Investigating the Role and Nature of Prior Knowledge in Conceptual Change: an fNIRS study

by

Anthony Naimi

A thesis submitted in conformity with the requirements for the degree of Master’s of Arts
Department of Psychology
University of Toronto

© Copyright by Anthony Naimi 2010
Investigating the Role and Nature of Prior Knowledge in Conceptual Change: an fNIRS Study

Anthony Naimi

Master’s of Arts

Department of Psychology
University of Toronto

2010

Abstract

We used functional Near-Infrared Spectroscopy (fNIRS) and a split ratio paradigm used to investigate the role and nature of prior knowledge in conceptual change in science. Sixteen participants, eight physicists and eight non-physicists were presented with two types of videos, Newtonian (two balls of unequal mass falling at the same rate) and Impetus (two balls of unequal mass, the larger one falling faster), to vary their exposure to plausible and implausible information. Whereas no increased neural activation was found in physicists, non-physicists showed recruitment in the frontopolar areas and DLPFC. Studies implicating these regions in integration and working memory support the notion that prior knowledge held by novices is flexible and context-dependent.
Acknowledgments

I would like to sincerely thank Professor Kevin Dunbar for his invaluable guidance throughout the Master’s year. Dr. Dunbar’s research program provided the inspiration for the study detailed in this thesis, and his abundant support and care has seen it through. This thesis would not be possible without him. I would also like to thank Professor Laura-Ann Petitto for opening her lab to me, providing the necessary training and tools for completion of the study, and for being a constant source of inspiration. I would also like to thank many of the members of the Dunbar and Petitto labs for their help in the study and for their enduring friendships: Eve, Shaaista, Gelareh, Faiza, Kaja and Marissa, because of you, I will always look back with fondness at my Master’s year.

I would like to thank my parents, Heather Thomas and Sirous Naimi, whose incredible sacrifices will always serve as an example to me, and to my wife, Nassim Collishaw, who is my deepest source of support.
# Table of Contents

1. Introduction
   1.1. Why (some) Ideas are so Difficult to Change
   1.2. Types of Conceptual Change and the Role of Previous Knowledge
   1.3. The Role of Neuroimaging in Conceptual Change Research
   1.4. fNIRS and Prior Knowledge in Conceptual Change

2. Methods
   2.1. Participants
   2.2. Stimuli
   2.3. Apparatus and Procedure
   2.4. Statistical Analysis

3. Results
   3.1. FCI Results
   3.2. Behavioural 1: Reaction Time Data
   3.3. Behavioural 2: Response Rate Data
   3.4. NIRS Results: Whole Brain Analyses

4. Discussion
List of Tables

Table 1. Reaction Times for Physicists and Non-Physicists for Entire Experiment

Table 2. Response Rates for Physicists and Non-Physicists for Entire Experiment

Table 3. Response Rates for Physicists and Non-Physicists Across Trials
List of Figures

Figure 1. MNI coordinates showing the placement of probe arrays

Figure 2. Reaction times for physicists and non-physicists across blocks

Figure 3. Right Lateral View of Newtonian – Impetus videos in Non-physicists

Figure 4. Left Lateral View of Newtonian – Impetus videos in Non-Physicists

Figure 5. Frontal View of Newtonian videos – Impetus videos in Non-Physicists

Figure 6. Dorsal View of Newtonian – Impetus video in Non-physicists
1 Introduction

Psychologists have long been interested in both the facility to generate some types of concepts and the inability to change other types of concepts (Bruner, Goodnow & Austin, 1956; Chi, 1992; Dunbar, 1993; Hull, 1920; Thagard, 1990). More specifically, the mechanisms underlying conceptual change have been under investigation for over 30 years in the fields of cognitive science, education and philosophy (Strike & Posner, 1992; Wiser & Carey, 1983) as they have immense implications for theories of knowledge representation and educational practice. Many methods have been devised to understand the potential mechanism(s) underlying lasting conceptual change (e.g., Chi, 2008), often providing inconsistent results. Although there has been significant advancement in our understanding of the types of conceptual change (Fugelsang and Dunbar, 2005; Klahr & Dunbar, 1988), the factors that hinder learners from achieving lasting conceptual change is still elusive. In this study, we investigate the role of prior knowledge in conceptual change by using a novel and powerful neuroimaging technique.

1.1 Why are (some) ideas so difficult to change?

Anecdotal and empirical evidence converge on the point that lasting conceptual change is extremely difficult to achieve (Chi, 2008; Ram, Nersessian & Keil, 1997). One need not go far to see examples of a failure to achieve conceptual change: crises in the environment can largely be attributed to a lack of public consciousness and an inability to change old patterns of thought, while many public health epidemics arise from our own inability to set aside age-old conceptions of health and well-being (Thagard, 1996). In addition to anecdotal evidence, empirical research has been obtained demonstrating that both adults and children hold on to incorrect concepts of the causes of the seasons (Stein & Dunbar, 2003). Many people believe that the cause of the seasons is the earth’s elliptical rotation around the sun, such that the seasons are governed by the distance of the earth to the sun, which depends on the point it is at in its ellipse. This notion is false, since the earths rotation around the sun is basically circular. The determinant of the seasons is the tilt of the earth on its axis, which determines the angle at which the rays of the sun reach the earth and therefore, the seasons. This idea that the distance of the earth from the sun causes the seasons has been shown to be very pervasive, with learners from varying ages and levels of education ascribing to the idea. In the documentary entitled “A Private Universe”,

students and faculty at a Harvard commencement ceremony were asked why the summer was hotter than the winter (Schneps & Sadler, 1988). Out of the 23 people asked, only 2 gave the correct response, while the remaining cited the earth’s distance from the sun as the causal reason for the changing seasons. Research in our own lab has demonstrated that the pervasiveness of the idea that the earth’s distance from the sun causes the seasons is not limited to students and faculty at Harvard, and furthermore, that misconceptions about the cause of the seasons are quite tenacious despite educational interventions. In one study, Stein and Dunbar (2003) showed that 94% of students tested at Dartmouth College explained the cause of the seasons in terms of the earth’s distance from the sun. When an instructional video was shown to the students that explained the true cause of seasonal change the video failed to produce any significant change or reorganization of conceptual understanding (out of about fifty students tested, only one reorganized the causal mechanism they used to explain seasonal change!). The fact that almost all students were incapable of deriving the necessary information from the instructional video is a very curious finding. Instead of using new information about the tilt of the earth and angle of the sun’s rays as a causal factor in seasonal change, learners stay with their current mental model, and therefore fail to correct their mental model after instruction. The question, then, is what can account for students’ difficulty in attaining conceptual change? In the following section, this question will be discussed in terms of theories positing two main types of conceptual change.

### 1.2 Types of Conceptual Change & the Role of Previous Knowledge

The field of conceptual change has been dealing with the problem of why ideas are difficult to change for over thirty years (Novak, 1977). Since the inception of the field of conceptual change, there has been general agreement that there are two types of conceptual change: concept revision, and radical concept reorganization (Chi, 1992; Thagard, 1990; Thagard, 1992). These types of conceptual change are distinct in that the former involves misconceptions arising from missing or incorrect beliefs, while the latter entails problems with the relational structure of a theory (Vosniadou, 1994). Conceptual change is based on the assumption of an overriding conceptual framework. It occurs naturally when the concept being instructed is consistent with
the learners underlying assumptions (known as concept revision). Conversely, radical revision is required when the concept being introduced to the learner runs contrary to underlying assumptions. Lasting conceptual change, therefore, is to be found when learners rearrange their theoretical presuppositions in a way that is consistent with the information that they are supposed to learn. But how can learners rearrange their background presuppositions? What are the factors that facilitate or hinder this process? Doubtless this question must be grounded in the role and nature of what the learners already know. Specifically, if the theories that novice learner’s hold are stable, coherent, and structured, lasting conceptual change will be achieved with intervention that is pointed towards the specific misconceptions held by learners. If, however, the theories held by novice learners are flexible and context-dependent, educational intervention can be broader.

Two camps in the field of conceptual change and science education hold these views about the nature of the tacit assumptions held by novices in physics (McCloskey, 1983; Smith, diSessa, and Green, 1994). Physics is a particularly powerful domain to investigate the nature of tacit assumptions held by novices because it is a domain in which learners have ample opportunity to build theories (McCloskey, 1983). Humans are presented with countless opportunities daily to interact with and observe the nature of physical phenomena, so if novices hold no stable theory of motion, the matter is adjudicated for all domains, that novices hold no set theory in any.

In this vein, McCloskey (1983) argues that novice learners hold stable and widespread lay theories about physical phenomenon that are consistent and structured. He argues specifically that novice learners’ view of motion approximate closely to the medieval ‘impetus’ view of motion, popular from the 14th to 16th centuries in Europe. The impetus view hold two main tenets 1) the act of setting an object in motion imparts an internal force or ‘impetus’ that sets the object in motion, and 2) this impetus gradually dissipates. McCloskey (1983) arrives at his conclusion by administering a number of questionnaires that test novices expectations about certain patterns of motion.

The other view in the field of conceptual change is that of Hammer and Elby (2002) and Smith, DiSessa and Roschelle (1994), who propose that novice learners hold no stable and consistent theory at all, rather that the understanding of physical and scientific phenomena held by novice learners is context-dependent and constructed from cues taken from the environment. They
propose that the view of McCloskey (1983) lacks an underlying theoretical framework and is not capable of predicting or explaining how students acquired the knowledge that they hold. Further, Hammer and Elby (2002) and Smith et al. (1994) believe that the position of McCloskey (1983) is a default presumption of the field of conceptual change, rather than the result of a deliberate process of investigation into the nature of tacit knowledge held by novices. On this ground, they state that, even though it may seem that non-physicists have stable and consistent views of motion, this can be attributed to common experience, and that any inconsistencies in their views cannot be detected.

The distinction held by McCloskey (1983), and Hammer and Elby (2002) is important as it bears upon an important deciding factor of the success or failure of educational interventions, and lasting conceptual change. If the theories held by novices are stable and consistent, it dictates what kind of intervention is necessary to achieve lasting conceptual change, namely, intervention that is specific and directed towards the misconception held by novice learners. If, however, the tacit assumptions held by novices hold no specific or stable form, then, educational intervention can be less directed and specific, and more focused on the contextual factors.

Importantly, the methods by which the field of conceptual change, has come to delineate the nature of the tacit knowledge held by learners have been threefold: protocol analysis (Ericsson & Simon, 1993), educational intervention (Chi, 2008) and, more recently, brain imaging (Fugelsang & Dunbar, 2005). In protocol analysis, researchers ask participants to externalize their ideas about a particular concept or process, which is documented and analyzed for its content and structure. As much of the mental structure as can be externalized in the form of verbal reports is used to uncover the nature of the mental model of a particular phenomenon, which, in turn is used in understanding the nature of conceptual change. A second method commonly used in conjunction with the first is educational intervention, where experimenters attempt to teach the participants a concept, and document the difficulties involved, from which hypotheses and predictions about the nature of conceptual change are proposed. Importantly, it is the latest experimental method used by the field of conceptual change that also seems to be the most promising: neuroimaging has proven revolutionary in the field of conceptual change, providing many clues that have been important in resolving some of the long standing debates of the field.
The question of why ideas are so difficult to change, and more specifically, what is the nature of the previous knowledge held by learners of scientific disciplines can be addressed with neuroimaging and there is an ever-growing body of neuroimaging studies done in the field of conceptual change (Fugelsang & Dunbar, 2005). It is to this research that we now turn.

1.3 The Role of Neuroimaging in Research on Conceptual Change

In recent years, neuroscience has provided new vistas of possibility in our ability to ask psychological questions. By giving us a new window into the brain, neuroscience can provide clues to research questions that have escaped traditional behavioural approaches. Neuroimaging is a powerful, non-invasive tool that can be used to capture neural processes, and can be adapted to understand the processes involved in conceptual change. In cognitive science, a tremendous amount of research has been done on concept learning, concept formation and categorization (Smith & Grossman 2008; Patalano, Smith, Jonides, Koepppe, 2002), yet, for the most part, this work has not taken into account research from an educational perspective on conceptual change (Chi, 2008; Vosniadou, 1994) distinguishing between concept learning and radical belief revision. The consequence of this is that cognitive neuroscience, and the methodologies it employs, have often investigated concept learning, but not radical belief revision. A line of studies in the lab of Dr. Kevin Dunbar has examined patterns of brain activation when participants received information that was varied in its plausibility in order to determine the interaction between participants’ held theories and information presented in situations involving conceptual change (Dunbar, Fugelsang, & Stein, 2007; Fugelsang & Dunbar, 2005; Fugelsang & Dunbar, 2009). This research, rather than looking at the process of learning, marries cognitive neuroscience with insight from educational research to investigate a deeper, more fundamental form of conceptual change.

In a first study, Fugelsang and Dunbar (2005) used functional Magnetic Resonance Imaging (fMRI) to highlight the neural regions involved in the processing of the relationship between theory and data with causal information. They presented participants with plausible and implausible information about the effectiveness of pills in relieving the symptoms of depression.
In plausible situations, participants were either given a red pill, which they were told contained a drug that led to a change in mood, or a blue pill, which they were told was a placebo that had no effect on mood. In implausible situations, participants were told that the red pill (containing the drug) had no effect on mood, while the blue pill (placebo) did. Brain imaging results showed that when participants (both novice and experts) were given plausible information, the caudate and parahippocampal gyrus were recruited, whereas, when inconsistent information was presented, the anterior cingulate cortex, precuneus and dorsolateral prefrontal cortex (DLPFC) were recruited. These findings may be interpreted in light of research implicating the medial temporal lobe, caudate and parahippocampal gyrus in learning and categorization (see also, Ashby & Crossley, 2010; Caramazza & Mahon, 2003; Kelley, Miezin, McDermott, Buckner, Raichle, Cohen, Ollinger, Akbudak, Conturo, Snyder & Petersen, 1998; McDermott, Ojemann, Peteren, Ollinger, Snyder, Akbukdak, Conturo, & Raichle, 1999; Smith & Grossman, 2008; Squire & Knowlton, 1995), the DLPFC in working memory and online processing, (Curtis & D’Esposito, 2002) and the anterior cingulate cortex in error detection and conflict monitoring (Botnivik, Nystrom, Fissell, Carter, & Cohen, 1999; Braver, Barch, Gray, Molfese, & Snyder, 2001; Pardo, Pardo, Janer & Raichle, 1990).

A subsequent study, Dunbar et al. (2007) compared participants who had undergone real conceptual change with those who had not, to see any differential patterns in their processing of plausible and implausible information. Those who had undergone lasting conceptual change were defined as physicists who had taken more than 5 courses in physics and who were validated by an independent standardized measure of physics expertise (the Force Concept Inventory, FCI; Hestenes & Halloun, 1995; Hestenes, Wells & Swackhamer, 1992). The study presented both novices and experts in physics with Impetus (where two balls of unequal mass fall at different rates) and Newtonian (where two balls of unequal mass fall at the same rate) movies and asked them to respond to whether the balls were falling correctly. Neuroimaging results of the study corroborated those of the Fugelsang and Dunbar (2005): implausible information led to activation of the ACC, precuneus and DLPFC, and plausible information led to the activation of the caudate and parahippocampal gyrus. These results, like those of Fugelsang and Dunbar (2005) can be interpreted to mean that information that is implausible to the learner requires more effortful and conscious processing, while those that are interpreted as plausible are treated as correct, without being subject to further deliberation. The fact that sites associated with error
detection were activated when expert physicists watched impetus movies, seems to indicate that these physicists have strong, stable and coherent theories with which to judge the information pertaining to physics. In a different vein, neuroimaging results from non-physicists seem to contradict behavioural findings: although brain sites associated with error detection were activated upon viewing Newtonian videos, non-physicists response rates indicated that they believe Newtonian videos to be correct. This contradiction in their outward, behavioural responses and the patterns of their neural activation seems to lend support to the theory of Hammer & Elby (2002) and Smith et al. (1994) in that novices have no stable and consistent view about the nature of scientific phenomena. In the next section of this paper, we will turn to a powerful and emerging neuroimaging tool that may help shed light on the nature of the prior knowledge held by novice learners in science.

1.4 fNIRS and Prior Knowledge in Conceptual Change

fMRI is arguably the most widespread imaging tool of cognitive neuroscience research today (Logothetis, 2008). Despite fMRI’s influence in cognitive neuroscience, many issues have been raised which highlight its limitations. Among the limitations of fMRI are its reliance on an indirect measure of blood oxygenation (the BOLD signal), which can be influenced by a host of non-neural factors, including blood flow and volume, excitation, and even drug abuse (Magalhaes, 2005; Logothetis, 2003). The degree to which fMRI is influenced by movement artifacts, and its external validity have also led to questions about its effectiveness in providing sound experimental data (Liao, Krowlick & McKeown, 2005). Lastly, although fMRI provides precise spatial resolution (approximately 3mm$^2$), fMRI’s temporal resolution is low, sampling about once every second. These limitations, although they do not invalidate the importance of fMRI, do paint an important picture about how fMRI findings are to be interpreted. Significantly, the best way to overcome limitations in the interpretation of experimental findings from fMRI is to supplement these findings with those of other neuroimaging techniques. With convergent evidence, conclusions can be drawn that transcend the limitations of the particular methodology used to obtain the findings.

A new, powerful neuroimaging technology that has garnered much attention in cognitive neuroscience in the past years is Functional Near-Infrared Spectroscopy (fNIRS). fNIRS has
proven revolutionary to the study of higher cognition by providing decided advantages over more traditional neuroimaging techniques (Shalinsky, Kovelman, Berens & Petitto, 2009; Richter, Zierhut, Dresler, Plichta, Ehlis, Reiss, Pekrun, & Fallgatter, 2009). Unlike other neuroimaging techniques fNIRS sacrifices neither spatial nor temporal accuracy, provides a direct measure of blood oxygenation, and can be used in a variety of contexts lending it external validity. fNIRS functions by emitting two different wavelengths of light into the brain (around 690 and 830nm), and sampling the light that is not absorbed. NIRS takes advantage of the differential light absorption properties of oxygenated (HbO) and deoxygenated (Hb) hemoglobin at the 690-830nm light range, and the fact that neural tissue is weakly absorbent at this end of the light spectrum. Because brain tissue weakly absorbs the red/infrared light, and because oxygenated and deoxygenated blood are differentially absorbed at this area of the light spectrum, a sample of non-absorbed light can be used to calculate the total changes in Hb and HbO. Importantly, changes in blood flow are registered to a spatial localization of about 2cm², with light being sampled by the machine every 100ms.

In the final analysis, fNIRS provides a relatively detailed and accurate view of the migration of oxygenated blood across the cortex in a way that transcends the limitations of more traditional neuroimaging techniques. The proposed study, then, will build upon and modify the previous studies (Fugelsang & Dunbar, 2005; Dunbar et al., 2007) with the goal of understanding the functional mechanisms of how prior knowledge influences conceptual change by using fNIRS to chart the migration of oxygenated blood across the cortex. We hypothesize specifically, upon presentation of implausible information, cortical sites associated with integration of information and cognitive control will be activated, such as the frontopolar area (Green, Kraemer, Fugelsang, Gray & Dunbar, 2005; Green, Fugelsang, Kraemer, Shamosh & Dunbar, 2009), the inferior frontal gyrus (Cho, Moody, Fernandino, Mumford, Poldrack, Cannon, Knowlton & Holyoak, 2009), and the Dorsolateral Prefrontal Cortex. Furthermore, when plausible information is presented, sites associated with concept learning and categorization will be activated (possibly the MTL (Smith & Grossman, 2008). As an added experimental measure, the ratio of presentation of Newtonian to Impetus videos will be varied across sessions in order to detect whether contextual factors influence participants interpretation of videos. If context does influence non-physicists prior understanding, we expect to see reaction time and response rate data vary with the ratio of the blocks.
2 Methods

2.1 Participants

Sixteen male participants (age range: 18-27) were taken from two groups of students from the University of Toronto Scarborough (UTSC): eight with a strong background in physics, and eight with no background in physics. Expertise in physics was assessed using two dimensions: physics students took five or more courses in physics, and scored highly on the Force Concept Inventory (FCI; Hestenes & Halloun, 1995; Hestenes, et al., 1992), which is a 12-question standardized measure of expertise in physics. Non-physics students took one course or less in physics, and fared significantly poorer on the FCI, which was scored out of 8 questions. No physicist obtained less than 6 out of 8, and no non-physicist obtained greater than 4 out of 8 questions correct. The mean score for non-physicists was 2.75 (out of 8), with SD = 1.39, while the mean and SD for physicists was 7.25, and .89, respectively. A paired samples t-test revealed a significant difference between FCI scores obtained by physicists and non-physicists, t(8) = 7.18, p<.01. Participants were compensated 10$ per hour of participation, plus transportation costs. Due to the demographics of physics students at UTSC, the experiment consisted solely of males.

2.2 Stimuli

During the experiment, participants were shown two types movies, ‘Impetus’ and ‘Newtonian’. A single trial consisted of showing participants a 1.5 second video displaying two white circles of different sizes falling at various rates at either side of a fixation cross located in the center of the screen. Impetus movies show circles of different size falling at different rates, while Newtonian movies display all circles falling at the same rate (according to the dictates of Newtonian mechanics). The experiment was administered in four sessions, each of which consists of four ordered blocks with 15 trials in the first block, and 21 trials in the three subsequent (trials separated by a 1 second interval, while blocks are separated by a 20 second fixation rest period). Sessions differed from each other in the relative proportion of Newtonian to Impetus trials in the following orders and ratio: Session one: 60% Newtonian- 40% Impetus,
session two: 20% Newtonian-80% Impetus, session three: 50%-50%, session four: 80% Newtonian-20% Impetus.

2.3 Apparatus and Procedure

Experimental stimuli were presented using E-Prime stimulus presentation software (Schneider, Eschman, & Zuccolotto, 2002) on a MacIntosh desktop computer. Hemodynamic response was measured using a Hitachi ETG-4000 with 42 channels arranged in two 3 x 3 probe arrays, over each temporal region, and one 3 x 5 probe array, covering the frontal pole (see Figure 1). Probes were placed to provide optimal coverage of cortical brain tissues involved in 1) conflict processing and integration, 2) learning and categorization, and working memory. To confirm proper placement of probes over the frontal and temporal lobes, 3D tracking information was obtained using the Polhemus Fast Trak system. Once the participant was welcomed into the lab, and seated, 18 probes and 15 detectors were positioned in the arrays according to the 10-20 system (Jasper, 1957). This process took about 20 minutes, after which participants sat for a 10-second baseline measurement of hemodynamic activity. Two types of videos, Newtonian and Impetus, were presented to participants, whereupon they were asked to respond whether the videos were ‘correct’ or ‘incorrect’ according to their expectations. Throughout the experiment, a video camera attached to the fNIRS machine recorded all participant information for comparison with hemodynamic information.
2.4 Statistical Analysis

Neuroimaging data were analyzed using NIRS-SPM, a MATLAB based statistical software package that quantifies cerebral blood flow data, and displays activation based on GLM statistics. Data were then transformed into Talaraich atlas space using the ICBM 152 brain template (Montreal Neurological Institute; Talairach & Tourneaux, 1988). For each participant, data were preprocessed to remove sources of noise and artifact (such as movement and heart rate) using a Gaussian filter, after which they were used for analysis. For each participant, a general linear model incorporating task effects, a mean and a linear trend were used to compute parameter estimates and t-contrast images for each comparison at each voxel. A random-effects analysis consisting of one-sample t-tests with a hypothesized mean of 0 was then applied to the individual subject t-contrast images to create mean t-images (thresholded at $P = .05$, uncorrected).
3 Results

Analyses centered around three types of comparisons. Firstly, physicists and non-physicists were compared in their results on a standardized measure of physics expertise (FCI). Secondly, physicists and non-physicists were compared in their behavioural responses (reaction times and response rates) to Newtonian and Impetus videos. Lastly, physicist and non-physicist brain activations were compared when viewing Newtonian and Impetus videos.

3.1 Behavioural 1: Reaction time data

ANOVAs comparing physicists and non-physicists reaction times to Newtonian and Impetus movies revealed two significant findings, namely, physicists and non-physicists treated Newtonian and Impetus videos differently upon first encountering them, and a potential mediation of the split-ratio paradigm upon reaction times. Specifically, reaction time was significantly slower for physicists than non-physicists for first session Newtonian videos, $F_{(1, 604)} = 6.58, p<.05$, and third session (50%-50%) Newtonian and Impetus videos, $F_{(1, 638)} = 6.54, p<.05$ and $F_{(1, 638)} = 6.02, p<.05$, respectively. Figure 2 depicts the comparisons between physicists and non-physicists in their reaction time to Newtonian and Impetus videos. Physicists longer reaction time in the first session can be interpreted to mean that physicists have strong theory with which to interpret the videos, since they respond differently to Newtonian and impetus videos, while non-physicists do not. Comparisons between physicist and non-physicists reaction times to impetus videos in the first session (60%-40%), second session (20%/80%) and fourth session (80%/20%) were nonsignificant: $F_{(1, 383)} = .114, p>.05$, $F_{(1, 1022)} = .291, p>.05$, and $F_{(1, 251)} = .350, p>.05$, respectively. Similarly, comparisons between physicist and non-physicist reaction time to Newtonian videos were non significant in the second (20%/80%) session: $F_{(1, 253)} = .431, p>.05$, and fourth (80%/20%) session: $F_{(1, 1005)} = .842, p>.05$. (See Table 1 and Figure 2). One point
emerges clearly from these data: physicists and non-physicists treat the videos differently in the first block. Presumably, this is because physicists have strong background theory, and clearly distinguish between Newtonian and Impetus videos, while non-physicists may not. Another important finding is an influence of the split ratio paradigm, in that reaction times differed between the 50%-50% block and those that were 80%/20%, although results diverge from what might be expected. Interpretation of split-ratio data, however, is best done in the context of NIRS analysis of the split-ratio paradigm, which, due to time pressure, are forthcoming.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Physicists (ms)</th>
<th>Non-Physicists (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian videos</td>
<td>1108</td>
<td>1054</td>
</tr>
<tr>
<td>Impetus videos</td>
<td>1086</td>
<td>1061</td>
</tr>
</tbody>
</table>

*Figure 2.* Reaction times for physicists and non-physicists across blocks
3.2 Behavioural 2: Response Rate Data

ANOVARs comparing physicists and non-physicists on response rates to Newtonian and impetus movies revealed two significant findings, namely, an influence of the split ratio paradigm in non-physicists' ratings of Newtonian and impetus videos, and a clear indication that physicists and non-physicists treat the videos differently. Specifically, non-physicists rated impetus movies as ‘incorrect’ significantly less often than physicists in the first (60%/40%) block, $F_{(1,383)} = 4.95$, $P<.05$; second (20%/80%) block, $F_{(1,1021)} = 10.45$, $p<.05$; and third (50%/50%) block, $F_{(1,685)} = 11.23$, $p<.05$. Correspondingly, they rated Newtonian movies as ‘correct’ significantly less often on the fourth (80%/20%) block, $F_{(1,1006)} = 9.51$, $p<.05$ (See table 3 for an in-depth view of response rates across sessions). There were no significant differences between physicists and non-physicists in response rates to Newtonian videos in the first [60%-40%, $F_{(1,511)} = 1.72$, $p>.05$], second [20%/80%, $F_{(1,256)} = .04$, $p>.05$] and third session [50%/50%, $F_{(1,592)} = .04$, $p>.05$], and no significant differences to Impetus videos on the fourth [80%/20%, $F_{(1,252)} = .344$, $p>.05$] session. These results can be taken once again to mean that the mental model with which
physicists and non-physicists approach the videos are different. An additional feature of the response rates, however, is the shift in response rates, where in the first three sessions Newtonian videos are treated differently, to the last session, where impetus movies are treated differently. This suggests flexibility in the mental models of non-physicists.

Table 2

*Response Rates for Physicists and Non-Physicists for Entire Experiment*

<table>
<thead>
<tr>
<th>Response type</th>
<th>Physicists</th>
<th>Non-Physicists</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Correct’</td>
<td>845</td>
<td>794</td>
</tr>
<tr>
<td>‘Incorrect’</td>
<td>274</td>
<td>381</td>
</tr>
<tr>
<td>Newtonian videos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>‘Correct’</td>
<td>222</td>
<td>297</td>
</tr>
<tr>
<td>‘Incorrect’</td>
<td>921</td>
<td>819</td>
</tr>
<tr>
<td>Impetus videos</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3

*Response Rates for Physicists and Non-Physicists Across Trials*
### NIRS Results: Whole Brain Analysis

**Task vs. Baseline**

Whole brain analyses were conducted comparing on-task activation to baseline in physicists and non-physicists. Baseline was defined as 10 seconds of brain activity before participants started viewing the videos. This period of activity is ideal for baseline measurements because participants have not yet been presented with stimuli, which encourage mental processing. On-task activity was compared to baseline using a p<.05 significance level (Sun’s tube formula correction, Ye, Tak, Jang, Jung & Jang, 2009). A total of 46 channels were analyzed (12 right temporal, 12 left temporal, and 22 frontal).

<table>
<thead>
<tr>
<th></th>
<th>Physicists</th>
<th>Non-Physicists</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>‘Correct’</td>
<td>‘Incorrect’</td>
</tr>
<tr>
<td><strong>Newtonian</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60/40</td>
<td>188</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>59</td>
<td>108</td>
</tr>
<tr>
<td>20/80</td>
<td>70</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>53</td>
<td>446</td>
</tr>
<tr>
<td>50/50</td>
<td>182</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>289</td>
</tr>
<tr>
<td>80/20</td>
<td>405</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>79</td>
</tr>
</tbody>
</table>

*** Indicates significance, p<.05
Impetus videos subtracted from Newtonian videos

Comparisons in hemodynamic activity between Newtonian and Impetus videos yielded significant results for non-physicists. Specifically, activation was found in the Frontopolar area (BA 25/29/30/34/39/43) and Dorsolateral Prefrontal Cortex (BA 44), and the Middle and Superior Temporal Gyri (BA 8/19/24; see figures 3-6). Physicists showed no activation for any task-related measurements relative to baseline (p<.05\text{uncorrected}).

Figure 3. Right Lateral View of Newtonian – Impetus videos in Non-physicists

Figure 4. Left Lateral View of Newtonian – Impetus videos in Non-Physicists
Figure 5. Frontal View of Newtonian videos – Impetus videos in Non-Physicists
4 Discussion

In this study we examined differences between physicists and non-physicists’ responses to plausible and implausible information with the aim of understanding the role of prior knowledge in conceptual change. Specifically, we looked at differences in how physicists and non-physicists responded to Newtonian and Impetus videos by looking at behavioural measures (both reaction time and response rates) and using fNIRS. Evidence garnered supports the view of Hammer & Elby (2002) and Smith, diSessa and Roschelle (1994) that novice learners hold no consistent, entrenched theory of scientific phenomena.

By firstly looking at the behavioural results, we see reaction time differences between physicists and non-physicists localized to the first session of videos (i.e. – when they first encounter the videos) and the third (50% impetus-50% Newtonian) session. Physicists were significantly slower than non-physicists in their responses to Newtonian videos on the first and third sessions, and to Impetus videos in the third session. Focusing particularly on differences in the first
session, differences in reaction time shows that physicists treated Impetus and Newtonian videos differently upon having first encountered them, while Non-physicists treated them in the same way. This supports the notion that the theory held by physicists was more consistent and stable than that of non-physicists. In the third session, differences between physicists and non-physicists might be attributed to the split ratio paradigm employed, although results diverge from what would be expected.

Similar to reaction times, behavioural response rates demonstrate differences in the way that Physicists and non-physicists understand Newtonian and Impetus videos. On the first three sessions, non-physicists rated impetus movies as ‘correct’ significantly more often than physicists, while their responses to Newtonian videos were equal to those of physicists. On the fourth session, however, their ratings shifted, and they deemed Newtonian movies as significantly more ‘incorrect’ than physicists, while Impetus movies were rated in the same way as physicists. These data clearly indicate that non-physicists are struggling between more than one interpretation of the videos. Non-physicists are generally able to recognize Newtonian videos as correct, but their ratings of Impetus videos are less clear and more variable throughout much of the experiment. Interestingly, their responses shift in the last session of the experiment, and they begin to rate Newtonian videos as less correct than they previously did. This is an important feature of the data, and provides a potentially important clue: If the ratings of non-physicists can shift in accordance with the ratio of a session, it is strong support for the idea that their background knowledge is not set, or rigid, but flexible and unstable. One feature of the data that tempers this interpretation is a potential inconsistency between reaction time and error rate data: how are non-physicists able to correctly identify the videos, while not having a stable or consistent theory?

Neuroimaging results obtained from the study help clarify our behavioural findings. No increased activation can be seen in comparisons made between Newtonian and Impetus videos in physicists. Non-physicists demonstrate activity in three distinct brain regions: 1) the frontopolar area, 2) the dorsolateral prefrontal cortex (DLFPC), and 3) the middle and superior temporal gyri. The frontopolar area has been linked to the integration of information in analogical and relational reasoning (Green, Fugelsang, Shamosh, Kraemer, & Dunbar, 2006; Green, Kraemer, Fugelsang, Gray & Dunbar, 2009), the DLPFC is a widely known neural correlate of working
memory (Curtis & D’Esposito, 2003), and the middle temporal gyrus has been linked with the perception of object movement (Beauchamp, Lee, Haxby & Martin, 2002).

The activation of Frontopolar regions and the DLPFC demonstrate that non-physicists had to actively think, and integrate the information they observed, rather than having a set theory with which to interpret the videos. If non-physicists had a set theory, as McCloskey (1983) and McCloskey, Caramazza, and Green (1980) suggest, one would expect to find a pattern of activation similar to that of physicists (i.e. – no increased activation). The fact that no activation was found in physicists can be attributed to a migration of cortical activity to deeper brain regions concomitant with the increase in expertise and automaticity (Hill & Schneider, 2006). Since fNIRS measures only cortical activity, it was not detected in our study. fNIRS has been able to demonstrate an important difference between physicists and non-physicists in centers for higher level cognition indicating an active effort at integration in non-physicists. Here lies the more evidence to the nature of prior knowledge of non-physicists, which, if interpreted with behavioural evidence points towards the fact that non-physicists do not interpret scientific phenomena with a strong background theory before having received significant instruction. Rather, their understanding of scientific phenomena is one that is contextually shaped, flexible and weak.

Taken together, what we witness in non-physicists can be thought of as a window into the actual process of conceptual change. The picture we get in this experiment is not one where non-physicists have a set, determined theory. Rather, non-physicists seem to be actively engaged in the reorientation of expectations and the integration of new information in an effort to correctly answer the question asked of them. Here non-physicists encounter videos, the underlying ideas of which they are not entirely familiar and they are actively thinking about in an effort to correctly perform their task. Importantly, this picture holds important implications for the nature of prior knowledge in conceptual change, and the proper approach of educational intervention in science education.
References


An Information-Theoretic Criterion for Intrasubject Alignment of FMRI Time Series: Motion Corrected Independent Component Analysis. *IEEE Transaction on Medical Imaging*, 24(1)


Representations of physical plausibility revealed by event-related potentials, NeuroReport, 20, 1081–1086.


Stark, C., Squire, L. (2001). When zero is not zero: The problem of ambiguous baseline conditions in fMRI. PNAS, 98(22), 12760-12766.


