

The Biology Of Physics: What The Brain Reveals About Our Understanding Of The Physical World

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Abstract. Fundamental concepts in physics such as Newtonian mechanics are surprisingly difficult to learn and discover. Over the past decade have been using an educational neuroscience approach to science education using a combination of ecologically naturalistic situations, classroom settings, and neuroimaging methodologies to investigate the different ways that scientific concepts are invoked or activated in different contexts. In particular, we have sought to determine how networks of brain regions that are highly sensitive to features of the context in which they are used are involved in the use of scientific concepts. We have found that some concepts in physics that are highly tuned to perception are often inhibited in experts (with increased activations in error detection and inhibitory networks of the prefrontal cortex) rather than having undergone a wholesale conceptual reorganization. Other, concepts, such as those involved in perceptual causality can activate highly diverse brain regions, depending on task instructions. For example, when students are shown movies of balls colliding, we find increased activation in the right parietal lobe, yet when the students see the exact same movies and are told that these are positively charged particles repulsing we find increased activations in the temporal lobe that is consistent with the students retrieving semantic information. We also see similar changes in activation patterns in students learning about phase shifts in chemistry classes. A key component of both students and scientists' discourse and reasoning is analogical thinking. Our recent fMRI work indicates that categorization is a key component of this type of reasoning that helps bind superficially different concepts together in the service of reasoning about the causes of unexpected findings. Taken together, these results are allowing us to make insights into the contextually relevant networks of knowledge that are activated during learning. This work is allowing us to propose why some educational interventions are more successful than others and why certain types of educational interventions are appropriate for some contexts, but not others.

Keywords: Educational Neuroscience, Causal reasoning, Scientific thinking, Analogy, Microcategory account, Scientific reasoning, Science Education, Unexpected findings, fMRI, NIRS

INTRODUCTION

In the early 1870's Jacques Loeb and Ernst Mach sought to formalize the disciplines of Biology and Physics. At the time Biology was in the throes of instinct theory in which over a thousand instincts, such as the "air hunting instinct" or the sleep instinct were proposed as explanations for human behavior [1]. In Physics, Mach was arguing against atomic theories such as those proposed by Boltzman. Both Mach and Loeb considered instinct theories highly subjective and circular. In an attempt to overcome this plethora of capricious concepts they proposed that theories should be based upon phenomena that could be directly observed [2]. While Loeb and Mach's theories have been displaced, they had an enormous effect on Biology, Physics, and Psychology and most specifically on Education. Loeb's students spawned behaviorism, and Mach and Loeb's writings espoused

that a true science was one in which scientists must demonstrate a control over nature. Loeb's writings led to a mechanistic Biology, a mechanistic Psychology, and a mechanistic approach to educational practice as opposed to a more contextually, or ecologically based approach (See [3] for a lively discussion of the way that this battle played out in Biology and its ultimate resolution in Biology). In Education, the Vygotskian and Piagetian approaches battled with the behaviorist and apparently mechanistic Cognitive Psychology approach with both the cognitive and the sociocultural approaches claiming to provide better insights into learning, thinking, and teaching. While the battle between these two approaches appeared to be unending, beginning in the 1970s researchers, sought not just to understand education by reducing it to one level but by combining different approaches into one (See [4] for our earlier work on combining ecologically and mechanistically oriented approaches to science education). Most recently, my colleagues and I have argued that the many different approaches

to education can come together in the new discipline of Educational Neuroscience [5-8]. The goal here is not to build bridges that could fall but to forge a new discipline that combines teaching practices, social factors, cognition, and brain functioning into one multifaceted discipline- Educational Neuroscience.

COMBINING BOTH MECHANISTIC AND SITUATED APPROACHES TO UNDERSTAND SCIENCE EDUCATION

We began our Educational Neuroscience approach with our naturalistic studies of scientists reasoning at laboratory meetings, and found that the scientists devoted most of their time proposing causal explanations for unexpected findings. Dunbar spent one year in three molecular biology laboratories and one immunology laboratory at a prestigious U.S. university. He used the weekly laboratory meeting as a source of data on scientific thinking, reasoning, and discourse. When he looked at the types of findings that the scientists made, he found that over half of the findings were unexpected and that these scientists had evolved a number of important strategies for dealing with such findings. One clear strategy was to reason causally about the findings: Scientists attempted to build causal models of their unexpected findings [9].

Many of the key unexpected findings were inconsistent with pre-existing causal models. To investigate these processes further we built a laboratory equivalent of the biology labs in which students obtained unexpected findings that were inconsistent with their pre-existing theories [10]. We examined this issue by creating scientific causal scenarios where experimental outcomes were either expected or unexpected and the underlying hypothesis being used was plausible or implausible. Put another way, we used fMRI and behavioral analyses to study the neural roots of causal reasoning in individuals where their task was to interpret data relative to plausible and implausible causal theories. We found that evaluation of data *consistent* with a plausible causal theory recruited neural tissue in the caudate and parahippocampal gyrus, whereas evaluating data *inconsistent* with a plausible theory recruited neural tissue in the anterior cingulate, left prefrontal cortex, and precuneus. We proposed that these findings provide a neural instantiation of *some* of the mechanisms by which theory and data are integrated in the brain. We have also found other brain sites that participate in analogical reasoning when students are integrating theories [11]. Thus, a number of different networks are activated when students and scientists reason about theory and data.

We also used fMRI to examine probe the ways that different contexts and expectations are

involved in the recruitment of specific brain regions when reasoning about physical scenarios such as balls colliding and falling, which are almost universal scenarios in physics education [12]. In one set of studies, participants were instructed to imagine that two objects were either billiard balls or positively charged particles. When the second object moved without being touched by the first object students found the event implausible, yet when shown the same movie but told that these were two positively charged particles they found the events plausible. Even though the movies that the students observed were identical in both scenarios, the patterns of brain activation were very different in the different contexts. Regions in the right medial frontal gyrus were selectively recruited for plausible relative to implausible events when judging billiard balls, whereas regions in the left middle frontal gyrus were selectively recruited when judging positively charged particles. These findings support the hypothesis that peoples' understanding of causality is multidimensional and that contextual information changes the way that neural networks are recruited for the task [12]. What is important to note here is that neuroimaging research can show the ways that different contexts and instructions alter brain activations, rather than revealing one hard-wired function for a particular brain site.

In another set of tasks physics and non-physics students were imaged while viewing videos demonstrating either classical Newtonian physics, in which a large and a small ball fall at the same speed, or a Non-Newtonian scenario, in which the larger ball drops faster than the small ball. When the non-physics students saw the two balls of different sizes falling at the same rate, the Anterior Cingulate showed increased activation, indicating that they regarded these events as strange or erroneous. Conversely, when the physics students saw the non-Newtonian movies (with the bigger ball falling faster than the smaller ball), the Anterior Cingulate showed increased activation [7]. Thus, the physics students appeared to be regarding the non-Newtonian movie as erroneous, whereas the non-physics students saw the Newtonian movie as erroneous. We have proposed that the selective recruitment of the Anterior Cingulate cortex coupled with other task related regions of interest could be used as an index of conceptual understanding and the effects of education on the brain [8].

In the next series of experiments [13] we turned to concepts discussed in most introductory chemistry courses – the molecular nature of matter. Using fMRI, advanced chemistry and non-chemistry students were imaged while judging representations of molecules before and after a phase change (liquid to gas). In keeping with decades of educational research, the chemistry novices displayed a very different

account of what happens when a liquid is heated from the Chemistry experts with chemistry novices stating that the H₂O molecule breaks into O₂ or H₂ molecules, and the chemistry experts stating that the spacing between the H₂O molecules increase when there is a change of state. Turning now to our imaging data, we found that Chemistry experts showed relatively high levels of left inferior frontal activity on this task compared to novices, while novices show relatively high levels of inferior temporal and occipital activity compared to experts. This pattern of results is consistent with chemistry novices treating the task as a form of perceptual classification, while chemistry experts treat the task as a form of semantic/conceptual classification. Thus, the results of this type of study suggest not that the advanced students have undergone a massive conceptual reorganization, but have recruited brain networks that indicate that they have classified the information in a different way.

The results of the experiments summarized here show a number of different mechanisms involved in the use of scientific concepts. First, when data is consistent with a preexisting concept, we see indicators of learning, which allows learning to take place [10]. Second, when data are presented that are inconsistent with instantiated concepts; we see specific brain structures, such as the anterior cingulate activated that may prevent the recruitment of particular concepts necessary for learning. Most important, the results of the experiments reported here indicate that even when students appear to be using scientific concepts appropriately, students may still have access to alternate explanations and may be inhibiting their old constructs. Our finding that students activate inhibitory networks when they encounter data that are inconsistent with a plausible theory sheds new light on why it is so difficult for students to adopt alternate constructs—they may be encumbered by having to inhibit information inconsistent with their current representation. Our neuroimaging data on chemistry concepts indicate that many mechanisms are at work when students reason about concepts, such as the placing of concepts into different categories that can be seen using fMRI. The findings that fMRI can be used to distinguish between different uses of concepts and that different patterns of activation are observed depending on the concept suggest that conceptual change is neither as all or-none, nor as complete as that suggested in the literature.

A key feature of the educational neuroscience approach is the use of multiple methodologies and conceptual frameworks. We have found this approach particularly useful when it comes to understandings the ways that scientists and students integrate different forms of knowledge. When we investigated scientists' discourse and reasoning in their own laboratories we found that scientists frequently used categorization, analogy, and unexpected findings together [4] and our fMRI work on analogical thinking reveals a similar pattern: Brain sites involved in categorization and in integrating information from different semantic domains are frequently activated together. In fact, a combination of our neuroimaging and naturalistic data led

us to propose the microcategory account on analogical reasoning [14]. This account emphasizes the role of categories in aligning terms for analogical mapping. Building upon our earlier work [4] we used a semantic priming paradigm, in which students judged whether an analogy was present in a set of items such as "cat is to mouse as fish is to worm" When given these four words students were asked to identify analogy relations, category relations, or conventionalized semantic relations in the four-word sets. After each four-word set was presented a single target word appeared and participants named this word aloud. Target words that referred to category relations in the preceding four-word sets were primed as strongly when participants identified analogies as when participants identified categories, suggesting that activation of category concepts plays an important role in analogical thinking. In addition, priming of category-referent words in the analogy and category tasks was significantly greater than priming of these words when participants identified conventionalized semantic relations. Since identical stimuli were used in all conditions, this finding indicated that it is the activation of category relations, distinct from any effect of basic semantic association that caused analogical reasoning to prime category-referent words. Thus, we found that aligning categories is an important component analogical reasoning. This aligning of categories is something that we have observed in our naturalistic studies of scientific thinking [4,15]. In our most recent research using fMRI we have found that the amount of activation in the frontopolar cortex is directly related to the semantic relatedness of the terms of an analogy. The more distant the two components of analogy there are, the greater the activation in frontopolar cortex. Furthermore, in our recent work on visitors discourse patterns at a science museum, we have found that providing the visitors with visual analogs helps the visitors coordinate the different information provided in an exhibit with their prior knowledge and expectations [15].

USING ANALOGY IN SCIENCE EDUCATION

While the above results point to some of the difficulties that students encounter when they are reasoning scientifically, or are engaged in scientific discourse, our work on the educational neuroscience of analogy points to clear findings that foster conceptual change. While many, teachers and scientists have found that students don't effectively use analogies in learning new scientific concepts [16], other research has been more successful with using analogy. In our work both in studying analogy generation in our lab and in leading molecular biology labs and science museums we found that distant analogies are useful in helping communicate abstract concepts. [4,15]. Reiterating the findings discussed in the previous section, analogies activate the frontal poles, which is a region that is involved in the integration of a source and a target. Furthermore, we have found increased activations in the frontal poles and temporal lobes for distant analogies, [11, 17]. Additionally, recent work by Cho et al. [18] has shown that students must also engage in the inhibition of inappropriate analogs to successfully analogize. Here, we hypothesize that this may be the area that provides the largest amount of difficulty for

students in acquiring new scientific concepts – the discarding of old concepts. Much needs to be learned here, and we are currently investigating which brain regions are activated at which times during analogical reasoning for good and poor science students using near functional Near Infrared spectroscopy. This is a new brain imaging technique that measures both oxy and deoxy hemoglobin levels in the brain, and is amenable to movement. Furthermore, the temporal resolution of the scans is much better than fMRI and participants can talk while performing a task [19]. We have just started using this methodology and are already seeing that different types of analogies recruit different types of tissue depending on the task [20]. Additionally, we are now using Evoked Related Potentials that are helping us disambiguate student’s reactions to unusual causal events [21].

CONCLUSION

What do these results mean for science education? The approach that we are taking is that to achieve a robust and usable science of learning it is important to move beyond the metaphor of building bridges between disciplines. Instead, our goal is to use multiple methods, theoretical stances, population groups and cultures that build a mosaic of knowledge, rather than the hegemony of one group over another. To paraphrase Wilson 1994, “when this unified approach is used, important problems are solved, rather than brushed under the carpet in a flurry of revolution.”

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