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Statistical Reasoning and Data Analysis

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Do Naïve Theories Ever Go Away? Using Brain and Behavior to Understand Changes in Concepts

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Many of the major revolutions in the history of science can be thought of as changes in the conceptual understanding of the world (Dunbar & Fugelsang, 2005a, 2005b; Nersessian, 1999; Thagard, 1992, 2003). In addition to entire fields in science, individual students and scientists can be seen to change their conceptual structures as they acquire new information, whether it be theoretical, methodological, or empirical, in a scientific field. Understanding this conceptual change, both within individuals and within scientific fields, is thus central to our understanding of science, science education, and the scientific mind. The acquisition of new theories and data are clearly at the heart of conceptual change, but what methods can we use to determine what happens when conceptual change occurs, and how can we use this knowledge to better inform the educational system? One approach has been to couch our understanding of concepts and conceptual structures in terms of changes in symbolic representations using the techniques, models, and theories of cognitive science. Many of the excellent chapters in this volume pursue this approach (e.g., Klahr, this volume); however, following our previous work integrating naturalistic research and cognitive models (Dunbar, 1995; Blanchette & Dunbar, 2001; Fugelsang, Stein, Green, & Dunbar, 2004) we use converging methods to understand conceptual change. A combination of traditional cognitive methods and contemporary brain imaging techniques are used to determine how new concepts are acquired, how theory and data are combined, and what happens when conceptual change occurs.

THEORY, DATA, AND CONCEPTUAL CHANGE

Since Thomas Kuhn's *Structure of Scientific Revolutions* (Kuhn, 1968) most researchers distinguish between minor and major changes in a concept (Chi, 1992; Thagard, 1992). Minor changes in a concept are thought to consist of additions or deletions of links to knowledge, whereas major changes (known as conceptual change) are thought to consist of widespread restructuring of knowledge around new principles. As Chi and Roscoe (2002) point out, minor changes are often easy to achieve as they involve a simple change such as classifying an insect as a type of animal, rather than as a unique entity. However, major changes in a concept require not just the addition or deletion of a feature, but the reorganization of the relations both between features of a conceptual structure and between different conceptual structures. This widespread reorganization both within and between conceptual structures is a complex process that is thought to be extremely difficult to achieve. Students in fields such as biology, physics, and chemistry often develop many faulty theories of the world (commonly referred to as *misconceptions*) that are very resistant to change. Put another way, conceptual change in science is notoriously difficult to achieve and is a key problem for our educational system.

Using naturalistic observations of scientist during lab meetings (a method we have termed *in vivo* cognition; Dunbar, 1995) we have been able to observe conceptual change first-hand. A major conceptual shift was found to occur after a group of immunologists obtained a series of unexpected findings, which forced the scientists to propose a new concept in immunology. This new concept, in turn, forced changes in other concepts (Dunbar, 2001). Using a more traditional cognitive experimental approach, termed *in vitro* cognition, we (Dunbar & Fugelsang, 2005b; Fugelsang et al., 2004) found that subjects also underwent conceptual changes analogous to those seen with scientists (Dunbar, 1993). However, not all changes in a concept are major conceptual changes. In fact minor changes in a concept are the norm and major conceptual changes appear to be quite rare. The factors at the root of this major conceptual change view have been difficult to determine, though there have been a number of studies developmentally (Carey, 1985; Chi, 1992; Chi & Roscoe, 2002), in the history of science (Nersessian, 1998; Thagard, 1992), and in physics education (Clement, 1982; Mestre, 1991) that give detailed accounts of the changes in knowledge representation that occur while people switch from one way of representing knowledge to another.

Although there have been numerous theoretical and applied accounts of the nature of conceptual change (e.g., Limón & Mason, 2002; Kalman, Rohar, & Wells, 2004), relatively little is known of the mechanisms that underlie the different types of conceptual change, what educational interventions really foster conceptual change, what is the role of data and theory in conceptual change, and how brain based mechanisms might constrain when and how conceptual change occurs. Here, we outline three different ways we have been investigating conceptual change, each of which highlight an important feature of the way that peoples' theories change, or for that matter, do not change. We begin with an investigation of the way students conceptualize the causes of the seasons.

CONCEPTUAL CHANGE AND THE CAUSES OF THE SEASONS

One area where students have great difficulty in acquiring new concepts is in understanding the causes of the different seasons. Many children, and even more importantly many adults, believe that the reason for the Earth's seasons is the distance between the earth and the sun at different times during the year. The two most commonly held explanations that students offer are: (1) physical proximity—that the earth is physically closer to the sun at different times of the year, and (2) hemispheric proximity—that one hemisphere is closer to the sun at different times of the year. Many of us believe that the earth travels around the sun in an exaggerated elliptical orbit, and frequently science textbooks display the path of the earths' orbit in this manner (e.g., in the Oxford Illustrated American Dictionary, 1998, p. 743). However, the earth's orbit around the sun is basically circular. In fact, the earth is slightly closer to the sun in the winter! However, even when this is explained to adults, they still believe that there is something about the distance between the earth and the sun that causes the seasons.

Much research over the last 20 years has revealed that even physics students have misconceptions *regarding the causes of the seasons. In the famous documentary* A Private Universe (Schneps & Sadler, 1988) 23 students, faculty, and staff at the Harvard University commencement ceremony were asked why it is hotter in the summer than in the winter, with all but two saying it is because the earth is closer to the sun in the summer than in the winter. These results were found for varying levels of education, from those students with no science background to those who had taken classes in planetary motion. Current research in our laboratory has demonstrated that Harvard is no exception. Like the Harvard students, undergraduates at Dartmouth College have strong misconceptions about seasonal change (Stein & Dunbar, 2003). Furthermore, research in the private Universe project has routinely found that students, and even teachers believe that the seasons are caused solely by the distance of the earth from the sun. Given that this concept is taught throughout elementary school, middle school, and high school it is important to determine how pervasive this conception of the seasons is and how easy or difficult it is to change concepts of seasonal change.

Before beginning on the task, we asked undergraduate students to write out an explanation for why the earth has different seasons. After completing their written descriptions, students were asked a series of multiple-choice questions to assess any misconceptions they might have about why the earth has different seasons. They were then presented with a series of trials in which they were shown a month corresponding to each of the four seasons and then presented with a picture of a globe with two spots marked on it. One spot was always located between 23.5 degrees North to 23.5 degrees South of the equator, whereas the other was always located outside of this range in the opposite hemisphere. Participants were asked to choose which of the two locations represented the shortest distance between the earth and the sun. After the first set of trials, participants were shown a video explaining why we have seasons (http://kids.msfc.nasa.gov/earth/seasons/EarthSeasons.asp). The video demonstrates how the orbit of the earth is, essentially, circular, and how the tilt of the earth influences the seasons. After watching the video, students completed another set of trials and answered the multiple-choice questions again. They were then given the opportunity to adjust their written descriptions of why the earth has different seasons (participants were provided with a blue pen when writing their original descriptions and a red pen when making any changes at the end of the study). Thus we were able to compare students' answers before they watched the video with their answers after they watched the video.

Let us first consider students' initial answers to the questionnaire. Our results indicate that 94% of participants have misconceptions about seasonal change, with the majority falling into the category of hemispheric proximity. Data from the task also indicates participants are taking into account the tilt of the earth's axis when making their decisions (overall accuracy was about 75%). Turning now to the effect of the NASA video on students' answers, we found that the short video intervention designed to address these misconceptions helped only with simple information regarding the shape of the earth's orbit around the sun, but had little effect on student's ability to integrate new information about how the angle of the suns' rays effect the different seasons. Before the intervention, only 25% of participants answered correctly regarding the shape of the earth's orbit around the sun compared to 75% after the intervention. However, only *one* student (2%) changed their answer from the incorrect (hemispheric proximity) answer to the correct answer regarding the reason for seasonal change. In addition, only 25% of the students added information about the angle of the suns' rays to their written descriptions after completing the task. Based on the changes to their written descriptions, we would have expected participants to have higher accuracy scores after watching the video, however, there was no change in accuracy scores after the intervention.

Why did the video, which was supposed to address the misconceptions, have a no significant effect on students? Interestingly both students' responses and their explanations, indicate that they did not encode the relevant information that was inconsistent with their theory. The key source of the students' difficulty is that they fail to integrate different sources of information correctly. In this situation they need to know that the orbit of the earth around the sun is basically circular and that the axis of the earth determines the angle of the suns' rays as they hit the earth. The students do take the axis into account and are willing to accept that the shape of the orbit is nearly circular, but fail to incorporate how this influences the angle of the suns' rays and therefore believe that the seasons are caused by the Northern hemisphere being closer to the sun in July than in January. Thus, students merely modify their old theory rather than engage in the reorganization of knowledge that is necessary for conceptual change.

Our work on the seasons illustrates the difficulty of achieving conceptual change. Even when students are presented with information inconsistent with their views, they maintain their incorrect theories. Why is it so difficult to change concepts in the face of new information? Another line of research on causal thinking that we have been conducting provides many clues and insights into why it is so difficult to achieve conceptual change. Below we discuss two studies that investigate these questions. In the first experiment (Fugelsang & Dunbar, 2005) we investigate what happens when students encounter data that are either consistent or inconsistent with their theory. In the second experiment, we investigate the degree to which students' theories are modifiable if given a preponderance of disconfirming data. We use fMRI to answer these questions and argue that these studies have important implications both for educational theory and educational practice.

USING fMRI TO INVESTIGATE THE EFFECTS OF DATA ON PEOPLES' THEORIES

Why is conceptual change so hard to achieve and what types of information are needed to foster this change? Our research on the seasons reported in the previous section demonstrates that even when students are given precise information about a theory, their theories do not change. One frequent approach to this problem is to present students with data that are inconsistent with their theories. The assumption is that by presenting students with anomalies they will realize that their original theory is incorrect and will then reorganize (restructure) their knowledge eliminating naïve theories. The use of anomalies has therefore been central to proposals for a constructivist education (e.g., Baker & Piburn, 1997; Mortimer & Machado, 2000). How can we determine what has happened when a student acquires a new scientific concept? The approach that we take here is to look at the recruitment of specialized neural circuits in the brain and ask what networks are involved when people are given data that are inconsistent or consistent with their theory. Because cognitive neuroscientists have identified the major brain areas involved in memory, learning, attention, and reasoning (see Gazzaniga, 2004, for a comprehensive account of what is known about the brain in these topics), it is now possible to understand the types of cognitive and neural changes that occur in educationally relevant learning. In the next section we provide an overview of our recent findings on conceptual change in science.

We (Fugelsang & Dunbar, 2005) used fMRI to investigate changes in concepts. We gave students data that were either consistent or inconsistent with a theory related to the effectiveness of drugs designed to relieve symptoms of depression. We also varied how plausible the theory was by presenting participants with a brief introductory statement that contained either (1) a direct plausible causal mechanism of action linking a red pill to a mood outcome, or (2) no direct causal mechanism of action linking a red pill to a mood outcome. Participants were then provided with data in a trial-by-trial format where they viewed multiple trials of data for each type of drug. These data were either *consistent* with their theory or *inconsistent* with their theory. After seeing 20 trials of data the participants were then asked how likely it was that the given drug was effective, that is, that it caused a reduction in patients' symptoms of depression. Note that this experimental procedure for studying participants' causal reasoning from data closely resembles that discussed in Danks (this volume).

We used two measures of conceptual change. First, we examined changed in participant's ratings of how causally relevant a variable was, and second, we examined changes that occurred in the brain as a function of theory and data consistency. Specifically, we were interested in the degree to which theory and data consistency modulates the recruitment of brain networks typically associated with learning (i.e., the caudate and parahippocampal gyrus) or areas commonly thought to be indicative of error detection and response inhibition (i.e., anterior cingulate cortex and dorsolateral prefrontal cortex). We propose that dissociations of brain-based measures of learning and inhibition may serve as a useful index of the degree to which participants are updating their representations in the face of new information.

We found that when people were given data that were consistent with their preferred theories, areas thought to be involved with learning (i.e., caudate and parahippocampal gyrus) showed increased levels of activation relative to baseline. However, when participants were presented with data that were inconsistent with their preferred theory the anterior cingulate, precuneus and dorsolateral prefrontal cortex showed increased levels of activation. The anterior cingulate is thought to be a region of the brain associated with error detection and conflict monitoring whereas the dorsolateral prefrontal cortex is thought to be one of the prime regions involved in effortful processing and working memory. These results indicate that when data are consistent with a theory, then minor changes in concepts are achieved through standard learning structures.

This experiment also demonstrates one of the reasons why conceptual change is so difficult: When people receive information that is inconsistent with their preferred theory learning does not easily occur. In a related study we sought to gain more information on the mechanisms underlying minor conceptual change by increasing the number of learning trials that a participant is exposed to and by tracking both behavioral and brain-based changes as a function of the number of data trials. Using this approach, we could see whether there is a differential rate of learning for plausible as opposed to implausible theories. What we found is that, as in the previous experiment, data that were inconsistent with a plausible theory did not preferentially activate learning mechanisms. Surprisingly, even after 96 trials of data we saw no increased levels of activation in learning associated areas. Furthermore, regions associated with error detection and response inhibition continued to be recruited throughout the data accumulation phase of the experiment. These results indicate that even minor conceptual changes are difficult to obtain. Both the behavioral data and the fMRI data are consistent with this interpretation.

How should we interpret the anterior cingulate activation? There are two main views of the primary role of the anterior cingulate in cognition. One view is that it is an area of the brain that notes unusual events or errors in the environment. The other view is that the anterior cingulate is involved in inhibiting responses. Either of these two views indicates that in our experiment, participants are treating data that are inconsistent with their plausible theories in ways that are different from consistent information. From the perspective of science education these data clearly show that just presenting students with anomalies will *not* produce conceptual change. What the results of these two experiments show is that prior belief in a theory influences the interpretation of data in a highly specific way. Specifically, data inconsistent with one's expectations are treated as errors and thus not easily incorporated into one's knowledge representation.

INVESTIGATING MAJOR CONCEPTUAL CHANGE

In our next study we examined the brain basis of major conceptual change by studying students who have had undergone a conceptual change with students who have not undergone a conceptual change. We also wanted to present students with information that was consistent or inconsistent with their current representation of a concept. From our previous study (Fugelsang & Dunbar, 2005) we knew that information inconsistent with a theoretical perspective should reliably recruit neural tissue in the anterior cingulate cortex, and that we could thus use this activation as an index of conceptual change. Here, we examined students that had taken no high school or college-level physics courses and compared them to students who had taken at least five college-level physics courses. Students were the same in all other respects having equal SAT scores, ages, and an equal distribution of genders.

We chose physics as a domain because physics concepts such as Newtonian conceptions of mechanics are very difficult for students to acquire. This issue has been the focus of much research in the physics education and cognitive science communities (Clement, 1982; diSessa, 1993; Hammer, 1996; McCloskey, Washburn, & Felch, 1983; Mestre, 1991; Reddish & Steinberg, 1999). On the basis of more than 20 years of research it is now known that students possess a knowledge of physics concepts that is quite different from that being taught in physics courses, and that students tenaciously hold on to their original views despite empirical demonstrations and theoretical expositions of the correct views. Many people hold erroneous beliefs about motion similar to a medieval "Impetus" theory (McCloskey, Caramazza, & Green, 1980). Furthermore, students appear to maintain "Impetus" notions even after one or two courses in physics (e.g., Kozhevnikov & Hegarty, 2001). Thus, it is only after extensive learning that there is a conceptual shift from "Impetus" theories of motion to "Newtonian" scientific theories.

We showed students movies of two balls falling and asked the students to press a key if this was the way that the balls should fall in a frictionless environment, or to press another key if the balls were falling in a way that was inconsistent with what they would expect. Subjects saw the two balls falling at the same rate or at a different rate. The balls could be of the same size (both large or both small), or could be of different sizes (one large and one small). We were particularly interested in comparing what we call "Newtonian" movies, where two balls of unequal size fall at the same rate, with "Impetus" movies in which the bigger ball fell at a faster rate than the smaller ball. The "Newtonian" movies are consistent with "Newtonian" mechanics where balls of different mass fall at the same rate. Thus, for these movies we expected the physics students to regard the movies as normal. We expected the physics students to classify the "Impetus" movies in which the bigger movie falls faster than the smaller movie as abnormal. Conversely, we expected the nonphysics students to classify the "Newtonian" movies as abnormal and the "Impetus" movies as normal. We were interested in whether the brain activation patterns for the two different types of movies would interact with students' background.

The fMRI data indicates that physics students had made the conceptual leap from a naïve "Impetus" view of physics to a "Newtonian" theory. First, when the physics students saw the "Impetus" movies (with the bigger balls falling faster than the smaller balls), the anterior cingulate showed increased activation relative to baseline. Thus, the physics students appeared to be regarding the "Impetus" movie as erroneous, whereas the nonphysics students saw the "Newtonian" movie as erroneous. Conversely, when the nonphysics students saw the two balls falling at the same rate regardless of size, the anterior cingulate showed increased activation, indicating that they regarded these movies as strange or erroneous thus resulting in response conflict.

The results of our physics study parallel those of our work on complex causal thinking: Information that is inconsistent with a currently held theory activates areas of the brain that are associated with error detection. What is interesting here is that half of our non-physics students correctly judged that two balls falling at the same rate is natural and thus gave normatively correct answers. However, these same students who gave normatively correct answers still showed relatively greater activation in the anterior cingulate cortex when they saw two balls of different mass falling at the same rate. This result indicates that despite giving the correct answer, brain imaging data reveals that the students had not undergone the deep conceptual change needed to produce the correct answer for the right reasons. One hypothesis that we have about the difference between the behavioral responses and the imaging data is that many students can give the right answer without truly understanding why. The imaging data allows us to gain a greater depth in understanding what students know. Activation in other brain sites, such as the medial prefrontal cortex also track students' understanding of concepts in physics. Thus, a key goal in our current research program is to understand the networks of brain sites that are involved in conceptual change.

ASSESSING THEORY, DATA, AND CONCEPTUAL CHANGE

Across three studies that have explored both varying amounts of experience with a theory and varying amounts of data consistent or inconsistent with a theory, we see that one's naïve theory can readily be invoked. These results have important implications for many types of educational interventions and for theories of what happens when we educate our students. The standard theory is that by presenting students with either large amounts of data, key anomalies, or new theories we can induce students to abandon their old theories and reorganize their knowledge. Many educational theorists see this conceptual reorganization as being *the* key goal of education and see conceptual change as so complete that students will not even be able to conceptualize their old theories following a conceptual change (Kuhn's notion of incommensurability). Yet the results of the experiments reported in this chapter indicate that even when conceptual change appears to have taken place, students still have access to the old naïve theories and that these theories appear to be actively inhibited rather than reorganized and absorbed into the new theory.

IS EDUCATIONAL NEUROSCIENCE "A BRIDGE TOO FAR"?

Whether knowledge of brain functions and learning can be used to benefit education has been a topic of great controversy over the past decade (see Petitto & Dunbar, 2004; Fitzpatrick 2005 for an overview of the controversy). Some have argued that studies in neuroscience are so far removed from educational practice that they have little relevance to education (e.g., Bruer, 1998, 2002, 2003). This has spurred an understandable worry in the education community that research on brain function is not relevant to education. Making inferences from brain imaging data to education is notoriously difficult. As Bruer (2004) has argued, many claims have been dubious. Often neuroscientists have extrapolated from a small sample using a non-educationally relevant task, which as Bruer has argued, is fraught with difficulties. We have attempted to avoid many of these problems in a number of different ways. First, we are using educationally relevant tasks rather than a vaguely analogous task. Our physics task is the topic of explicit instruction in almost every school in the country. Our complex causal thinking task is similar to many mechanisms that are taught in schools and the types of consistent and inconsistent information are the same as that used in most science curricula. We need to ask what does functional brain imaging work tell us that educators don't already know, cognitive theories don't already tell us, or standard, and less expensive, cognitive methodologies already tell us? Functional brain imaging can allow us to grasp a deeper understating of the mechanisms that underlie learning. In so doing, these methodologies can help us better develop teaching techniques and curricula that facilitate and promote better learning.

It is important to note that the very same criticisms that have been made of Cognitive Neuroscience have been made of Cognitive Psychology. In fact there is an entire literature devoted to criticizing cognitive psychology that uses exactly the same arguments that Bruer raises against Educational Neuroscience (see Cole, 1988; Dunbar & Blanchette, 2001; Gibson, 1968; Neisser, 1978; Suchman, 1988). Where does this leave us? One way of framing the issue is in terms of there being a correct level of analysis for education. Here, Bruer attempts the classic reductionist approach of boiling everything down to cognition. An alternative approach is to use converging evidence from multiple disciplines to answer important questions in education. Rather than proposing one level as basic, educators use knowledge from disciplines as diverse as sociology, cognitive psychology, neuroscience, and even molecular biology that together constrain the types of models and theories that researchers propose to understand educational issues. This is precisely the methodology we adopt when attempting to understand the important issue of what happens when students evolve theories of scientific phenomena. Cognitive Psychology is the appropriate level of analysis to solve many problems in education. Cognitive Neuroscience provides us with another level of analysis that when used together with traditional cognitive approaches, can provide us with a deeper understanding of learning and education.

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