converging evidence from a range of neuroscientific methods has implicated the dominant role of the DLPFC in many everyday reasoning tasks (e.g., Shallice & Burgess, 1991; Stuss & Alexander, 2000; Baird & Fugelsang, 2004).

Analogical Reasoning

Analogical thinking is another central cognitive tool that scientists and laypeople alike use to aid in scientific thinking. Analogies have featured prominently in science (see Holyoak & Thagard, 1995, for a review), enough so to warrant the publication of many academic and popular books, highlighted by Joel Levy's recent book *A Bee in a Cathedral: And 99 Other Scientific Analogies* (Levy, 2011). Indeed, by analyzing the use of analogies in real scientific discoveries, several researchers (e.g., Dunbar & Blanchette, 2001; Gentner & Jeziorski, 1993; Nersessian, 1999; Thagard & Croft, 1999) have shown that analogical reasoning processes play a fundamental role in the scientific discovery process. That is, scientists use information from one relatively known domain ("the source," or earlier situation) and apply it to another domain ("the target," or present problem) (Dunbar & Fugelsang, 2005). Perhaps the most famous example of a scientific analogy is that between the hydrogen atom and the solar system (see Figure 9.7), originally formulated by Ernest Rutherford, where he explained

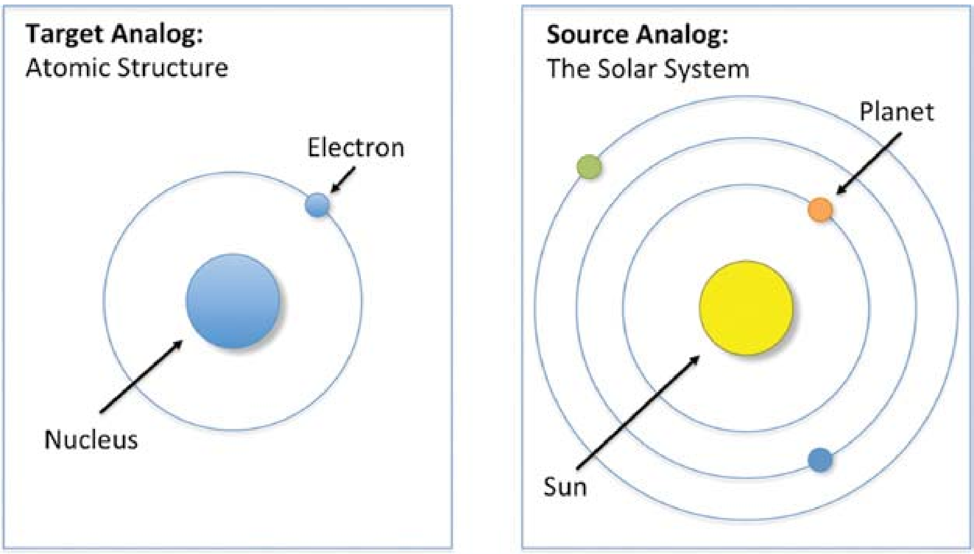


Figure 9.7 The "atom is like the solar system" analogy, credited to Ernest Rutherford, is one of the most famous examples of analogies in science. He explained the structure of the atom by picturing the atom as a solar system whereby the electrons orbit the nucleus in a similar way to how the planets orbit the sun. Figure credit: Daniel Brady.

the structure of the atom by picturing the atom as a solar system whereby the electrons orbit the nucleus in a similar way to how the planets orbit the sun (Gentner, 1983). Other examples of the use of analogies in major scientific discoveries (noted by Green, Kraemer, Fugelsang, Gray, and Dunbar, 2012) include William Harvey likening the circulatory system to a water pump, and James Crocker mapping an extendable showerhead to the position control mechanism on the Hubble telescope. Scientific discoveries in psychology are also replete with analogies. For example, researchers have discussed "bottleneck" (Broadbent, 1958) "filter" (Treisman, 1964), and "spotlight" (Posner, 1980) theories of attention, and computer metaphors of information processing (Neisser, 1967; Atkinson & Shiffrin, 1968). Perhaps not surprisingly, one's ability to draw analogies between two disparate domains has also been linked to fluid intelligence (Ferrer, O'Hare, & Bunge, 2009) and creativity (Sternberg, 1977; Green, Cohen, Kim, & Gray, 2012).

The precise role of analogical thinking in science has been greatly informed by the work of Kevin Dunbar, who has conducted several real-world investigations into how scientists make use of analogies during the scientific discovery process in their respective laboratories. To do this, he immersed himself in several prominent laboratories around the world and recorded, transcribed, and analyzed their laboratory meetings. He also conducted in-depth interviews with the scientists (including the principal investigators, post-docs, and graduate students) in order to get first-hand accounts of the scientific reasoning process. He made several key discoveries. Strikingly, he found that scientists would make use of between 3 and 15 analogies in a single one-hour laboratory meeting (Dunbar & Blanchette, 2001; see also Dunbar, 1995, 2001, 2002). He also discovered that scientists made use of both superficial (focusing on surface similarities between domains) and structural (focusing on deeper relational issues between more distant domains) analogies in their laboratory meetings. The degree to which scientists made use of superficial versus structural features, however, depended on the goal of the scientists. Specifically, Dunbar and colleagues found that, if the goal of the scientist was to fix a methodological problem in one of their experiments, the analogies generated were predominantly based on superficial features close to the domain of interest. However, if the goal was to formulate new hypotheses, the scientists generated and focused on analogies that were based upon sets of higher-order structural relations. These findings are important as they highlight the critical role of both superficial and structural features of analogical reasoning in scientific thinking (which we will discuss in greater depth below), and also its flexible and goal-driven nature. In the remainder of this section, we will probe further into the operations that guide successful analogical transfer between domains. Furthermore, we will review research that looks at the variables that influence the degree to which one will, or will not draw an analogy between disparate domains, and cover research revealing the neural mechanisms underlying successful analogical transfer.

Interestingly, research on analogical reasoning has found that participants in the cognitive laboratory do not easily use analogies when reasoning (Gentner et al., 1997; Holyoak & Thagard, 1995). For example, consider the classic studies by Gick and Holyoak (1980, 1983). They found that only about 30% of college student participants spontaneously noticed an analogy between a source (the general problem) and the target (the tumor problem). The percentage of participants solving the problem increased significantly, however, if they were explicitly told that the general story would be useful in coming up with a solution to the tumor problem. The difficulty of spontaneously noticing analogies has also been found in several other laboratories. For example, Reed, Ernst, and Banerji (1974) found that participants' reasoning performance was facilitated by exposure to a previous analogous problem only if the analogy between the two problems was made explicit to them.

Much headway has been made in recent years towards understanding the neural underpinnings of analogical or relational reasoning, in both adults and children. As with causal reasoning, one must be careful to differentiate between the direct perception of relational similarity (e.g., perceiving the relations "same" or "different") as opposed to the higher-order processes associated with analogical inference. These may, in fact be subserved by different neural systems. To this end, Bunge, Wendelken, Badre, and Wagner (2005) evaluated the contributions of different subregions of the prefrontal cortex (PFC) to different components of verbal analogical reasoning tasks. To do this, they presented participants with a pair of semantically related words (e.g., *bouquet* and *flowers*), followed by an instructional cue that signaled participants to either (a) judge whether a second word pair was analogous to the first word pair, or (b) judge whether a second word pair was simply semantically related to the first. In addition, they manipulated the associative strength of the first word pair in order to further dissociate the effects of analogical reasoning from those of semantic relatedness. They found that verbal analogical reasoning depended on multiple PFC-mediated systems. Specifically, they found that the lateral frontopolar cortex was sensitive to the integration of multiple sources of semantic information required to complete the analogical equivalence judgments, whereas the anterior left inferior PFC was modulated by the associative strength of the first word pair. These results are consistent with the finding that the left anterior PFC extending to frontopolar cortex is sensitive to the number of elements that need integrating in a nonverbal visual analogy task (Kroger et al., 2002). Similar "relational-complexity" effects have also been found in bilateral frontopolar regions when participants are engaged in Raven's progressive matrices tasks (Christoff et al., 2001).

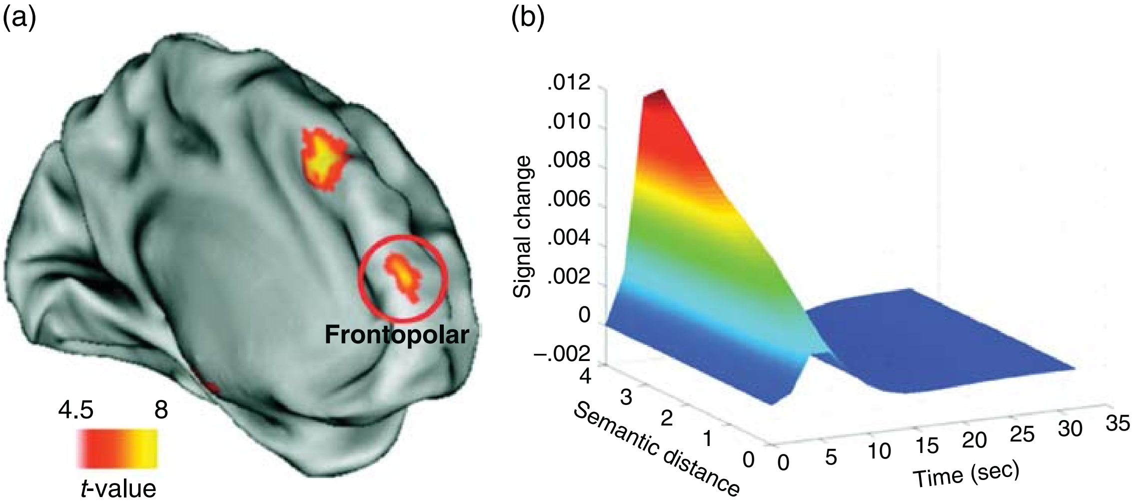


Figure 9.8 Neural response to semantic distance in reasoning. (a) Brain activity (orange) shown on an inflated cortical rendering of the left hemisphere; (b) percent signal change in the frontopolar region of interest as a function of increasing semantic distance between analogies. Reprinted from Green, A., Kraemer, D., Fugelsang, J., Gray, J., & Dunbar, K. (2010). Connecting long distance: Semantic distance in analogical reasoning modulates frontopolar cortex activity. *Cerebral Cortex*, *20*, page 72, with permission from Oxford University Press.

This prior work was extended in a series of studies by Adam Green and his colleagues (Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010; Green et al., 2012b), who examined the degree to which the *analogical distance* between the two word pairs modulated the recruitment of the frontopolar cortex. Specifically, they parametrically manipulated the “closeness” of the two word pairs to be judged, such that some four word pairs had deep-lying similarities between relational representations that are superficially dissimilar (e.g., kitten:cat::spark:fire), referred to as *cross-domain* analogies, whereas other analogies were superficially quite similar (e.g., kitten:cat::puppy:dog), referred to as *within-domain* analogies. They (Green et al., 2010) found a parametric relation between the semantic distance between the analogies and the recruitment of frontopolar cortex, such that activity in frontopolar cortex increased as the semantic distance in the analogies increased (see Figure 9.8). This pattern was found in both a verification (Green et al., 2010) and a production (Green et al., 2012b) version of the task. Taken together, these findings significantly extend previous evidence that the frontopolar cortex plays a central role in analogical mapping (Bunge et al., 2005; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006) by showing that this region of the brain is sensitive to the relational distance of the stimuli that are being reasoned with. It should be noted, however, that the degree to which frontopolar cortex is specifically responsive to the relational integration component of analogical reasoning or more general hypothesis generation is a matter of recent debate (see Shallice & Cooper, 2011).

Several laboratories have now begun to explore the emergence of these functional neural systems in children's relational reasoning. For example, Crone et al. (2009) found that, like adults, 8- to 12-year-olds engaged lateral PFC and parietal cortex during relational matching tasks similar to Raven's matrices. However, they exhibited a different timecourse and overall activation profile. Specifically, while children also engaged rostrolateral PFC (a region just lateral to frontopolar cortex) when relational integration was required for single relations, they failed to do so when required to integrate across two relations. Crone et al. (2009) argued that this key finding suggests that improvements in this ability as a function of development may be dependent on changes in the profile of rostrolateral PFC engagement. Indeed, a more detailed analysis of similar data using age (from 8 to 19 years) as a covariate during a visual–spatial relational reasoning task suggests a gradual shift with age from a more widespread frontal–cingulate–striatal pattern (regions associated with effortful executive processing) in childhood to a predominant occipital–parietal–frontal pattern (regions associated with faster and more efficient visual–spatial processing) in late adolescence (Eslinger et al., 2009).

Finally, Wright, Matlen, Baym, Ferrer, and Bunge (2008) measured the neural responses of 6- to 13-year-olds while they completed visual A:B::C:D proportional analogies. As with the adult work, they found preferential recruitment of the rostrolateral PFC when the task required the integration of semantic relations. However, in contrast to adults, they found that, as a group, the children tended to engage the rostrolateral PFC too late in a trial to impact their behavioral responses, suggesting that critical developments in the function of rostrolateral PFC continue well into adolescence and likely beyond.

Summary

In the current chapter, we have discussed some of the major domain-general cognitive processes that contribute to scientific reasoning. As noted above, we focused on causal, deductive, and analogical reasoning processes for several reasons. First, these three domains have all been shown to be used frequently by scientists and nonscientists alike when making discoveries about the world. Second, over the last decade there has been much headway in understanding the neural mechanisms that subserve these domain-general processes. Finally, the convergence of research with adults (often university students) and children allow us to gain insights into how these competencies develop. In so doing, a number of key themes regarding the development of the brain and scientific reasoning ability emerge. Here, the brain imaging data are especially informative, particularly as they relate to how domain-specific content influences domain-general reasoning processes (and subsequent brain recruitment). In the current chapter, we have highlighted multiple ways whereby content can influence reasoning processes. For example, content can facilitate reasoning in both children and adults. Here, in a range of tasks it has been shown that the integration of real-world knowledge (which involves recruitment of dorsolateral regions of the PFC) facilitates reasoning in multiple domains. In addition, domain-specific knowledge can also challenge and hinder reasoning performance when such knowledge is in conflict with available evidence. Here, we saw the critical role of conflict processing in multiple domains of reasoning, and the resultant interplay between the anterior cingulate cortex and multiple regions with the prefrontal cortex in the detection of, and subsequent modification of, reasoning behavior in response to conflict. A reasonable hypothesis is that one's ability to suspend belief is highly dependent on the efficiency with which these processes unfold. Finally, when reasoning analogically, the furthest reaches of prefrontal cortex (notably frontopolar) support one's ability to integrate disparate sources of information. Taken together, a clear picture emerges regarding the dependence on multiple regions in the prefrontal cortex for effective scientific reasoning. Considering this, it is not surprising that such abilities take time to develop due to the finding that the DLPFC is relatively late in maturing (Zelazo et al., 2008).

Future Directions

The majority of neuroimaging results reported above have been obtained with young-adult (most often college students) or adolescent participants. This is because of the technical difficulties associated with testing young children (see Chapter 2) in MRI scanners. While these results are highly informative, they nevertheless remain only suggestive of what might be happening with regards to children's scientific reasoning because many of the changes that occur do so before adolescence, particularly between 4 and 8 years of age (see Zimmerman, 2007, for a review). Consequently, it is vital to extend these sorts of study downwards to younger ages. This would allow us to better understand the modes of reasoning that are most effective in young children (e.g., perceptual versus linguistic presentation of information) and the kind of training that might be most effective at promoting proper scientific reasoning (e.g., training in inhibition). Such findings would also help us to identify *when* and *which* skills are receptive to training, such as that provided in the classroom, and which skills are not developed enough to be receptive to classroom-based science education.

The current adult studies suggest that participants engage different reasoning processes when presented with hypotheses that are consistent with their domain knowledge rather than those not consistent with the current knowledge. If this holds true in children, then it suggests that increasing domain knowledge should be a precursor to teaching children about the domain-general inferential techniques. Thus, when approaching a new topic, early emphasis should be in providing early experiential knowledge of relevant phenomena on which later explicit inferences can be constructed.

Conceptual change also plays an important role in scientific reasoning. What is not clear is how and when this conceptual change takes place in an individual. Neuroimaging, particularly EEG methods, offers the promise of individualized assessment of semantic and conceptual organization (see Gliga & Mareschal, 2008, for further discussion of this). Though currently not practical on a large scale, the promise of low-cost portable EEG systems (see, e.g., Davies, Segalowitz, & Gavin, 2010) may make this a real tool in the schools of the future.

In summary, scientific reasoning is a complex multidimensional activity. Methods in neuroscience provide new windows into the domain-general and domain-specific processes involved and have the potential to help tailor educational practice to the individual needs of individual pupils.

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