FACTORS INFLUENCING LEARNER CONCEPTIONS OF FORCE: EXPLORING THE INTERACTION AMONG VISUOSPATIAL ABILITY, MOTIVATION, AND CONCEPTIONS OF NEWTONIAN MECHANICS IN UNIVERSITY UNDERGRADUATES FROM AN EVOLUTIONARY PERSPECTIVE

by

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Factors Influencing Learner Conceptions of Force: Exploring the Interaction among Visuospatial Ability, Motivation, and Conceptions of Newtonian Mechanics in University Undergraduates from an Evolutionary Perspective

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Dedication

This work is dedicated to my grandfather, Harold M. Gates, whose example molded the man I have become.

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I would like to thank the many friends, relatives, and supporters who have made this happen. Many thanks go to my major professor, Dr. Leonard Annetta, for support, encouragement, and guidance well beyond the duties of a mentor. I am also grateful to my committee members Erin Peters-Burton and Wendy Frazier, without whom this document would not exist. I would also like to thank Richard Lamb for informal tutoring in the quantitative methods used in this dissertation, and Dr. M. Layne Kalbfleisch for her work during the portfolio and proposal process. Finally, I would like to thank my mother, Debra Gates Vallett, for thirty-four years of encouraging me to seek answers to my curiosity.

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Abstract

FACTORS INFLUENCING LEARNER CONCEPTIONS OF FORCE: EXPLORING THE INTERACTION AMONG VISUOSPATIAL ABILITY, MOTIVATION, AND CONCEPTIONS OF NEWTONIAN MECHANICS IN UNIVERSITY UNDERGRADUATES FROM AN EVOLUTIONARY PERSPECTIVE

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This study examined the relationships among visuospatial ability, motivation to learn science, and learner conceptions of force across commonly measured demographics with university undergraduates with the aim of examining the support for an evolved sense of force and motion. Demographic variables of interest included age, ethnicity, and gender, which served to determine the ubiquity of the effects of the exogenous variables. Participants (n=91) self selected from introductory physics courses at a large public university in the Mid-Atlantic region of the United States. Utilizing a single-group exploratory design, all participants completed a series of anonymous online instruments to assess the variables of interest. Analysis consisted of an ANOVA for significance testing of demographic variables and a single-level structural equation model (SEM) to ascertain the causal influence of visuospatial ability and affect in the form of motivation on learner conceptions of force. Results of the SEM indicated that while motivation had a nonsignificant ($p>.05$) impact with this sample, visuospatial ability had a strong (.5 unit change in physics achievement per unit of VSA, $p<.05$) influence on Newtonian conceptions of mechanics. The results of this study inform physics educators as to the factors underlying conceptual change in Newtonian physics and generate hypotheses regarding the cognitive processes and corresponding neural substrates associated with successful Newtonian reasoning.

Chapter 1

Physics educators have long struggled in seeking effective means to change learner conceptions of force and other Newtonian mechanical concepts that physics educators deemed essential to building an understanding of introductory physics concepts (Champagne & Klopfer, 1982). Osborne (1985) describes the naïve conceptions of force in detail through interviews with learners, categorizing their conceptions of force as largely Aristotelian in nature and associated with the notion that force 'dies out' gradually to decelerate objects in motion. Naïve conceptions in general, as well as naïve conceptions of force in particular, are hypothesized to be rooted in children's' ad hoc means of explaining the world around them (Keil, 2012). Such folk scientific concepts can be carried forward into adulthood, or at least through adolescence, by individuals that have had no need to examine the mental paradigm through which they explain observed phenomena. Likewise, Keil (2012) noted that misconceptions are exemplars of the human tendency to rely on others to supply information and the predilection to accept that information until forced to reconsider it. In slight disagreement with Keil, Geary (2000), as well as Pinker (2002), suggested that the naïve models of force and motion were developed by early hominids (if not before) to track objects, and that these are now the direct result of an evolved neurocognitive subsystem rather than something (sub)consciously constructed by individuals of borrowed from the information of others.

The existence of evolved heuristics for reasoning about real world events, given the importance of such events to science instruction, may have a profound impact on education.

Regardless of their source, misconceptions of Newtonian mechanics and forces are both pervasive in the population as a whole and of concern to physics educators who must overcome these mental models in order to successfully educate their students (Ebison, 1993). It is thus crucial to the field of physics education that a more widely effective means of promoting conceptual change from learners' naïve models of force and mechanics to the scientifically accepted Newtonian models be developed. In order to develop an effective intervention it is essential that the source of the misconception be identified so that conceptual change techniques can be matched to the situation at hand.

Purpose of the study

This study of physics education examined the potential relationships among visuospatial ability, learners' motivation to learn science, and learner conceptions of force across all demographics in order to gain a more complete picture of the factors involved and their interactions with one another. As with most studies of human behavior and cognition, it is first important to determine the effects of context, specifically the oft-used variables of ethnicity, gender, and age, before moving on to a more universal model of the phenomenon.

Given that learner models of force are used to explain the motion of real-world objects, and constructed or at least often employed in a three-dimensional space, this study also examined the potential relationship between visuospatial ability and conceptions of force. This may prove particularly important in contexts, including those in classrooms, where three-dimensional movement is represented with two-dimensional diagrams or text.

Motivation has been established as a key factor in conceptual change, indicated by Taasoobshirazi and Sinatra (2011) through a structural equation model to be a strong influence on the occurrence of conceptual change in undergraduate physics students. As a result, the present study incorporates a measure of motivation to learn physics and seeks to establish the relationship between that motivation and student conceptions of force.

A detailed review of the history of conceptual change theory, misconceptions research, and how they specifically apply to research on learner conceptions of force in physics education will be employed to create a cogent view of the problem and establish the need for further study. Given the general lack of effective interventions in teaching force, the model created by the examination of relationships among the aforementioned variables will create the basis for the development of interventions that are better suited to address the problem of persistent learner misconceptions of force. From a theoretical perspective, the outcomes of this study will also serve as a test of the evolutionary psychology hypotheses of Dawkins and Wong (2004), Geary (2000), and Pinker (2002) that suggest difficulties in accepting Newtonian conceptions of force and motion lie in an evolved, subconscious reasoning system. The practical significance of this study lies in its potential to develop a base from which to create effective interventions in physics education. Dependent upon the outcome, the previously underexplored variable of visuospatial ability may prove important to the development of an effective intervention in teaching force.

Research Questions

1. What is the relationship between demographic factors and learner conceptions of force in university undergraduate physics learners?

2. What are the influences of motivation, visuospatial reasoning, and the interactions between these on learner conceptions of force in university undergraduate physics learners?

3. How do the influences of visuospatial reasoning, adjusted for demographics, support or refute the existence of an evolved ability to predict object motion?

Definition of Terms

Aristotelian Concepts in Physics- an understanding of force and motion that mirrors that of Aristotle and/or medieval impetus concepts; these typically include an understanding of force that views force as something that dissipates after being added to an object (Osborne, 1985).

Biologically Primary- concepts and competencies that humans have evolved heuristics for learning in order to make sense of the natural world (Geary, 2002).

Biologically Secondary- concepts and competencies that have been socially constructed by humans and require the use of fluid intelligence/working memory to successfully learn (Geary, 2002).

Conceptual Change- the development of learners' conceptions into more complete or scientific concepts and the overarching theories needed to make sense of those concepts (von Aufshaniter & Rogge, 2010).

Hominid Evolution- phylogenetic change over time of humans and species ancestral to humans, including the genera *Homo*, and *Australopithecus.* For this study ”the evolution of the human mind and brain resulted from the advantages that gradually emerged as a result of our ancestors’ ability to modify and control ecologies and to cope with rapidly changing social dynamics” (Geary, 2008).

Misconceptions- incorrect beliefs (Taasoobshirazi & Sinatra, 2011). For this study, used interchangeably with “naïve conceptions,” “intuitive conceptions,” and “alternative conceptions” without value judgments.

Motivation- a complex, multidimensional construct that includes intrinsic motivation, extrinsic motivation, task relevancy, self-determination, self-efficacy, and assessment anxiety (Taasoobshirazi & Sinatra, 2011). For the purposes of this study, motivation will be operationalized as a latent psychological construct that fosters and sustains learner action towards a specific goal.

Phylogenetic- stemming from evolutionary relationships between extant and extinct taxa (Campbell & Reece, 2005).

Self-efficacy- “An individual’s conceptions of his or her ability to perform given actions” (Schunk, 1991).

Visuospatial Ability- the ability to visualize and manipulate representations of objects in three dimensions. (Shepard & Metzler, 1971).

Chapter 2

The purpose of this study is to examine the potential relationships among visuospatial ability, learners’ motivation to learn science, and learner conceptions of force across commonly measured demographics in undergraduate physics education.

Conceptual change, operationally defined here as the development of learners' conceptions into more complete or scientific concepts and the overarching theories needed to make sense of those concepts, lies at the heart of classroom instruction (von Aufschnaiter & Rogge, 2010). Upon further examination, the essence of instruction in any subject is to supplant naively conceived theories and gaps in knowledge with the societally (or scientifically) accepted 'truth', allowing for the addition of detail as learning continues. Understanding of this process, although the specifics are contested, draws largely from two disparate sources, one each in philosophy and psychology. Posner, Strike, Hewson, and Gertzog (1982) related this process directly to Piaget's conceptions of assimilation and accommodation: the incorporation of new information into previously existing idea structures and the rational replacement of previous ideas with new ones when presented with counter-evidence for the old, respectively (Piaget, 1975). The other classically employed metaphor for conceptual change is drawn from the work of T.S. Kuhn (1996), using the overarching idea of large-scale paradigm shift in science disciplines to describe how conceptual change occurs within an individual (Posner et al., 1982; Vosniadou & Mason, 2012).

Literature Review Methodology

This review of literature will synthesize the origins presented above with a history of conceptual change theory in the literature and misconceptions research with a focus on science education. Additionally, it includes a specific example of misconceptions research, the attempts at bringing about conceptual change, and a suggested course of action for continuing that particular quest. Literature searches were conducted using the ProQuest and APAPsychNet databases, searching the keywords "conceptual change," "conceptual change theory," and "misconceptions.” The searches for "misconceptions" were also filtered for "science education" in APAPsychNet after drawing recent (<10 year old) examples from other disciplines. With the exception of those works described as seminal (in Vosniadou & Mason, 2012, or another source noted in the text) and the specific example presented, articles published prior to 1995 were discarded. In addition, the search was primarily focused on peer-reviewed journal articles with the inclusion of some book chapters and the complete exclusion of dissertations and theses.

Origins of Conceptual Change

As previously noted, Posner et al. (1982) marked the first academic foray into conceptual change in the education literature, with the majority of early work in the subject being conducted in science education (Vosniadou & Mason, 2012). Initial definitions of conceptual change, as well as several later revisions, drew heavily upon the work of Kuhn (1996) prior to the release of the third edition of that book. As a result, the relationship of Kuhn's notion of paradigm shift and models of conceptual change bears significant examination.

While much of Kuhn's work in *The Nature of Scientific Revolutions* (1996) has been pared back in response to critics, the underlying themes may still represent a description of conceptual change on an individual level that deserves close examination (Kuhn, 2000; Vosniadou & Mason, 2012). Vosniadou and Mason (2012) conduct a cursory examination of this analogy, which will be extended here.

Kuhn's (1996) description of the paradigm of normal science, a framework of rules and assumptions, often tacit, within which investigation of new ideas are carried out and into which new discoveries are assimilated, provided that they are commensurate with the paradigm. This is a useful analog for learning as envisioned by the conceptual change model: learners operate under naive theories about the world, which both guides their investigations and serves to connect each discovery with the broader array of facts and concepts they have already learned. The utility of these naive theories lasts only as long as the conditions Kuhn (1996) elucidated for the priority of a paradigm exist: it provides a parsimonious, if ill-considered, structure that determines which types of questions and problems are legitimate; it persist so long as the previous queries and their answers are accepted without question, and much as Kuhn describes the scientific community, the thinking and naive theories of learners may be heavily compartmentalized so that a profound change in one area has no effect in another (Margolis 1993).

The extension of this metaphor is also effective in describing what may occur when an anomaly is encountered in a new discovery. The discovery is first second-guessed and examined (this is an alternate hypothesis that stems from an over-arching theory, although naive theories within a learners mind may lack the explanatory power and internal consistency that mark scientific theories) before any consideration is given to the notion that the theory itself is insufficient. A preponderance of evidence that refutes the original theory leads, in Kuhn's view, to the emergence of a new theory with strident resistance on the part of some that may cling to the old theory. This mirrors both Piaget's (1975) accommodation and Posner et al.'s (1982) conception of how conceptual change occurs within an individual. A marked change in thinking must occur, which reorganizes related concepts into the new paradigm; as with scientists in Kuhn's description, there may be some concepts or ideas that are not immediately taken under the new paradigm, a difficulty in the learning of new ideas that can be compounded by the tendency to compartmentalize knowledge.

Difficulties with Kuhn

The post-positivist backlash that prompted the partial retraction of Kuhn's paradigm shift model in 2000 is mirrored in educational psychology by the Piagetian concept of assimilation, and several authors' insistence that conceptual change takes place gradually, as described in Vosniadou and Mason (2012). In brief, Piaget (1975) describes an alternative to a complete change in the theory of understanding that prompts investigation when presented with an anomaly. This alternative, termed “assimilation,” (reference page number) consists of the expansion of the theory to incorporate the anomaly and others like it rather than the wholesale replacement of the theory-paradigm. Notably, this model is the most substantial criticism of the model of paradigm shift, and reinforces the disposition to view science as tentative (McComas, 1996; Toulman, 1972). Vosniadou and Mason (2012) highlight a shift in the educational psychology community's view of conceptual change to align more tightly with the gradual view, paralleling the inclusion of “warm factors” (p. 228) in models of cognition (cognition as influenced by affective factors, motivation, and the ilk) in research agendas. Consideration of the precise wording of Kuhn reveals that he championed abrupt paradigm shifts if, and only if, two theories were incommensurate (Kuhn, 1996). Although incommensurability is ascribed to nearly any pair of theories by Kuhn, a sweeping gesture that is denied by academics in both philosophy and psychology, a simple thought experiment would indicate that while it is unlikely to be the most common form of conceptual change, an abrupt accommodation cannot be discarded as a potential means of conceptual change (Carey, 1985; Kuhn, 1996; Toulman, 1972). Socially controversial concepts related to the origin and evolution of life, or anthropogenic climate change, illustrate this potential: competing ideas on the origin and evolution of life are logically, and often emotionally, incompatible. Individuals confronted with the scientific evidence in these cases may completely deny it, completely change their viewpoint, or attempt to reconcile the two viewpoints into a logically inconsistent yet emotionally satisfying belief.

Conceptual Change in Educational Research

Chang, Chang, and Tseng (2010) conducted a content analysis of trends in science education articles from 1990-2007 in the four most impactful journals at the time of the study, and discovered that "conceptual change and concept mapping" was the most frequently studied topic with a decline in the number of publications on that topic over the ten years prior to the study. This reflects an important trend in science education research wherein a lively debate ensued regarding the nature of knowledge and what constitutes an appropriate model of conceptual change (Vosniadou, 2007a). While setting aside the philosophical debate regarding the nature of knowledge as somewhat tangential to this discussion, it is certainly important for us to delve, at least summarily, into the debate within science education and educational psychology as a means to ascertain the current model of conceptual change that serves as an underpinning for misconception research. As an interesting aside, however, it is important to note that the philosophical debate in the cognitive science literature still rages with well-known theorist such as J. Fodor claiming that the issue with conceptual change theory is that we as academics do not have an accurate understanding of the representational structures of knowledge in the mind/brain (Laurence & Margolis, 1999). Given the fractured state of the field with regards to the topic of concepts and knowledge representation, we shall instead concentrate on the debate within education itself.

Cognitive Beginnings

Posner (1982) outlined what might be considered the forerunner of the initial models of conceptual change as the theory detailed in that work discussed, at length, the cognitive foundations of cognitive change theory and the practical applications of that model to curriculum development, and hence to classroom teaching. In essence, that model of conceptual change mirrored Kuhn's model of scientific revolutions, sans revisions: conceptual change as a rapid, complete process undertaken in response to the presentation of information that did not fit with prior conceptions, leading to a complete reorganizing of the theories within which concepts and their relationship to one another are understood. Related research suggested that instruction design to foster conceptual change was successful only because it created alterations in overall conceptions of the subject matter, supporting the view of conceptual change as a rapid and complete process (Hewson & Hewson, 1984). Smith and Lott (1983) attributed failures in teaching for conceptual change to much the same issue; conceptual change, in their view, cannot occur until the entire framework or paradigm with which the learner makes sense of the material is altered.

While research persisted under this paradigm for a decade (and much continues to maintain this theoretical framework as a base for its studies currently), anomalous findings began to lead to some questioning of the notion that conceptual change was sudden and complete (Treagust & Duit, 2008). One of the earliest challenges to this ontological perception of conceptual change was presented by Vosniadou and Brewer (1992). In an empirical study of children's (grades three to five) conceptual knowledge about the earth, analysis of qualitative data indicated that the responses elicited from learners about the shape of the Earth were largely not consistent with either the scientific view or their intuitive view (Vosniadou & Brewer, 1992).

Tellingly, children responded with some facts that parroted the information with which they had been presented in class ("the world is round"), yet still held onto beliefs that one could "fall off of the edge." These inconsistencies, while initially explained by stating that the children held a different mental model of the earth from that which was taught, also suggested that the two models existed in parallel without the concepts within being transferred to the new model. As a result, a shift in the understanding of concepts as a whole occurred, adjusting from the theory-theory (conceptions are welded together as full beliefs, complete with all subordinate information) to 'knowledge in pieces', wherein it was recognized that information exists as a series of elements that are unconnected by theoretical (in this case conceptual) ties (diSessa, 1993). Further challenges to Posner's (1983) views would arise from more pragmatic objections.

Situative Conceptual Change

With the increase in situated cognition and sociocultural theories of learning over a strict information processing model in the late 1980's and early 1990's, it is unsurprising that these criticisms were applied to conceptual change theory as well (Schunk, 2012). Pintrich, Marx, and Boyle (1993) elaborated upon the weaknesses of a theory of conceptual change that ignored learners' motivations and beliefs, as well as potential interactions within the classroom environment with other individuals that could also affect the process of conceptual change. Despite hyperbolic labeling of the opposing theory as “cold conceptual change,” (p. 228) a rational argument was made that the inclusion of motivational constructs including goals, values, self-efficacy, and control beliefs is essential to understanding how instructors can best induce conceptual change in learners (Vosniadou & Mason, 2012;Pintrich, Marx, & Boyle, 1993). Specifically, it is theorized that contextual factors in the classroom impact motivational factors, which in turn affect the cognitive factors necessary to create the appropriate conditions for conceptual change. For example, the learning tasks themselves must be authentic and challenging enough to foment the generation of mastery goals on the part of the learner, which in turn foster selective attention to the task and the dissatisfaction with prior knowledge that is necessary for a change in concepts to occur (Pintrich, Marx, & Boyle, 1993). The model contained in this example assumed that there are specific cognitive factors inherent in successful conceptual change (dissatisfaction, intelligibility, plausibility, and fruitfulness), as well as the likelihood that motivational factors can and do influence those cognitive factors. Pintrich, Marx, and Boyle (1993) posit that neither assumption is a great logical leap given the historical body of literature from whence this version of conceptual change theory was drawn. Importantly, a theory of conceptual change that includes affective measures adds ecological validity to the understanding of how conceptual change can be brought about without making a marked progress on the mental processes themselves. This, while not suggested in the literature supporting a situative version of conceptual change, implies that the two theories are complimentary, rather than competing.

Theory Synthesis and New Directions

More recent literature has highlighted the need to unite the seemingly competing theories of conceptual change into a pragmatic version that is more useful to instruction as a whole (Merenluoto & Lehtinen, 2004; Vosniadou, 2007b). Treagust and Duit (2008) lamented the divide in the field, stating in their commentary that educational researchers would be better served by ceasing to build and knock down strawmen of the other perspective's position and beginning to recognize the contributions of each perspective to conceptual change theory. Likewise, it was noted that classroom instruction does not reflect any understanding of conceptual change theory on the part of practitioners, and that the road to implementation of pedagogical practices that align with conceptual change theory will be long and arduous (Treagust & Duit, 2008). Researchers that once sat firmly on one side of the fence have also espoused this position, stating that both approaches are necessary for a complete understanding of the process of conceptual change (diSessa, 2007). Interestingly, while much has been said about the cultural-cognitive divide, little attention has been paid to the need for both perspectives on the pace of change. A theoretical paper reported this disconnect and suggested that a change in the metaphorical representations of concepts is necessary to stimulate the change between naive and scientific theories, thus implying that the piecemeal knowledge must be altered before profound ontological change can occur (Amin, 2009). Lee, Jonassen, and Teo (2011) supported this viewpoint with an exhaustive review of the literature, concluding that a complete theory of conceptual change must include not only the sociocultural and cognitive perspectives on conceptual change theory, but an understanding of knowledge building. In this light, knowledge building is thought to be a mediator for the conceptual change process, a view that is commensurate with both 'knowledge in pieces' and paradigm shifts, given that in either case sufficient evidence for the new framework must be obtained before any change can occur (Lee, Jonassen, and

Teo, 2011). This paper marked the combination of the call for unification of the field on sociocultural and cognitive perspectives, and the differing perspectives on the pace and completeness of conceptual change, with a call for a deeper understanding of the nature of knowledge and knowledge acquisition.

Further studies served to provide confirmatory evidence for each side of the debate. Taasoobshirazi and Sinatra (2011) generated a structural equation model of conceptual change as a means to test Dole and Sinatra's (1998, in Tassoobshirazi & Sinatra, 2011) Cognitive Reconstruction of Knowledge Model (CRKM) theory of conceptual change. Results yielded the importance of the cognitive aspects of conceptual change, along with motivation as a key factor in influencing whether or not any conceptual change occurred. By looking specifically at undergraduate physics students' conceptions of force as related to their motivation and course grade, the simplified model presented in Taasoobshirazi and Sinatra (2011) suggested both the validity of both approaches to understanding conceptual change and the need for more complex study, including more quantitative variables and incorporating interviews, to fully understand conceptual change. Similarly, Larsson and Hallden (2009) conducted an empirical study via interviews to examine the process of conceptual change in young school-aged children (ages four to six years) over the course of three years with reference to earth science topics. Findings from this study suggested that learners reconstructed knowledge frameworks to accommodate the amount of information they had taken in, which the author reported as evidence that conceptual change is an intentional process. Regardless of the accuracy of the finding regarding intentionality in conceptual change, the results reported by Larsson and Hallden (2011) indicated that both knowledge in pieces (in the accumulation of various subconcepts) and theory-theory (in the eventual Piagetian accommodation that followed) are pertinent to a complete understanding of the conceptual change process. A test of conceptual change theory in undergraduate psychology classes (n=227) that was focused on the view of psychology as a science further corroborated this finding (Amsel, Johnston, Alvarado, Kettering, Rankin, & Ward, 2009). Amsel et al. (2009) noted that learning in psychology may have less to do with confronting and revising misconceptions than it does with categorizing beliefs and making the appropriate ontological shifts to reflect the material that is taught, especially with regards to understanding the scientific nature of psychology. The two studies described immediately prior illustrate the means by which conceptual change theory can be, and is, applied to classroom instruction and the alternate hypotheses it generates can be, and are, tested. This echoes much earlier theoretical contributions from Tyson, Venville, Harrison, and Treagust (1997), who methodically examined the research literature and collectively stated that the field would benefit from the incorporation of all perspectives on conceptual change: epistemic and ontological, cognitive and situative.

In addition to confirmatory evidence and calls for the unification of opposing camps within the field of conceptual change, recent literature also spotlighted the growth of the field through the introduction of new models, which incorporate earlier models as well as introducing novel suggested methods of conceptual change. For example, in a theoretical paper, Ohlsson (2009) suggested that one mechanism for conceptual change might be “resubsumption” (p.23), or the inclusion of concepts from discarded frameworks under frameworks that were previously (or are currently) in use for understanding other topics. Reactions to Ohlsson were mixed: Shtulman (2009) indicated that the major weakness of Ohlsson's theory is that it failed to account for difficulties in initiating conceptual change, focusing rather upon the difficulties in completing it; other researchers embraced the idea of multiple modes of conceptual change drawn from Ohlsson's argument for a novel mode (Chinn & Samarapungavan, 2009). This example illustrated the importance of conceptual change theory to pedagogy, as well as the revisions needed to make it truly useful in a classroom context.

Conceptual Change in the Classroom: Misconceptions Research

Misconceptions have offered both the most practical venue for application of and most fruitful means of testing conceptual change theory in the classroom (Taasoobshirazi & Sinatra, 2011). Through the application of conceptual change theory, numerous researchers have attempted to address misconceptions and develop interventions that can be converted to everyday pedagogical practices.

Sources of Misconceptions

The various terms for misconceptions, while serving to confuse much of the literature on the subject, also shed some light on the potential sources of incorrect beliefs, particularly with regards to Science, Technology, Engineering, and Mathematics (STEM) education.

Keil (2012) portrayed the predominant view on the origins of misconceptions: misconceptions and folk science are children's' ad hoc means of explaining the world, which sometimes carry over into adulthood. However, while this view is popular, Keil

(2012) does not accept that it fully accounts for the perniciousness of folk science and misconceptions of concepts that learners have yet to experience firsthand, or explains what misconceptions persist into or arise during adulthood. Rather, it is suggested that misconceptions are a classic example of how humans rely upon other minds to supply information and explanation until dissonance occurs as a result of contrary evidence (Keil, 2012). Cited as evidence for this view is that fact that folk science (misconceptions in the domain of science, for our purposes) does not only arise as a means to explain causal mechanisms, as circularity of argument is prominent and evaluation of source is often absent. In addition, Keil (2012) stated that children are often completely ignorant of the mechanistic detail needed to create a viable explanation, and this is readily apparent in adults as well, especially when outside of their areas of professional or recreational expertise.

Empirical work uncovered the prevalence of misconceptions and incomplete understandings of concepts in pre-service and in-service science teachers (ostensibly adults), particularly for abstract concepts or those that occur on temporal and physical scales out of sync with everyday experience, such as earth and space science (Bulunz & Jarrett, 2010). Ahopelto, Mikkila-Erdmann, Anto, and Penttinen (2011) further demonstrated this effect with pre-service teachers studying photosynthesis and other biochemical processes, reinforcing both the finding that misconceptions and incomplete understanding persist into adulthood, and that these are prevalent in topics with which learners have little physical experience.

Despite the prevalence of misconceptions research in the literature, and the importance placed on conceptual change as the end goal of instruction, there are studies that suggested misconceptions are of less importance in learning than they are afforded. An empirical, qualitative study of students' conceptual development in physics indicated that students did not hold misconceptions on the subject and lacked any explanatory knowledge that could be applied to the information with which they were presented (von Aufschnaiter & Rogge, 2011). These findings were used to make a theoretical argument that missing conceptions, rather than misconceptions, are of the most importance in classroom instruction of science topics. In another qualitative study, Hamza and Wickman (2008) audio-recorded eight pairs of students during learning interactions on electrochemistry. Misconceptions appear both in interview transcripts and during learning interactions, but the misconceptions during lessons were either summarily dismissed by the other learner or served as a springboard for more scientific reasoning on the subject, leading to the generalization that misconceptions do not present a barrier to understanding by interfering with learning (Hamza & Wickman, 2011). Given their small sample sizes and limited generalizability, both of these studies chose science topics that do not lend themselves well to misconceptions research as there is neither a need for a mechanistic explanation (the prevailing view of misconceptions) until the topic is presented nor a body of folk knowledge to be passed to learners by others (Keil's alternative view) (Keil, 2012). Consequently, it is unsurprising that conceptions of the subject matter in both studies were either missing or not a significant hindrance to learning. Furthermore, as the Hamza and Wickman (2010) study did not conduct any sort of test for conceptual understanding, the assertion that the misconceptions present in that study had no effect is highly suspicious. One recent theoretical piece went so far as to argue that science educators are ethically wrong to attempt to supplant intuitive conceptions of science content, particularly those that might be culturally rooted, and that educators should instead generate discourse that allows both views to coexist (Zhou, 2012). This runs counter to the purpose of science education: to educate learners about cross-cutting scientific concepts and develop learners' understanding of these overarching themes and a more complete understanding of science as a discipline (Achieve Inc, 2013)

Interventions in Misconception Research

Regardless of their source, education researchers are largely in agreement that misconceptions are phenomena to be documented and addressed in the classroom (Keil, 2012). Thus, misconception research has generated numerous studies in the attempt to find a means to evoke conceptual change in the face of learners' prior conceptions of subject matter. Venville (2004), in a case study of students five to six years of age, reinforced the importance of conceptual change theory to classroom teaching by noting that discursive pedagogy and social construction of knowledge was not sufficient to induce deeper understandings of scientific views of living things, but rather the students tended to assimilate new ideas into coherent, naive frameworks instead of revising those frameworks. This finding reinforced the need to seek adequate pedagogical means to address misconceptions, rather than simply ignoring them and applying what are considered best practices for teaching concepts not prone to that type of interference.

Much of science instruction, despite calls for it to be otherwise, remains rooted in the reading of expository text on the part of the learner and other non-inquiry, teacher centered methods (Bybee, 2011). While comprehensive studies of science teaching methods in the United States are rare, research in other Western nations echo this trend (Yildirim, 2010). Some learners with misconceptions have responded to coherent expository text, reaching learning goals despite misconceptions or incomplete understandings of the subject matter (Ahopelto, Mikkila-Erdmann, Anto, & Penttinen, 2011). In their study of future elementary teachers, Ahopelto and colleagues noted a strong correlation between learning goals and learning outcomes and also reported that misconceptions of photosynthesis were overcome using expository text. This is in conflict with the majority of findings and popular researcher viewpoints on the use of expository text in science instruction (Broughton & Sinatra, 2010). Given the nature of the subject matter and thus the misconceptions themselves, it is likely that the researchers' report of misconceptions would be more aptly identified as incomplete understandings; reported participant data demonstrated partial mechanistic explanation of photosynthesis.

Rather than rely upon expository text, researchers in science education espoused the use of refutational text, writing that explicitly identifies common misconceptions as such, and presents contrary evidence coupled with the prevailing scientific framework for the concept in question (Broughton & Sinatra, 2010). Broughton and Sinatra (2010) reported that the use of refutational texts has been shown to scaffold conceptual change, and fostered the ontological shift that is necessary for such change to occur. Palmer

(2003) laid some of the groundwork for these findings with a mixed-methods study of Canadian grade 9 students (n=87) enrolled in a course on biology. Forty-four percent of these participants held misconceptions on ecological roles, and a controlled comparison between the use of simple expository text and refutational text yielded results on a post-test that were little different from one another when controlling for motivation and other affective factors (Palmer, 2003).

A more diverse approach to instruction aimed at combating misconceptions can be found with researchers who have supported a multi-representational approach to instruction (Adadan, Trundle, & Irving, 2010). Louwerse and Jeuniaux (2010) described conceptual processing as both linguistic and embodied in nature, requiring language to effectively explain, yet also necessitating visual or manipulative experience to fully comprehend. Furthermore, students' propensity for intentional conceptual learning through mediated symbolic structures is put forth as central to fostering conceptual change (Louwerse & Jeuniaux, 2010). A less theoretical discussion of this matter can be found in Adadan, Trundle, and Irving (2010); this empirical study presented secondary students (n=19), ages sixteen and seventeen, with multirepresentational instruction on the nature of matter. Multirepresentational, in this instance, is operationalized as contained text/verbal information, visual information in the form of diagrams and models, and manipulatives (Adadan, Trundle, & Irving, 2010). Adadan and colleagues analysis of qualitative data after three months suggested that various conceptual pathways representing several degrees of conceptual progress (from drastic changes to a stable model) were affected by the implementation of multirepresentational instruction. A further case for the incorporation of personal meaning-making, and the prevalence of embodied cognition in learners, was presented by Tytler and Prain (2010). This qualitative study, combining a variety of data sources from interviews to work samples, noted that student-held concepts were 'fuzzy' and heavily dependent upon context. From these findings, an argument can be made that conceptual instruction would benefit, in part, from concrete examples.

Concrete examples employed to foster conceptual change have taken several forms. Van Dooren, De Bock, Hessels, Janssens, and Verschaffel (2004) conducted a study in which 8th grade Belgian mathematics learners (n=35) in a unit on geometry were presented with a conceptual change model of instruction (including representational graphs and physical manipulatives) to introduce non-proportional concepts (specifically volume). Participants in the experimental group fared better on both an immediate post-test and a knowledge retention test given three months after the intervention (VanDooren et al., 2004). In particular, the experimental group overcame the tendency to use linear methods to solve non-linear questions, to the point of a slight tendency to do the reverse. On the other hand, the control group retained the misconception that linear methods could be applied to all types of test items. The results of this study suggested that a multirepresentational approach, specifically one that incorporates an embodied experience, is sufficient to promote complete conceptual change in some cases, as evidenced by the retention of the material and the transfer of the new paradigm to a more familiar context.

Apart from the reasonably obvious use of physical manipulatives and laboratory exercises, there has been an interest in promoting conceptual change through the use of models and concept mapping. Uzuntiryaki and Geban (2005) combined conceptual change texts (presumably refutational texts, although not defined by the authors) with concept mapping in a study of understanding of solutions in 64 eighth grade students. A control group received what is explained as 'traditional instruction' provided through discussion and lecture methods; results showed that the experimental group acquired scientific conceptions of solutions more readily than did the control (Uzuntiryaki & Geban, 2005). It should be noted that a control group consisting of 'traditional instruction', even as defined by the authors, introduces a potential confound to the study due to ambiguity of methods. Liu (2004) presented a classic example of the use of computerized concept mapping to foment conceptual change, implemented in a rural Canadian 12th grade chemistry class (n=15). Giving careful attention to prior research and theory in conceptual change, Liu (2004) incorporated discourse and cooperative groups to foster motivation, and ensured maximum benefit to participants through training students in the construction of concept maps before asking them to take part in the intervention. The intervention itself consisted of the creation of a concept map prior to the unit of instruction, in pairs, and the revision of the maps every two weeks as well as after the unit (Liu, 2004). Motivational data was collected through interviews of students and the teacher, and the concept maps themselves aggregated and subjected to content analysis; interpretation of results indicated that students maintained high level of motivation toward creating the concept maps (most noted in the interviews that it was beneficial to their overall understanding and learning to create and continue to revise the maps), and that all students underwent a measure of ontological revision (complete or near complete in most cases) between the initial and second concept maps (Liu, 2004).

Computer-based instructional technology has been effectively employed in other instances to promote conceptual change, and seems to hold the most promise for concepts that are not readily concretized in the classroom. Li, Law, and Lui (2006) noted that inactive simulation is insufficient to promote conceptual change as it lacks the capability for students to interact with their own frameworks, although it does afford exploration of scientific models. In an effort to overcome this, an empirical study that employed dynamic models (World Maker 2000) was undertaken; the use of cognitive perturbation similar to discrepant events (presentation with counter-intuitive examples, or creating dissonance in Piagetian terms) was a key feature of model implementation (Li, Law, & Lui, 2006). For the purposes of this study, the authors defined simulations as a type of dynamic model with set rules, although not all models are simulations. Twenty students, all approximately age 12, took part in a two-week intervention, broken into eight sessions of thirty-five minutes each (Li, Law, & Lui, 2006). Researchers assessed the models themselves at different time points to determine the level of conceptual change; although each group of students took a different conceptual path, all reached a viable scientific explanation of the topic (evaporation) by the end of the study period (Li, Law, & Lui, 2006).

Lee, Jonassen, and Teo (2011) also incorporated the construction of interactive electronic models into a conceptual change based intervention, which yielded similarly positive results when interview data was analyzed. Additionally, researchers noted that key requirements in fostering knowledge and problem solving skills using model building include sufficient time to construct and revise the models according to observations along with time for interaction with both the model and other learners to explore the validity of each iteration of the model (Lee, Jonassen, & Teo, 2011).

Finally, some researchers substituted virtual worlds for the real world in order to present learners with embodied experiences of concepts they might not otherwise witness. Hobson, Trundle, & Sackles (2010) involved students (n=21) aged 7 to 9 in an interactive, inquiry activity that combined learner investigations with planetarium software to teach lunar phase concepts. Data were collected through interviews, student work products, a card sorting task, and classroom observations; analysis using qualitative means and non-parametric statistics suggested that learners made significant progress in their conceptions of the causes of lunar phase. Other researchers employed serious educational games (SEGs) to present mathematics concepts to elementary students (n=401) in both laboratory and classroom environments (Ketamo & Kiili, 2010). The authors reported that conceptual change was fostered, and models of conceptual change confirmed, when games included elements that triggered reflection, students were highly motivated (a variable highly correlated with game play), metacognitive strategies were introduced by the instructor, and sufficient playing time was allows). Specifically, Ketamo and Kiili (2010) employed AnimalClass, a game wherein learners teach a virtual pet that in turn reasons based on how it was taught, concepts related to rational number reasoning (fractions, decimal numbers, and percentages), coupled with comparison groups and a pre/post measure in a laboratory group and virtual observation in a classroom based experimental group. Pre- and post-test data from the lab group was analyzed alongside game play data from the classroom group that indicated the level of conceptual understanding (correct responses, time to response, etc). K-means cluster analysis demonstrated that conceptual change was greatest amongst those learners that invested the most time in playing the game, whether in teaching their virtual pet or competing against other players (Ketamo & Kiili, 2010).

In summary, while several models for intervention to produce conceptual change exist, the most effective are those that confront misconceptions directly, afford ample opportunity for exploration of both incorrect and scientific models of concepts, are highly motivating, and present information in multiple forms. Of these, interventions that incorporate model construction of some form and instructional technology appear to be particularly effective, perhaps due to the motivating effects of the opportunity to use technology in the classroom on learners.

Misconceptions in Practice: The Case of Force Concepts in Physics Instruction

Early in science education research, a causal model of physics learning determined that an understanding of Newtonian mechanics was fundamental to conceptual understandings in the remainder of the field (Champagne & Klopfer, 1982). Teaching and learning of these essential concepts is complicated by student preconceptions that are both inaccurate and persistent: students appear to misunderstand the effects of passive forces, believe that continual force is needed to maintain motion (in contrast to the first law), and that velocity is independent of the frame of reference

(White, 1983). White (1983) performed a detailed analysis of student conceptions of force, specifically their understandings of how force caused and object to move, and determined that students held beliefs that better matched the medieval notion of impetus than modern understandings. In other words, participants in White's study believed that objects require the constant application of force to move, and regard the slowing and cessation of such movement to be a result of the dissipation of that force rather than the action of passive forces like friction. Osborne (1985) characterized the thinking of students regarding force through a series of interview questions, with telling results. Quotes from students such as “It’s just putting force on by itself, from the force you gave it before” (p. 44) and “the force from the golf stick which slowly dies out” (p. 44) accurately depicted the difficulties students have coming to grips with a Newtonian conception of force, as opposed to their predilections for Aristotelian thinking.

This coincided with the work of Minstrell (1982), who reported from classroom observations that students held misconceptions regarding the nature of objects at rest. Specifically, students observed in that study held beliefs that objects remained at rest due to 'air pressure', balanced winds on the x axis, or gravity alone (Minstrell, 1982). Less formal interviews of elementary school-aged children by Watts and Zylbersztajn (1981) demonstrated conceptions of motion through continuously applied force that match those uncovered in White's (1983) study. Further investigation of this phenomenon, delving into conceptions of objects both at rest and in motion, indicated the tendency of physics learners to discount passive forces: the normal force of a table acting on an object resting upon it, or the tension in a string counteracting gravity and forces applied to swing the object (McDermott, 1984). Ebison (1993), in a lengthy theoretical discussion of the scientific shift from Aristotelian conceptions of physics to a Newtonian view, offered both an apt description of the misconceptions of learners as well as a plausible explanation for their existence, in line with preceding and subsequent characterizations of misconceptions as a whole. In the view of that author, learners' intuitive conceptions of mechanics and forces are Aristotelian in nature, a conception that arose because it aligned well with common sense explanations of object motion in everyday experience (Ebison, 1993). Kruger (1990) conducted a survey of primary school teachers in the United Kingdom, many of whom had completed formal physics instruction in secondary school or university, and noted that their conceptions of mechanics concepts were no more sophisticated than those of the students they were assigned to teach. Rowlands, Graham, Berry, and McWilliam (2007) confirmed these findings, and further noted that their participants viewed velocity as an absolute quantity, instead of a vector dependent upon the frame of reference of the observer.

In response to the ubiquity of Aristotelian reasoning in physics instruction, Hestenes, Wells, and Swackhammer (1992) developed a diagnostic instrument, the *Force Concept Inventory*, to assay the level of scientific conception of Newtonian mechanics in physics students. Designed as a compliment to this instrument, for learners with some instruction in physics, was the *Mechanics Baseline Test* (MBT). The MBT incorporated more advanced conceptions of Newtonian mechanics in order to develop a more accurate representation of the conceptions of students that had completed at least a rudimentary level of physics instruction (Hestenes & Wells, 1992). In the words of the authors:

> it has been established that (1) commonsense beliefs about motion and force are incompatible with Newtonian concepts in most respects, (2) conventional physics instruction produces little change in these beliefs, and (3) this result is independent of the instructor and mode of instruction. (pg. 141)

a strong case for the need for both the diagnostic instrument and a valid means to address learner misconceptions that affect the remainder of a modern physics curriculum (Hestenes, Wells, & Swackhammer, 1992).

Attempts at Intervention and Distribution of Misconceptions

Since the literature on learner misconceptions on force and motion and the implementation of diagnostic measures intended to reveal those misconceptions in learners, there have been a number of attempts to formulate interventions to effectively address those misconceptions through instruction and document the extent of alternative beliefs regarding mechanics in populations varied in their demographics.

Mildenhall and Williams (2001) interviewed a sample of British students in years 8, 11 (GCSE), 12, and 13 (the final two samples were students in Advanced Level, or A-level courses in 'Mathematics and Mechanics' or Physics) in order to uncover their level of understanding of force and its resulting effects on the motion of objects. Combined with the interview protocol was a questionnaire completed by each of the forty participants in the study. Across all four groups, the learners interviewed displayed misconceptions related to the magnitude of the force required to begin motion, consistent with an Aristotelian model of mechanics (Mildenhall & Williams, 2001). The ten percent of respondents that employed a Newtonian model on any questions consisted of those who had received the most instruction in physics (completed an A-level in Newton's Laws of Motion or currently enrolled in A-Level Physics) or demonstrated the greatest mathematical ability on GCSE examinations, although these differences disappeared in the interview portion of the study (Mildenhall & Williams, 2001). This is noteworthy in large part due to the similarities in reasoning between students who had no physics instruction and those in their A-level courses who had passed national exams that included the subject matter (and in many cases passed well), and the insignificance of age as a variable. Likewise, a Taiwanese study of children across the span of K-12 education employed concept mapping and interviews to determine the level of understanding of general physics concepts; while learners' conceptions did improve with age in many cases, those regarding electrical circuits and force/motion relationships did not (Chang et al., 2007).

In a large (n=396) quasi-experimental study of American secondary students, Eryilmaz (2002) compared the changes induced in classes that were given additional conceptual change discussion assignments to learners in physics classes that received identical instruction, but for those assignments. Subjects ranged in age from fifteen to nineteen years, with a greater proportion of the students being male (59%) (Eryilmaz, 2002). Analysis of the collected data indicated that male students and those with prior knowledge in physics were more likely to perform well on the pre-test, and that conceptual change discussions had a statistically significant but small effect on inducing conceptual change for force and mechanics topics; a lack of interaction effects between variables was also noted, and further analysis in the form of a step-down F-test (intended to control for covariance of the dependent variables) yielded an insignificant result for the conceptual change discussion intervention as well as gender. Improved performance from students with greater knowledge of physics is unsurprising, while the gender differences (if corroborated) can be attributed to either a difference in visuo-spatial ability or stereotype threat gender effects that have previously been documented in mathematics related fields (Wraga, Helt, Jacobs, & Sullivan, 2007).

Apostolides and Valanides (2008) assessed tenth (n=40), eleventh (n=33), and twelfth (n=40) grade Cypriot students in after their participation in constructivist designed courses on physics through open-ended questions centered around three problems that required an understanding of force and motion. The resultant responses indicated that learners who what been introduced to one of the question types (and responded with conceptions consistent with the scientific view) were unable to transfer that understanding to the other two types (Apostolides & Valanides, 2008). The results of this study suggested that constructivist teaching methods alone are not sufficient to induce wholesale conceptual change in learners of physics, and that students who are able to respond correctly to test items in a familiar context may be unable to transfer that framework to other contexts. Bayraktar (2009), employed the Force Concept Inventory (FCI) to examine the beliefs of Turkish pre-service teachers regarding forces and motion, and compared the results to those taken from similar programs; the results of this study suggested that preconceptions are common to all three cultures, with some variation in understandings of Newton's Third Law. Further analysis also indicated that demographic variables, specifically gender and level of education (in years), had no significant effect on which participants held those ideas (Bayraktar, 2009). Aggregation of results previously discussed with those from additional studies around the world would seem to suggest that this phenomenon is not unique to American, or even Western, learners (Planinic, Boone, Krsnik, & Beilfuss, 2006; Suzuki, 2005).

Roth (2001) studied a teaching paradigm design that used situated cognition to teach the concepts of force and gravity, noting that students could be coached to provide the correct descriptions but still appeared to hold the misconceptions when not primed to give the correct response. As many students are less than comfortable in school settings, Phillips and Barrows (2006) surveyed participants on their out of school science experiences and compared those results to gain scores on the FCI; students that indicated greater amounts of out of school experience with physical science had both greater gains and higher initial scores on the FCI. Additionally, a study of learners in Japan indicated that concept mapping techniques involving metaphor and co-construction of knowledge through cooperative learning had little effect in changing student conceptions of force (Suzuki, 2005).

A more sophisticated approach incorporated situated cognition and conceptual change approaches through problem-based learning (PBL), the embedding of learning within “ill-structured” (p.19) and “real-world” (p.13) problems (De Lisle, 1997).This yielded modest positive gains in FCI scores over traditional instruction with a low effect size Sahin, 2010). Conceptual understanding, in that study, compounded with and confounded by differences in epistemological beliefs regarding physics; the positive correlation of physics epistemology and score on the FCI indicates that some ability to override the misconception does exist. It should be cautioned that the effect noted in the Sahin (2010) study was found between groups that were significantly different during the pre-test, with the PBL group scoring markedly higher on the FCI and epistemological measure before the intervention, as well as on measurements of general reasoning ability. The results of the Sahin (2010) study, coupled with the Phillips and Barrows (2006) study would seem to indicate that learners who have a more advanced conception of mechanics are better able to overcome the misconceptions to which all learners seem to be susceptible.

Along with the examination of the potential effects of age, schooling, and gender, numerous researchers devoted serious attention to attempting to correct preconceptions related to Newtonian mechanics through the use of various teaching methods, Clark and colleagues (2011) employed a Serious Educational Game (SEG) to teach physics concepts to students in Taiwan and the United States. Serious Educational Games are immersive virtual environments that ground learning in authentic contexts often through the use of ill-structured problems (Annetta, 2008). Clark and colleagues' study employed an SEG that fused game-play mechanics with conceptual physics, specifically the exploration of Newtonian mechanics. The results demonstrated statistically significant learning gains on some concepts for the gaming group, but FCI results within the study indicated little change in participant understanding of Newtonian concepts despite high scores on measurements of learning engagement (Clark Et al., 2011). Specifically, while the pre-test/post-test differences in total score for American students was reflected in *t*-

tests, both American and Taiwanese students only demonstrated gains on two of the twelve test items. Given the shortened version of the FCI administered and the relatively small reported gains (SD 0.1758- 0.365), the effectiveness of this intervention as implemented is questionable, while there does seem to be some promise in the concept. This effect carried across both the groups from the United States and Taiwan, regardless of age or gender (Clark et al., 2011).

Reasons for Failure?

It is suggested in the science education literature that preconceptions, also termed “misconceptions,” “naïve conceptions,” and “alternate conceptions,” may in fact not be concepts or previously exist at all, but rather are schemas or heuristics that arise in response to meaning-making given a situation (Rowlands et al., 2007). It has also been hypothesized in the science education literature that intuitive reasoning about mechanics serves to sufficiently explain occurrences in the natural world, and that those preconceptions are based on “common sense” (Ebison, 1993; White, 1983).

An Evolved Ability to Predict Object Motion?

In 1991 Brown published an exhaustive list of human universals that spanned the range of human experience and behaviours; included in this list are a number of universals that can be applied to learning and education, such as schema for classifying occurrences and objects in the natural world and logical heuristics for dealing with real-world situations and the behaviours of other humans (Brown, 1991). These human universals imply that there are innate structures that underpin much of human culture despite some intellectual’s conceptions of learning and behaviour as socially constructed

(Werstch 1985). While learning is considered a culturally mediated phenomenon by constructivists, the existence of innate, universal structures for certain types of learning have been hypothesized by psychologists and cognitive scientists that could shed light on how to educate learners.

In *The Blank Slate* (2002), Pinker synthesized the works of cognitive scientists into a set of ten intuitive faculties that can be viewed as adaptive from an evolutionary standpoint, which included:

> An intuitive physics, which we use to keep track of how objects fall, bounce, and bend. Its core intuition is the concept of the object, which occupies one place, exists for a continuous span of time, and follows laws of motion and force. These are not Newton's Laws but something closer to the medieval conception of impetus, and "oomph" that keeps the object in motion and gradually dissipates (p. 220).

Other proposed innate mechanisms for learning, particularly as related to number sense and an intuitive pre-Newtonian conception of physics, have been espoused by others in the fields of evolutionary biology and education in discussions of learning and the evolution of the human mind (Dawkins 2004, Geary 2000).

Pinker's set of intuitive faculties are based on an underlying set of assumptions that bear further examination. Firstly, it is assumed that humans share an evolutionary history and that history resulted in a number of traits that are applicable across all cultural boundaries. The fields of evolutionary biology and anthropology stand as a body of evidence to support this assumption, and leave it on rather firm ground. For example, Dawkins laid out the fossil, geographic and biochemical evidence for the evolution of all species in *The Greatest Show on Earth,* devoting a full chapter to the concept of the “missing link” and hominid evolution (Dawkins 2009). The intuitive faculties raised by evolutionary psychologists also assume that all humans naturally treat these situations the same, given similar levels of cultural learning that preclude the inclusion of other methods derived from human experience. Each proposed faculty generates its own set of testable predictions that can be compared to data that has already be obtained or tested for in experiments explicitly designed for that purpose.

In contrast to more traditional thinking about conceptual change, Geary (2000) suggested that certain faculties and abilities evolved, and that these intuitive processes act subconsciously. While much of Geary's work focused on mathematical skills like proportional reasoning and number sense, his hypotheses have extended to other fields. In *The Blank Slate* (2002), Pinker suggests that a concept of object motion similar to the medieval 'impetus' concept (a frequent misconception of the First Law, as noted above) is an adaptation of early hominids. This is taken yet a step further, to suggest that object tracking and concepts of motion are innate, subconscious, and may phylogenetically precede hominid evolution (Dawkins & Wong, 2004).

Such broad generalizations were initially resisted in science education due to a lack of data and questions about context and transferability between contexts (Gunstone & Watts, 1985). In light of the wealth of data since that time, and the general convergence of results from multiple sources and contexts, this seems a safer assumption to make than it initially was.

The apparent ubiquity of misconceptions regarding Newtonian force (see Table 2.1) suggests that an evolutionary explanation of such misconceptions may not be all that far-fetched. Geary (2008) presented a strong case for both the existence and importance of evolved "folk systems" in both biology and physics. Specifically, evolved folk systems for physics that include conceptions of motion, tool use, and navigation through the use of visuospatial faculties were supported through the citation of non-human primate studies, and the correlation of primate studies with human behavior (Geary, 2008). In this case, the prediction of prey movement in the biological world was hypothesized to give rise to an evolved talent to predict object motion, using the visuospatial reasoning system; the ability to predict motion as described by Geary (2008), and the predictions it makes, effectively mirrors the Aristotelian descriptions of force and motion detailed by Rowlands, Graham, Berry, and McWilliam (2007).

Visuospatial Ability

Pinker's conjecture about an innate spatial sense leads to the hypothesis that humans should show a natural tendency to construct mental maps based on a relative reference scale and that conceptions of size should be rooted in a human-sized scale if that supposition holds true. Dawkins and Wong, in *The Ancestor's Tale* (2004), postulates that humans evolved to see objects in "Middle Earth;" we innately perceive objects on a human scale and track objects that move at relatively slow speeds, such as can be naturally observed on the Pliocene savannah. For example, if humans had evolved to view objects at a micro scale, then we should perceive rocks as mostly empty space (Dawkins, 2004). Byrne (2000) extended this thinking into non-human primates, surmising that primates that foraged far afield in order to find food (or hunted, for that matter) would be selectively favoured if they were in turn able to plot their progress and determined which foraging areas were best or had already been visited. This leads to the concept of primates developing a mental map of an area with relation to reference points in order to successfully foment foraging behaviour.

The propensity for an innate spatial sense has been examined thoroughly in geography literature where spatial reasoning as it relates to navigation and map reading has been investigated. Gattis (2000) attributed some spatial reasoning to the relational hypothesis, wherein conceptual elements are mapped to spatial elements for purposes of cognitive representation. Gattis' research tentatively confirmed this hypothesis with the corollary that spatial and conceptual relations are dependent on the use of relational language. Hegarty, Richardson, Motello, Lovelace, and Subbiah (2002) reported that people were better able to maintain sense of direction from real-world experience than from video, with which they in turn fared better than with a two-dimensional virtual environment. This research also demonstrated significantly greater spatial reasoning abilities based on experience in males than in females, particularly with regard to navigation and direction sense.

More recently, further study of spatial reasoning has been conducted in cognitive neuroscience, which has a greater bearing on the research questions as the definition of VSA in recent studies matched the definition employed in this dissertation. Cohen and Hegarty (2007), examined performance on a novel spatial inference task, where participants were asked to visualise and then draw a cross-section of a 3-dimensional object, with interactive control of two computer visualisations. The study found large individual differences in the frequency with which participants utilised the computer visualisations, correlated to their spatial ability, which suggests that computer simulations or visualisations for mathematical and scientific problem solving are only useful to a subset of individuals, namely those who already have a greater level of spatial reasoning ability (Cohen and Hegarty, 2007). A study employing surveys to determine the preferences of meteorology students in a computer assisted cartography exercise further indicate that despite the desire to make such tasks an abstraction, participants preferred those digital representations that were more realistic, with concrete clues, over simplified and more abstract maps (Hegarty, Smallman, Stull, & Canham, 2009). Wolbers and Hegarty (2010) examined the literature pertaining to individual variation in spatial abilities and found that there are gender differences in the types of navigational strategies employed, a discrepancy in the neural correlates for retrieval of cognitive maps as opposed to familiar routes through a known area, and a decline in the effective use of navigational cues with age coupled with a degradation of the signal-to-noise ratio in the processing of current position. These findings suggest that the type of spatial reasoning task is an important factor in individual success in virtual environments that require, such reasoning, and that age may also have an impact on the ability of students to successfully manage an online environment that requires navigation (Wolbers and Hegarty, 2010).

For spatial tasks that involve a transfer or movement of other objects (mental rotations) as opposed to an image of the movement of self, there appears to be a correlation between brain activation in the parietal lobe as measured by hemodynamic response and the degree of rotation that was not present in imagined transformations of the self (Keehner, Guerin, Miller, Turk, & Hegarty, 2006). This suggests that the cognitive processes for mental rotations of objects and manipulation of personal spatial perspective are separate. However, in their correlational study of small and large scale spatial reasoning, Hegarty, Montello, Richardson, Ishikawa, and Lovelace (2006) noted an overlap in spatial reasoning ability between the scales although the predictive value of success on small area tasks was better correlated with virtual and 2-dimensional learning than with real world experience, suggesting that learning from visual input utilises both schemas. If learning environments that access spatial reasoning ability are more likely to employ methods that rely upon visual cues more than kinaesthetic, a means of predicting student performance on those tasks through tests of small scale reasoning may be possible. It has also been suggested that working memory plays a vital role in these types of tasks but spatial and verbal working memory are separable (Shah and Miyake, 1996).

Response to a Conundrum

Regardless of the source of misconception, recent variants of conceptual change theory elucidated the importance of motivation in the initiation of conceptual change with empirical support (Ketamo & Kiili, 2012). Hestenes, Wells, and Swackhammer (1992) noted that learners are forced to learn through rote memorization when they lack the correct overarching framework, which decreases motivation. This alone could account for difficulties in inducing conceptual change in mechanics reasoning, whether the source of the misconception is 'common sense' or an evolved heuristic. Furthermore, many of the studies elaborated upon above employed a conceptual change methodology that failed to incorporate multiple representations of knowledge or allow for sufficient learner exploration of their own frameworks in order to create the cognitive dissonance that must precede theory-change. Clark et al. (2011), the only intervention that reported moderate success, also marked the only intervention to have high metrics for engagement and some means of learner exploration allowing for embodied cognition.

The issue that arises from this body of literature is then twofold: firstly, we as a research community have failed to determine the source of these misconceptions, or more importantly the reason why misconceptions in Newtonian mechanics are ubiquitous to the human experience and highly resistant to change; and, perhaps more directly related to classroom instruction, we have yet to devise pedagogical tools to effectively teach Newtonian conceptions of mechanics in the face of these widespread misconceptions.

The hypothetical answer to the first of these issues is both interesting in its own right, and has the potential to serve as a foundation for a useful response to the second. The previously discussed literature on evolutionary psychology, along with the elimination of variables in Table 1, suggests that the misconceptions related to Newtonian mechanics are in fact an evolved characteristic of humans (Dawkins & Wong, 2004; Geary, 2000). If this hypothesis were borne out, it might be reasonable to expect that the cognitive and corresponding neural systems responsible for the heuristic reasoning are different from those responsible for understanding and applying a scientific conception of mechanics (Middleton & Strick, 2000).

As FCI items in particular (the most common means of assessing conceptions of force), and considerations of Newtonian mechanics in general, involve visualization of objects and their interactions, if not pictorial representations of the same, it follows that this process would mirror other visuospatial reasoning tasks. Alternately, some researchers noted activations during visuospatial tasks that are not in brain regions typically considered primary reasoning areas. For example, Petrosini, Leggio, and Molinari (1998) found that the cerebellum activated during 'how to find and object in space' tasks, as well as left/right discrimination, and suggested that there exists an allocentric spatial system as well as an egocentric control system for reasoning; this particular study employed animal models (*Rattus norvegicus*) rather than humans.

Table 1. Variables eliminated through review of literature.

Study(s)	Variable Eliminated
Bayraktar, 2009	Gender
Mildenhall and Williams (2001); Fischbein & Schnarch (1997)	Age
Kruger (1990); Bayraktar, 2009; Mildenhall and Williams (2001);	Physics Education Experience
Apostolides & Valanides, 2008; Chang et al., 2007; Eryilmaz, 2002; Mildenhall & Williams, 2001; Planinic, Boone, Krsnik, & Beilfuss, 2006; Suzuki, 2005; Trumper, 1999	Ethnicity/Culture/Geographic Location

The suggestion of a dual-system means of reasoning is not unique to the Petrosini study, nor is it limited to spatial reasoning. In quantitative reasoning tasks, Stavy, Goel, Critchley, and Dolan (2006) found that there appeared to be simultaneous recruitment of a conscious reasoning system and a subconsciously acting intuitive system. The intuitive system seemed to interfere with reasoning that was under conscious control. Theoretical work incorporating Stavy and colleagues (2006) and other studies, along with the psychological and philosophical underpinnings of the concept, suggested that a dual-system framework underlies intuitive reasoning in children and some adults, dependent on task (Osman & Stavy, 2006). This is commensurate with psychological models of reasoning wherein there exists a System 1 (Intuitive, fast, effortless, and automatic, but also slow learning) and System 2 (slow, serial, controlled, and effortful, but also flexible) that can simultaneously operate on a task, causing interference between the two cognitive systems (Kahneman, 2003; Roser & Gazzaniga, 2004).

Addressing misconceptions in Newtonian mechanics

Without performing functional Magnetic Resonance Imaging or similar techniques to isolate the specific regions of the brain active during reasoning about mechanics, as compared to more general reasoning tasks, it is still possible to put forth and pare down the variables involved in such reasoning from previous studies. A summary of these potential variables and reference to the studies that spawn their selection can be found in Table 2. Beginning with the frequently used Force Concept Inventory to assess understanding of Newtonian mechanics, a model can be constructed that employs the potentially correlated variables and their level of influence (Savinainen & Viiri, 2008). In a study of the conceptions of psychology students (similar to a nature of science study), Kowalski and Taylor (2004) noted that misconceptions were best overcome by those participants who exhibited the greatest general reasoning and critical thinking abilities. The importance of motivation to the facilitation of conceptual change is an underlying theme in the literature, and has been for some time (Pintrich, Marx, & Boyle, 1993; Taasoobshirazi & Sinatra, 2011). As most assessments of Newtonian mechanics involve diagrams, and the phenomenon itself is frequently taught using hands-on materials and visualization, it follows that visuo-spatial reasoning ability may have an effect on the ability of learners to complete conceptual change in physics (Kumaran, Summerfield, Hassabis, & Maguire, 2009). This is supported by the work of Reiner (2009), who indicated that learners' tacit knowledge of physics is often expressed in pictorial representations while hands-on sensory experiences can be employed to foster the development and expression of learners' tacit knowledge.

Table 2. Variables potentially correlated with conceptual change in physics.

Variable	Reference
Understanding of Newtonian Mechanics	Hestenes, D., Wells, M., and Swackhammer, G. (1992).
Affect/Motivation	Taasoobshirazi & Sinatra, 2011
Visuo-spatial Reasoning	Kumaran, Summerfield, Hassabis, and Maguire (2009)

Summary

Ultimately, the importance of Newtonian mechanics to physics instruction makes it vital that an effective means of teaching those concepts is devised. Conceptual change theory and an understanding of misconceptions serves as a viable place to begin although most documented attempts have failed to completely incorporate all the corroborated recommendations of the conceptual change literature. Isolating the variables that impact conceptual change in physics, and determining the level of interaction between those, seems the most plausible starting point for educators who are seeking to create and implement interventions to teach Newtonian mechanics. If it can be demonstrated that this particular set of misconceptions is evolved, or depends heavily on visuospatial ability, successful interventions may hinge more on our ability to augment learners' visuospatial ability and their motivation to learn physics than the (still needed) direct attempts to combat the misconceptions. An understanding of evolved heuristics for learning and reasoning is noted by Sweller (2008) as having profound implications for how instruction must be adapted to biologically primary (concepts humans have evolved to learn) subjects, as opposed to those that are biologically secondary (concepts that must be actively acquired and demand the use of working memory resources).

Chapter 3

The purpose of this study is to examine the potential relationships among visuospatial ability, learner motivation to learn science, and learner conceptions of force across commonly measured demographics in undergraduate physics education.

The participants for this descriptive study were drawn from undergraduate physics courses at a large public university in the Mid-Atlantic region of the United States, a convenience cluster sample selected due to proximity to the researcher and the amenability of the physics faculty at that university to assisting with administration of the measures. Participants within the clusters (i.e. students within those instructors' classes) can be reasonably assumed to be a random sampling of students required to take an introductory physics course, as they comprise all introductory physics students for the course of the 2012-2013 academic year. Demographic information collected from all participants included gender, ethnicity, age, educational experience in physics, university major, and current physics instructor; while the review of literature indicated that demographics are not an influence on conceptions of force, demographic information was needed to make inferences to the population of physics learners as a whole through demonstration that the sample is the equivalent of the overall population, due to the lack of randomness. The total number of participants is 117, with 91 completing all measures and thus being included in the analysis.

Description of Sample

The sample for the present study (n=117) was drawn from two undergraduate physics courses, one a calculus-based course for physics and engineering majors, and the other an algebra-based course for non-majors that focused heavily on concepts. Of this initial sample, twenty-six were disqualified for failure to complete items ranging from demographics to measurement instruments, leaving a final sample size of 91.

Of those participants that were disqualified for failure to complete instruments, five did not complete any information at all apart from giving their consent to participate. The remaining disqualified participants (n=21) where overwhelmingly male, white, and under 21 years of age; this is similar to the sample retained for analysis (see Table 3).

Table 3. Demographic distribution of disqualified participants.

Variable	Distribution
Age	Mean= 21.09 (S.D. 5.47)
Gender	Male= 15 (71.4 %), Female=6 (28.5 %)
Race/Ethnicity	White=15 (71.4 %), Asian=5 (23.8 %), Multiracial=1 (4.7 %)

The sample retained for analysis (see Table 4) was also heavily male (61.1 %) and White/Caucasian (57.1%), although with more diversity than the excluded sample. It is noteworthy that there are few physics majors in this sample, but a number of those coded as ‘science, other’ declared their major in some form of engineering.

Table 4. Demographic distribution of sample.

Variable	Distribution
Age	Mean = 21.26 (S. D. 3.51)
Gender	Male = 55, Female = 35, Missing=1
Race/Ethnicity	White = 52, Hispanic= 9, Black = 5, Asian = 16, Native American =1, Multiracial= 8
# of Physics Courses Taken	Mean= 2.26 (S. D. 1.46). Range= 1-10
University Major	Physics =1, Science and Engineering = 35, Social Science/Arts/Humanities= 55

Study Design

This study employed a single group exploratory design in which participants from all classes completed the measures at a single time within the semester. As a snapshot of the participants at that temporal juncture, this allows for correlation of continuous variables given the lack of an intervention in the study. Since the purpose of this study was exploratory in terms of developing a working model of conceptions of force with regards to the causal variables that influence those conceptions, performing an intervention, particularly in light of the ineffectiveness of those presented in the literature, was deemed unnecessary. Likewise, a post-test was deemed an unnecessary complication due to the lack of a true intervention; participants took part in the physics courses in which they enrolled without adjustment to instruction due to the research described here. Any between group comparisons were generated through analysis of the significance of demographic variables. All measures were delivered through an anonymous, online instrument comprising both multiple choice and open-ended response, as dictated by the measures selected for the study.

Variables and Measures

In addition to the aforementioned demographic variables, several measures were employed to develop a clearer picture of participants' visuospatial ability, motivation to learn physics, and understanding of force from a Newtonian perspective (see Table 5). Of subsequent interest are the potential interactions between these factors.

Table 5. Variables of interest and variable types.

Variable	Type
Gender	Nominal (Binary)
Ethnicity	Categorical
Age	Numeric
Credit Hours in Physics Courses	Numeric
University Major	Nominal
Visuospatial Ability	Numeric
Motivation to Learn Physics	Ordinal
Newtonian Conception of Force	Numeric

Visuospatial ability. Visuospatial ability (VSA) is defined as the ability to visualize and manipulate images of objects in three dimensions, and the functional equivalent of physically manipulating an object in space (Shepard & Metzler, 1971). The classic measure of VSA is the Shepard-Metzler test of mental rotations, later adapted to a two-dimensional test by Vandenburg (Sternberg, 2009). For this proposed study, the original Shepard-Metzler test consisting of 20 items will be employed. Each test item consisted of a 3-dimensional image and six figures that are similar, two of which are spatially rotated versions of the original image. Participants were asked to select which combination (through multiple choice) of figures are rotated versions of the original, and scored for veracity, with a possible point range of 0 to 20. A positive relationship between visuospatial ability and conceptions of force would indicate that force concepts are more concrete than abstract, and require spatial visualization. If this proved to be true, then conceptions of force may also recruit the same cognitive processes that are associated with heuristics for spatial visualization in other tasks (Petrosini, Leggio, & Molinari, 1998).

Motivation to learn physics. Taasoobshirazi and Sinatra (2011), in a study examining the relationship of several affective measures on conceptual change in physics, noted the motivation is a complex, multidimensional construct with a significant influence on learning through interactions with cognition. As such, it was necessary to include a measure of motivation, specifically a measure of motivation to learn physics, in this study. Prior studies with similar aims, namely the exploration of a model of conceptual change in learners' conceptions of force, employed the *Physics Motivation Questionnaire* (PMQ) (Taasoobshirazi & Sinatra, 2011). An updated version of the PMQ, the PMQ-II, was published by Glynn, Brickman, Armstrong, and Taasoobshirazi (2011) in an attempt to shore up construct validity, and included five components of motivation: intrinsic motivation, self-determination, self-efficacy, career motivation, and grade motivation.

It should be noted that in the case of both the original PMQ and the PMQ-II, the published and validated instrument was named the Science Motivation Questionnaire, to be adapted to physics by replacing the word 'science' with the word 'physics' throughout. The SMQ-II, and subsequently the PMQ-II, consists of 25 items, 5 per subscale, with a five category Likert-like set of response options. Participants in this proposed study completed all 25 items, as delivered on a single pane of the online instrument, with no time limit.

Glynn and colleagues (2011) employed a cross-validation approach, consisting of both an exploratory and confirmatory factor analysis, to establish construct validity for the SMQ-II. The SMQ-II reduced to five significant factors that accounted for 67% of the variance, with internal reliability in the subscales ranging from .81 to .92, and a Chronbach's alpha for all 25 items of 0.92 (Glynn, Brickman, Armstrong, & Taasoobshirazi, 2011); Both validity and reliability were determined to be good by the authors of the instrument.

Concepts of force. Hestenes, Wells, and Swackhammer (1992) developed the *Force Concept Inventory* to measure student and teacher conceptions of force and motion, and to categorize subjects' thinking as Newtonian or non-Newtonian. The FCI, in the format of a 30 item multiple choice test, has been widely used for both of these purposes as reported in Chapter 2 of this work. The original authors of the FCI report satisfactory reliability and construct validity through qualitative assurances that the frequency of use and responses typically given to items are consistent and commensurate with the questions being asked, respectively.

In 2010, Nieminen, Savinainen, and Viiri constructed a Representational variant of the Force Concept Inventory (RFCI) using nine questions from the revised 1995 version in various representations including vector diagrams, graphs, and motion maps. This version of the FCI measures representational consistency on each of Newton's three laws and gravitation, as well as correlating well (coefficients between .78 and .86) with the original FCI instrument for measurement of learner understanding of force concepts (Nieminen, Savinainen, & Viiri, 2010). The 27 question RFCI assesses fewer dimensions of force than does the 30 item FCI, but maintains integrity on the force concepts that are crucial to learning across physics curricula of differing levels, namely Newton's three laws and gravitation. For this reason, this proposed study employed the somewhat simplified RFCI instrument, delivered in an online format. In addition, the RFCI leaves open the option of examining consistency of thinking about each concept as a function of the predictor variables in a post-hoc analysis.

Participants will be asked to choose one of five multiple choice responses to each of the twenty-seven questions. Raw score was computed to represent the level of Newtonian thinking regarding force concepts.

Analysis

As noted previously, the sample itself was composed of students taken from a nonrandom cluster of instructors; the option to decline participation in the study was present at both the instructor and student level. Thus, due to the participation rate at the instructor level, the sample consisted of a portion of undergraduate physics students during the semesters of interest. Descriptive statistics for the sample were compared to those of the school population, and the population of college undergraduates, in order to establish equivalency and foster some level of generalizability for the results of the study. The study sample was more heavily male than the general university population (60% vs. 46%). Ethnicity for the sample was composed as follows: 57% Caucasian, 10% Hispanic, 5% African American, 17.5% Asian, 8.7% Multiracial, and 1% Native American. By way of contrast, the university population (obtained from public records) as a whole consisted of 49% Caucasian, 9% Hispanic, 8.6% African American, 13.9% Asian, 3.4% Multiracial, and 0.016% Native American.

Data cleaning, Interpolation, and Conversions

Demographic variables that are categorical or nominal in nature (see Table 5) were coded into a range of numerical categories beginning with 0 for the baseline and moving numerically upwards in increments of 1. Specific codes for each categorical or nominal variable are presented in Table 6. For measures that involve correct and incorrect responses, all correct responses were coded as 1, and incorrect responses as 0, with total raw scores computed and conversion to scale scores using the instrument instructions completed prior to analysis.

Table 6. Coding of categorical and nominal variables.

Variable	Codes
Gender	0= male, 1= female
Ethnicity	0=Caucasian, 1= Hispanic, 2= African American, 3= Asian, 4= Native American/Pacific Islander, 5= Multiracial
University Major	0= Physics, 1= Other Science, 2= Non-science

Characterization of university major divided all participants into three possible groups: physics majors, other sciences majors, and non-science majors. For coding purposes, psychology and engineering were coded with other sciences due to the use of experimental methods and design processes similar to the natural sciences in those disciplines.

Of the measures used to collect data that will function as independent variables, all but one was numeric. However, the Physics Motivation Questionnaire II queried participants using Likert-type items, which will resulted in ordinal data. Ordinal data are data that can be categorized in rank order by number, but the ranks themselves, or the distance between the numbers are not consistent and therefore the resulting numerals cannot be used for analysis in the same manner as ratio and true numeric data (Dimitrov, 2009). In order to address this issue, this analysis employed a Rasch model using the Winsteps software. Rasch modeling is a single parameter Item Response Theory model that predicts the likelihood of endorsement of test items based on the rate of endorsement of other items; this likelihood is modeled as a logistic function (Linacre, 1999). It is important to note that Rasch modeling is intended for instruments that have a single orthogonal construct; the reported construct validity information from the PMQ-II will serve to establish to appropriateness of using a Rasch model for data gathered from this instrument (Glynn, Brickman, Armstrong, & Taasoobshirazi, 2011). Linacre (1999) indicated that a major purpose of the Rasch model beyond the model's use in instrument validation is to generate numerical values from categorical responses through placing the categorical responses on a logistic scale, thus converting categorical responses to ratio data. As the use of the Rasch model in this study is not intended to assist in instrument construction or reform, the application of the Rasch model to the PMQ-II will be limited to the reporting of the logit equation generated, the conversion of PMQ-II raw scores to scale scores in order to convert the ordinal Likert responses into numerically useful ratio data, and to report the model fit. Model fit itself, while reported, is not a significant concern of this study, although poor fit would raise questions about the validity of the PMQ-II instrument, and subsequently any conclusions drawn using data from that instrument. Instead, the primary use of the Rasch model for this data is to transform the ordinal Likert data generated from the PMQ-II into numeric data that is more appropriate for a variety statistical analysis.

Influence of demographic variables

Initial analysis of participant data consisted of an analysis of variance (ANOVA) to test for the significance of the relationship between the demographic variables and scores on the RFCI. While a number of variables have been eliminated through the review of the literature (see Table 2.1), cautious assessment of the sample is necessary due to the lack of true randomness in the sampling technique. ANOVA was selected for this portion of the analysis due to the numeric dependent variable and largely categorical demographic variables. A separate Pearson correlation was performed to ascertain the significance of the relationship between numeric demographic variables, specifically age, and the dependent RFCI score. Demographic variables with a significant relationship to either the dependent variable or independent measures were retained for inclusion in the full analysis, while those demographic variables that do not have a significant relationship with the measures or dependent variable were discarded at this point.

Structural Equation Modeling of Learner Conceptions of Force

Taasoobshirazi and Sinatra (2011), in a similar study of learner conceptions of force the focused upon student achievement in the form of course grades and affective measures including motivation, employed a structural equation model (SEM) to generate causal connections between aspects of learner affect, student achievement, and understanding of Newtonian force. Structural equation models, similar to a path analysis, provide a means to test for causal dependence of variables upon one another, but differs from path analysis in that SEM allows for the inclusion of latent constructs rather than solely direct measures (Dimitrov, 2009). Another advantage to employing an SEM, as opposed to path analysis, is that the inclusion of latent factors reduces measurements to error free 'true scores', rather than measure dependent scores, which in turn allows the results of the study to be replicated with different measures and generalized to a greater population (Dimitrov, 2009).

Given the prior use of SEM in a similar study, and the advantages conferred by SEM in multivariate analysis including attribution of causation, this study employed a structural equation model for final analysis of data. Independent variables, including those demographic variables found to have significant relationships to the independent variables, and the dependent variable were regressed upon one another within the correlation matrix to establish significance in their relationships, with the coefficients reported in the final model. It is expected motivation may act as an endogenous (mediating) variable, whilst the visuospatial ability, unless significantly related to a demographic measure, will be exogenous (truly independent).

Limitations

The assumptions of ANOVA include a normally distributed random sample, which may in fact not be obtained from the study design. While this may be counteracted by establishing the lack of importance of demographic variables to the study, establishment of equivalence between the sample and population, or both, it is important to be cautious in assuming broad generalization from the study results. Likewise, as data collection is anonymous, it is be possible to rule out sampling bias in non-responders. Response rate may have been improved by incentives (extra credit points for completion) offered by instructors, which may also have introduced a slight bias. This limitation again calls for caution in generalizing to the population at large. Discussion of results will include generalization without bringing into account these limitations, although the reader is encouraged to keep them in mind when interpreting the results and reading the discussion. More importantly, if issues of sampling bias and randomness can be set aside, there remains the issue of the population from whence the sample is drawn: undergraduate college students are not representative of learners of all ages. Checking for a relationship between conceptions of Newtonian force and both age and experience with physics is intended to counteract this weakness, but it would not be sound reasoning to extrapolate the results obtained from this study to, for example, a middle school age population without replication of the study with that age group.

Finally, the format in which the instruments are delivered was intended to reach as broad a sample as possible while eliminating any concerns of the participants that their information will be shared with their instructors or others. However, due to the length of the administration, and the invariance in task order across subjects, the potential for test fatigue in the sections administered at the end of the procedure cannot be eliminated as a possible confound. This is somewhat ameliorated by all participants being subject to the same length and order of instruments; in other words, any degradation in performance will be shared across groups.

Chapter 4

The purpose of this study was to examine the potential relationships among visuospatial ability, learner motivation to learn science, and learner conceptions of force across commonly measured demographics in undergraduate physics education.

Association of demographic variables with RFCI score

The initial analyses addressed Research Question 1, determining the association of demographic variables with variations in understanding of force concepts. The significance of demographic variables and the interaction between them, with regard to participant achievement on the RFCI, was tested using ANOVA and Pearson correlation for categorical and numeric data, respectively. Correlation of age, number of physics courses taken, and age*courses taken yielded no affirmative result in the complete model ($p=.0587$, r-square=.08). Furthermore, despite the nearness of the p-value to our alpha level, the practical significance with an r-square of .08 is not high enough to warrant detailed discussion. Tests for main effects indicated that only the interaction between age and number of courses taken was statistically significant ($p=.0245$) with a correlation coefficient of .15. Examination of the plot for this correlation suggests that a single outlier is responsible for this significance (see Figure 1), the implications of which will be discussed in Chapter 5. However, due to the anomalous nature of this finding, the interaction of age and courses taken was not included in the SEM analysis.

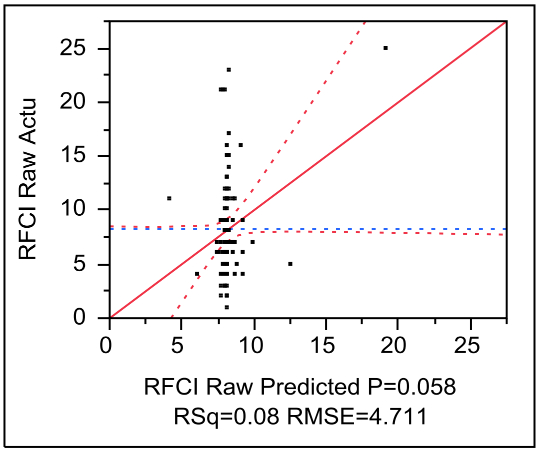


Figure 1 Response RFCI raw whole model actual by predicted plot.

Analysis of more traditional demographic variables yielded no significant (α=.05) results. Males (mean 8.78) did not score significantly higher on the RFCI than females (mean 7.48), with a two-tailed probability of obtained the same data, given a true null hypothesis, of .165 (i.e. p=.165). Likewise, although there were some differences in means between racial and ethnic groups as classified in the coding (see Table 7), these differences were not statistically significant (p=.90). The interaction of race and gender also yielded a result that was not statistically significant (p=.62).

Table 7. RFCI mean by race/ethnicity.

Race/Ethnicity	Mean RFCI (standard error)
White/Caucasian	8.76 (.75)
Hispanic	6.77 (1.67)
Black/African-American	8.40 (2.27)
Asian	8.04 (1.25)
Native American	7.00 (not estimable)
Multiracial	7.37 (1.76)

Rasch validation and scaling of PMQ-II

In order to convert the Physics Motivation Questionnaire -2 from ordinal data to numeric for further analysis, the data were fit to a polytomous Rasch model for transformation to a logit scale using Winsteps. In doing so, the originally validated subscales (Glynn, Brickman, Armstrong, & Taasoobshirazi, 2011) were kept intact, and names for each construct retained. All five subscales had high (>.9) levels of item reliability and raw-score to measure correlation, with excellent model fit according to the work of Gustafson (1980). Fit statistics and logit transformation equations for each subscale are detailed in Table 8. Ideal infit and outfit statistics are 1.0; fits below 1.0 indicate an overfit, with the data being more predictable than expected. These data demonstrate a slight overfit to the model, with a loss in percent variability corresponding to the difference between the fit statistic and 1.0. Furthermore, the tight fit of these data to the model suggest strong construct validity for the instrument as used with this sample.

Table 8. Model fit and logit equations for PMQ-II (all subscales).

Subscale	Infit MNSQ (ZSTD)	Outfit MNSQ (ZSTD)	Chronbach's alpha test reliability	Raw-score to Measure Correlation	Logit equation
Person fit	.90 (-.1)	.88 (.0)	.30	.65	
Item fit	.96 (-3)	.98 (-.1)	.95	.98	Measure = Score * .2916 + -2.9109

Structural Equation Modeling

A more complete analysis was employed to investigate the responses to Research Questions 2 and 3, the impacts of motivation and VSA, and the plausibility of an evolved ability to predict object motion, respectively. This final analysis of the data was accomplished using a Structural Equation Model (SEM) derived in the M-Plus software platform. Model selection began with generating the most complex model of the data possible, including all interaction terms, and removing terms as specified by model convergence and fit. The complete list of variables included in the model can be found in Table 9, with the M-Plus code for the final model presented in Appendix A.

Table 9. Variables included in SEM.

Variable	Model Label
PMQ2- Intrinsic Motivation	Y1
PMQ2- Career Motivation	Y2
PMQ2- Self-determination	Y3
PMQ2-Self-efficacy	Y4
PMQ2- Grade Motivation	Y5
Representational Force Concept Inventory	Y6
Shepard-Metzler Mental Rotations Test	Y7

Variables included in the SEM (see Table 9) were labeled in accordance with the constructs said to be observed by the validated instrument, or subscale thereof, with which they were measured. In the complete model, latent factor 1, defined here as motivation due to the prior validation of the instrument used, was derived from the five subscales of the PMQ-2. The final model (see Figure 2) dropped variable y1 (Intrinsic Motivation) due to the inability of the model to estimate the standard error of these data, resulting in model misfit. Factor 2, defined as visuospatial ability, was derived solely from the results of the MRT, a well-validated measure of VSA; as latent factors cannot be properly derived from a single observed measure, factor 2 was removed from the model in favor of using the observed measure. As a result, the final model is a hybrid between a path analysis and an SEM. In addition, testing of alternative models indicated that the best fit, according to the Bayesian Information Criterion, was obtained through the removal of Y5 (Grade Motivation).

Fit statistics for the final model are presented in Table 10. The number of free parameters in the model was 14, resulting in a final ratio of sample size to free parameters of 6.5, meeting the 5:1 goal set by Bentler and Chou (1987). Overall model fit was good, with the Chi-square test of model fit being nonsignificant. The Root Mean Square Error of Approximation (RMSEA) was estimated at 0.00, with a confidence interval (.90) of 0.0 to 0.081. Desirable estimate ranges for this statistic are less than .08 for moderate fit, less than .05 for good fit, and less than.01 for excellent fit (MacCallum, Browne, & Sugawara, 1996). The probability of an RMSEA below .05 is .909 for this model, which suggests a good if not excellent fit. The Tucker-Lewis Index (TLI) for this model is 1.029. TLI is an incremental measure of model fit that tests the ratio of chi square and degrees of freedom in both the null and proposed models; an ideal result for TLI is 1.0, with .95 and above considered good fit, as incremental fit indices can be best compared to an R^2 (O'Boyle & Williams, 2011). Standardized Root Mean Square Error (SRMR) for this model is 0.010; any value less than 0.08 is considered a good fit according to Hu and Bentler (1999).

The only alternate model that also achieved model convergence with complete estimation of parameters and standard errors included Y5 (Grade motivation), but had a substantially worse fit when compared to the chosen model using Bayesian Information Criterion (Chosen model BIC= 1315.78, alternate model BIC= 2051.25).

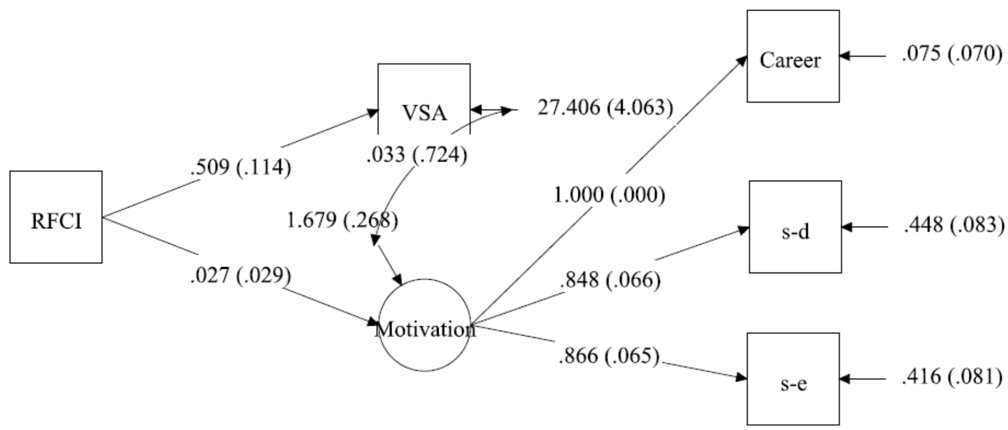


Figure 2. Final SEM (all relationships).

The final model, in complete form, consisted of the latent variable of motivation (constructed as discussed above) and the observed variables of visuospatial ability and RFCI score. RFCI was regressed on both exogenous variables, while the co-variance between the exogenous variables was also represented. Figure 3 displays those relationships that were significant at an alpha level of .05 or below.

Table 10. Model fit information.

Number of Free Parameters	14
Bayesian Information Criterion	1315.733
Chi-square Test of Model Fit	X^2= 1.259, DF=4, p=0.8682
Root Mean Square Error of Approximation	Estimate = 0.000 90 % CI (0.000, 0.081) Probability RMSEA <=.05 = 0.909
Tucker-Lewis Index	1.029
Standardized Root Mean Square Residual	0.010

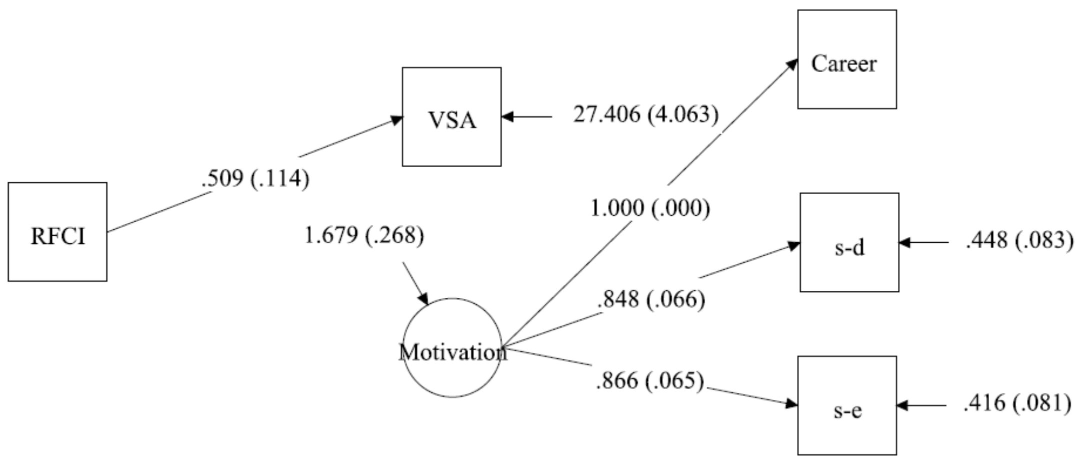


Figure 3. Final SEM (all relationships).

As displayed in Figure 3 above, the final model, when controlled for significance, consists of RFCI score regressed on visuospatial ability, and a confirmatory factor analysis for the latent motivation construct. The regression of RFCI on motivation (p=0.35) and the covariance of motivation with VSA (p=0.96) were not statistically significant, nor were the regression coefficient and covariance value large enough to merit further discussion (see Figure 2).

The composition of the latent factor labeled ‘motivation’ can be seen in Figure 3, with strong factor loadings for both self-determination and self-efficacy. Career motivation resulted in the greatest factor loading when all parameters were freed, and thus was given the primary position in the factor analysis. This primary position, when completing CFA within an SEM using M-Plus, assigns a factor loading of 1.0 and a standard error of 0 to a measure used in that manner.

Regression of RFCI on VSA found a significant ($p<.001$) relationship, with a regression beta coefficient of .509. This means that a one unit increase in scores in the MRT resulted in a .5 unit increase in scores on the RFCI.

Summary of Findings

Analysis of demographic variables using ANOVA and regression found no significant results for traditional demographics, although some groups were small enough that this could be attributed to a lack of statistical power. The interaction of age and number of physics courses taken did yield a statistically significant result, with an R^2 of .08; the plot for this interaction indicates that the correlation may be due to a single outlier, which will be discussed further. SEM model fit was good, and improved with a reduction in the number of observed variables used to construct the latent variable labeled as motivation. Significance testing of the SEM found that only the regression of RFCI score on visuospatial ability (as measure by the MRT) was significant at a .05 level, with a beta coefficient of .509, suggesting a strong causal influence of visuospatial ability on learner understanding of Newtonian mechanics.

Chapter 5

The purpose of this study was to examine the potential relationships among visuospatial ability, learner motivation to learn science, and learner conceptions of force across commonly measured demographics in undergraduate physics education. The results indicated that while motivation and demographics did not have a statistically or practically significant influence on conceptions of Newtonian mechanics, participants' visuospatial ability exerted a strong causal influence on RFCI scores.

SEM and Causality

Before launching into a detailed discussion of the results, it may be helpful to the reader to briefly discuss the use of the term cause within this document and how the regression analysis that serves as the basis for SEM is employed to make valid casual descriptions.

Regression analysis in general, along with simple linear correlation, is not sufficient to establish a linkage between two or more variables beyond that of a simple correlation relationship; in other words, regression and linear correlation (ANOVA included) simply determine the existence and magnitude of a relationship between variables, not the direction itself. SEM, on the other hand, draws upon qualitative hypotheses gleaned from observation or the literature base in order to establish causal relationships between variables using only observational data, rather than the more traditionally applied experimental methods (Bollen & Pearl, 2013). The causal assumptions taken from the literature are by no means sacrosanct: it is entirely possible for assumptions drawn from the literature to be incorrect or for the model itself to be incomplete. This, then, is the reason for performing the quantitative test of causal assumptions. Consequently, it should also be noted that the causal assumptions tested rarely represent a complete picture of a phenomenon without an extensive background literature.

Causes are typically described in metaphysical terms as necessary (needed to cause an event), sufficient (able to cause an event on their own), or a combination of the two (Carroll & Markosian, 2010). Just as it is possible, logically, for causes to be necessary but not sufficient, or sufficient but not necessary, it is also possible within an event described by SEM. For example, this model attributes potential casual influence on learner conceptions of Newtonian mechanics to visuospatial ability and motivation. While the results suggest that visuospatial ability is both necessary and sufficient to cause changes in learners' conceptions of force (i.e. the impact was directly discernible within the model), motivation may be necessary as described by Taasoobshirazi and Sinatra (2011), but not sufficient without combination with a variable that has been excluded from the analysis conducted in the current study. Lastly, as stated in Maxwell (2012), there is a difference between causal description and causal explanation. SEM analysis informs us the variables involved in causing an outcome, but does not necessarily explain to us how that cause occurs without a multi-level analysis, or a detailed description of process, that delves inside how each of the variables operates upon the outcome of interest. In the case of the present study, a series of 'think-aloud' studies, coupled with the quantitative results, may shed some light on casual explanation as well as description.

Discussion of Demographic Results

The findings of the ANOVA analysis, while not statistically significant, are significant in a practical manner with regards to the generalizability of the study to larger populations and in their contribution to the literature base. The lack of effect for gender, ethnicity, race, age, university major, and physics courses taken on participants' understanding of Newtonian force is commensurate with the findings of the literature review (see Table 1). Agreement with the lack of significant in demographic variables adds to the collective literature on interactions between demographics and conceptions of force, particularly in the case of gender, which was only specifically examined in the work of Bayraktar (2009). Furthermore, given the differences between the composition of the sample and the university population as a whole, nonsignificant findings for the impact of demographic variables on conceptions of force help to support the external validity of the current study. If demographics, particularly ethnicity and gender, are not influential in learners' conceptions of Newtonian mechanics, the results of this study, along with others taking place in the same educational framework, are applicable to other populations within the same general educational framework. Furthermore, as the impact of age was also not significant, the findings of force concept studies including university and adult learners are generalizable within the adult population. As there may be developmental differences that come into play at younger ages, it should be cautioned that this generalizability may not extend to learners in secondary or elementary schools without further examination.

However, the interaction between age and the number of physics courses taken by the participants did prove to be significantly predictive of participants' score on the RFCI instrument (see Figure 1). Further examination of Figure 1 suggests that any significance in the value of predicting RFCI score from the interaction of age and courses taken is due to the presence of a single outlier: this individual reported their age as 43 years, has taken 10 courses in physics, and scored a near perfect 26 on the RFCI. Setting aside the possibility of a data entry error due to participant entry of information, and considering that the RFCI score was the upper limit of those reported within the sample, we must consider that there is something important at work here. Speculatively, it would appear possible that the individual reporting these numbers (if they are indeed accurate) might be the course instructor, or at least a student who was taking the course for some reason other than those that are traditional, as the classes from which the sample was drawn were introductory physics courses.

Discussion of the Influence of Visuospatial Ability

Visuospatial ability, measured in the present study using the Shepard-Metzler Mental Rotations Test, had a regression β of .509 on RFCI scores. In other words, for every unit of increase in participant score on the MRT there was a .5 unit increase on the RFCI.

This impact, coupled with the casual claims of the hypotheses generated from the literature, bears further examination. The paired evolutionary hypotheses of Pinker

(2002) and Dawkins and Wong (2004) are that humans as a species evolved the ability to predict the motion and path of objects subconsciously; this prediction depends upon the use of heuristics that are able to accurately (enough) determine where an object will end up based upon its current motion vector and the forces acting upon it, coupled with the ability to picture that path as it coincides with the surrounding environment. The results of the present study are supportive of at least a portion of the evolutionary hypothesis: learners' visuospatial ability has a direct influence on their ability to answer questions regarding Newtonian forces, regardless of whether or not this ability is being used consciously or is part of a subconscious heuristic. That this influence persists despite differences in demographics also suggests that there is a more universal human experience at work (or at least one that holds true across demographics within the United States) than a learned, naïve cultural explanation of the object motion.

A causal influence of VSA on conceptions of force also serves as an explanatory mechanism for the partial success of employing multiple representations of concepts, and in those interventions that used a primarily visual technology to convey such concepts (Kumaran, Summerfield, Hassabis, & Maguire, 2009; Reiner, 2009; Clark Et al., 2011). In addition, VSA causing changes in RFCI score provides a reason for the shortcomings of numerous interventions in Newtonian mechanics that made use of conceptual change strategies found to be effective in other contexts: employing a refutational text, situated cognition, or even problem-based intervention is ineffective because it does not leverage existing VSA in learners, nor does it mitigate any potential shortfalls that could cause difficulty in learners visualizing the motion of objects in Newtonian terms. Given the information obtained from the present study, and the mild success of Clark and colleagues' work with SEGs in teaching force concepts, it would appear that a fruitful way to proceed in teaching force concepts would be to include instruction that explicitly models changes in object motion due to force visually, combined with scaffolds that allow the students to shed their preconceived ideas of how those forces are acting and the use of pictorial representations by both student and instructor to uncover existing conceptions of force (Reiner, 2009).

Motivation and Conceptions of Force

Prior studies indicated that motivation is a key factor in student learning in general, and specifically in conceptions of force (Taasoobshirazi & Sinatra, 2011). However, the present study found a trivial β coefficient, along with a lack of statistical significance.

Interpreting the regression of the PMQ-II on RFCI scores in light of the results of previous studies suggests that the findings of this study are either anomalous, or should be examined in combination with variables that were excluded from the final analysis. Taasoobshirazi and Sinatra (2011) employed a similar methodology to the present study, and determined that motivation had a profound impact on student learning in physics. However, there are differences between the two studies that may account for the difference in findings. Taasobshirazi and Sinatra (2011) included all five subscales of the PMQ-2 in their analysis, whereas the present study removed two subscales (grade motivation and intrinsic motivation) due to a lack of variability that adversely affected model fit. Furthermore, the Taasoobshirazi and Sinatra (2011) study, rather than using the

RFCI alone as an outcome measure as the present study did, instead used final course grades as both an outcome and predictor variable along with FCI change score. Motivation and final course grade were both demonstrated by the Taasoobshirazi and Sinatra (2011) to have a significant impact (both in terms of p-value and path coefficient) upon FCI change score; the use of final course grade as a predictor for FCI change score, given the causal framework, is questionable. The results of the present study, with significance for the relationship between motivation and RFCI score not noted in either the path coefficient or the p-value, suggest that either motivation covaries with some untested variable, or that motivation has an impact on change in conceptions of force during an intervention but not necessarily on gaining initial understanding of force concepts. Both of these possibilities are reasonable at face value, and require further observational or experimental testing to untangle. It is also possible that the lack of variance in grade motivation and intrinsic motivation in the present sample account for the discrepancy in findings between the current study and Taasoobshirazi and Sinatra (2011).

Evolutionary Hypotheses

The results of the present study contribute to the support for hypotheses regarding an evolved faculty for reasoning about motion and force. Specifically, the separation of reasoning regarding mechanics from demographic influences present in other domains of academic knowledge bolsters the assertion that reasoning regarding force may be universal. Furthermore, the establishment of a strong causal connection between small-scale VSA and Newtonian reasoning supports the assertion that some process other than active reasoning and problem solving is at play. Given the evidence for the evolved nature of spatial reasoning and separability of mental rotations from conscious perspective taking, the findings of the present study are commensurate with the hypothesis that reasoning about force is not a wholly conscious or active process, and imply that the faculty for prediction of object motion may in fact be an evolved heuristic.

Implications

The results of the current study support the notion of a more universal heuristic, conscious or not, that supplants and interferes with Newtonian conceptions of force in learners of various demographics. More importantly, the finding that visuospatial ability exerts a heavy influence on conceptions of force has implications for the types of interventions that should be designed and implemented to teach force concepts, and the teaching of Newtonian concepts in general.

Neuroscience Hypothesis Testing

While the hypothesis drawn from evolutionary psychology, that a subconscious evolved cognitive or neural system is responsible for the ubiquity of misconceptions of Newtonian force, has resisted disproof with the current study, there are behavioral variables, and corresponding neural structures, that need to be examined to accomplish a more complete test of that hypothesis.

If the hypothesis regarding intuitive conceptions operating on a separate neural system from active reasoning proves correct, cognitive control could be a crucial factor in whether or not students are able to apply the scientific conceptions of force and motion over those at which they arrive intuitively (Roser & Gazzaniga, 2004; Stavy, Goel, Critchley, & Dolan 2006). Cognitive control is defined here as a construct that refers to a variety of executive processes including but not limited to task switching, response inhibition, selective attention, and decision-making; in the context of this discussion, cognitive control is used synonymously with response inhibition (Matsumoto & Tanaka, 2004). Response inhibition is the ability of an individual to override an intuitive response (the hypothesized source of the misconception, in this case) in favor of a more effortful, and likely more correct System 2 response (Kahneman, 2003; Roser & Gazzaniga, 2004).

Kowalski and Taylor (2004), in a study of the conceptions of psychology students (similar to a nature of science study), noted that misconceptions were best overcome by those participants who exhibited the greatest general reasoning and critical thinking abilities. Intelligence, as defined by Sternberg (2009), is “the capacity to learn from experience, using metacognitive processes to enhance learning, and the ability to adapt to the surrounding environment.” (p. 530). Since the work of Spearman in the early 1900’s, this trait has been represented as the psychological construct *g*, for the latent trait of general intelligence on which all measures of intelligence load to some extent or another (Sternberg, 2009). Spearman (1927), as interpreted by Sternberg (2009), employed what may be the first factor analysis to determine that intelligence is composed of a general factor that undergirds all reasoning (*g*), and specific sub-factors that are measured only by tests of mental ability which correspond to those sub-factors. In brief, the combination of the results of Kowalski and Taylor (2004) with the history of testing for individual differences in reasoning and intelligence in psychology suggest that intelligence cannot be ignored as a potential causal factor in generating Newtonian conceptions of force, either alone or in combination with affective variables such as motivation.

Following behavioral studies that incorporate the additional variables of cognitive control and intelligence, neuroimaging studies to associate the neural systems active during reasoning about force concepts and compare activations during force reasoning tasks to tasks that recruit systems associated with general reasoning, visuospatial tasks, and response inhibition may be needed to isolate the underlying cause of misconceptions about Newtonian force concepts. However, while this would prove scientifically interesting, changes to pedagogical methods for teaching force concepts can be made through the design and testing of interventions created from behavioral data alone.

New Directions for Interventions in Physics Instruction

Based upon the results of this study, along with the partial success of previous interventions that, intentionally or not, leveraged visualizations to teach force concepts, it is possible to begin constructing more effective means of teaching Newtonian forces than currently employed techniques ranging from direct instruction to student-directed constructivist environments. Given the influence of VSA on learners' holding a Newtonian understanding of forces, any new intervention should employ visualization techniques for two disparate reasons. Firstly, the use of visualizations in the short term may mitigate differences in VSA between learners, which creates more general access across demographics that may be less motivated to take on higher level (university and above) physics instruction due to frustration with learning the material. In addition, the use of visualizations may improve learner understanding of force concepts, which in turn provides a more solid conceptual base on which to construct an in-depth knowledge of physics for students in STEM fields. In the long term, the right intervention may not only mitigate differences in VSA, but could also assist in improving VSA in learners, which in turn may further bolster their conceptual change in Newtonian mechanics, along with other fields that rely in part upon visualization.

Interventions aimed at mitigating differences in VSA, or improving it in the long term, might take the results of Clark and colleagues' (2011) work as a point from which to begin. The use of computer technology, in this case SEGs, allows for more rapid manipulation of physics constants, along with rapid resetting of experiments, and the potential for learners to experience thousands of iterations of motion affected by a specific force concept rather than the few trials possible using hands-on materials. That is not to say that hands-on materials do not have their place in such an intervention; indeed manipulation of real world-materials may be advisable in order for students to transfer knowledge between the game environment and the physical world, rather than thinking that object behaviors only follow Newtonian rules within the context of the game itself. Along with Malone and Malone's (2013) finding that students completing a physics course that employed multi-representational models, the findings of both the present study and that of Clark and colleagues (2011) suggest that the development of a multi-representational, multi-format means of teaching Newtonian forces that includes frequent visual representation of concepts may be necessary to engender greater conceptual change in physics learners. Any such intervention cannot wholly ignore the wealth of knowledge to be gained from examining the literature base on conceptual change, but rather should incorporate the repeated findings of conceptual change studies regarding motivation and scaffolding within its framework. Ideally, a successful intervention in Newtonian mechanics may have to include something that motivates students to learn the material, effective scaffolding of concepts, visual representations of concepts along with multiple representations (algebraic, textual, 2 and 3 dimensional visual/kinesthetic) of the material.

Finally, the results of this study serve to repurpose a debate on conceptual change in physics that has become mired in ontological discussion and explain more complex models of student reasoning based on cognition (Gupta, Hammer, & Redish, 2010). Bao and Redish (2006), for example, noted that students are capable of holding both intuitive and sophisticated (accurate) conceptions of force, which are accessed differently dependent upon context; the results of the present study can explain this in terms of the priming of conscious reasoning over evolved intuitive systems in the contexts in which more learners are able to communicate a Newtonian view of force. As presented by Scherr and Hammer (2009), collaborative learning environments may serve as a means to prime learners to access knowledge of Newtonian conceptions of force. The flaw in Scherr and Hammer (2009) that is addressed through the present study is the sociolinguistic supposition that undergirded their study: in the view of Scherr and Hammer, all learning in physics is framed by the social context and recruits conscious reasoning exclusively. As the results of the present study indicated, learners are able to access conscious reasoning regarding force and motion, and context may well be an important factor, but the cognitive systems in use are not necessarily conscious.

Implications for Practice

Cautiously, the results of the present study stress the importance of using multiple representations of data within the science classroom in order to level the playing field for learners with lower VSA. For example, it appears that it is not adequate to present concepts that leverage object motion through text and two-dimensional diagrams, rather teachers need to employ hands-on experiences, animations, and simulations, coupled with careful scaffolding, to allow students to interact with the concepts. Once more precise interventions are created and tested, these recommendations can be expanded. For example, the modeling curriculum approach (Jackson, Dukerich, & Hestenes, 2008) employs extensive hands-on manipulatives and requires students to justify conclusions based in experimental evidence; the modeling curriculum approach may successfully employ student interaction with the concepts, but as described it fails to scaffold for Newtonian interpretation of results. In brief, while Jackson, Dukerich, and Hestenes (2008) have the beginning of an effective model for instruction consistent with the findings of the present study, their model fails to support students in shifting from an Aristotelian to Newtonian view of force.

The explanation given by Sweller (2008) of Geary (2000) demonstrated that while biologically primary concepts, such as an Aristotelian conception of force and motion, can be learned through simple immersion in the subject, more carefully crafted means of instruction are necessary for biologically secondary concepts (Newtonian force and motion, for example). This is explained in terms of language learning and simple numeracy in young children, wherein repeated exposure to environments rich in the necessary components for such concepts is sufficient to foster learning (Sweller, 2008).

However, the extension of this idea to learning Newtonian physics presents some challenges. According to Geary (in Sweller, 2008), biologically secondary information cannot be learned in the same immersive manner as biologically primary information. While Sweller (2008) uses this to support his own cognitive load theory, this finding also suggests a reason behind the failure of constructivist environments: immersing learners in the components of concepts about force and motion will result in the reinforcement of their misconceptions. Thus, interventions stemming from this work not only need to leverage VSA, but proper scaffolding of the junction between VSA and Newtonian concepts is needed to assist learners in confronting their misconceptions. It would seem to imply that while the reason more traditional means of conceptual change instruction like Broughton and Sinatra's (2010) refutational text fail to correct misconceptions of force is the lack of a visuospatial component, more modern interventions like Clark and colleagues (2011) or Sahin (2010) may well have failed to be as effective as they could have due to an overly constructivist viewpoint that did not incorporate sufficient levels of scaffolding.

Speculatively, a quality intervention designed to teach Newtonian mechanics and employing the findings of the present study should have a visual component, the means to manipulate that visual component, and constant scaffolding to guide learners through the conceptual change process. A Serious Educational Game similar to that of Clark and colleagues (2011) that includes verbal (text and auditory) cues should be able to provide both necessary components while employing different working memory resources and preventing excess cognitive load (Baddeley, 2007; Kirschner, Sweller, & Clark, 2006).

While a technology-based solution like Serious Educational Games is not the only potentially effective means of instruction, it does have the added advantage (over, for example, a hands-on experience with a teacher scaffolding) of being able to individualize instruction for each student at the same time.

In brief, the implications for practice can be summarized as the need to use multiple representations of concepts to leverage VSA, the need to scaffold information effectively rather than rely on immersive teaching methods, and the revelation that effectively meeting these needs is going to require highly individualized instruction, whether directly by the teacher, a peer, or a technology designed specifically for that purpose.

Conclusions

In summary, the present study examined the relationships among visuospatial ability, learner motivation to learn science, and learner conceptions of force across commonly measured demographics in undergraduate physics education. The results indicated that while motivation and demographics did not have a statistically or practically significant influence on conceptions of Newtonian mechanics, participants' visuospatial ability exerted a strong (β=.509) causal influence on RFCI scores. Finding that visuospatial ability impacts learner conceptions of force contributes explanatory and predictive power to the literature on conceptual change in physics, but a more complete study that includes individual differences in intelligence and response inhibition is needed to better frame these findings, and to reconcile the differences in findings between this study and prior studies with regards to motivation.

The fundamental implication of the results of this study is the need to include tasks that leverage and develop visuospatial ability in interventions aimed at teaching Newtonian conceptions of force, as well as the inclusion of multiple representations including visualizations in any such intervention. However, these findings are somewhat limited in that the sample was drawn from university undergraduates and testing for continuity of findings with younger learners has not been undertaken. That the study findings were consistent across the measured demographics and the age range of all participants (18-43) spanning from late adolescence into adulthood aids the generalizability of the findings to other populations of post-secondary learners. Addressing the limitations in terms of unexamined variables and age ranges will only serve to expand the usefulness of these findings, and move us towards more effective instruction in introductory physics.

Appendices

Appendix A: Mplus Code

Mplus VERSION 7

MUTHEN & MUTHEN

03/26/2013 2:01 PM

INPUT INSTRUCTIONS

```
TITLE: Newtonian Reasoning
DATA: FILE IS finad2.dat;
VARIABLE: NAMES ARE y1-y7;
USEVARIABLES ARE y2-y4 y6 y7;

MODEL:
F1 BY y2-y4;
F1 ON y6;
y7 ON y6;

F1 WITH y7;
```

Appendix B: SMQII

SCIENCE MOTIVATION QUESTIONNAIRE II (SMQ-II)

In order to better understand what you think and how you feel about your science courses, please respond to each of the following statements from the perspective of "When I am in a science course…"

Statements	Never 0	Rarely 1	Sometimes 2	Often 3	Always 4
01. The science I learn is relevant to my life.					
02. I like to do better than other students on science tests.					
03. Learning science is interesting.					
04. Getting a good science grade is important to me.					
05. I put enough effort into learning science.					
06. I use strategies to learn science well.					
07. Learning science will help me get a good job.					
08. It is important that I get an "A" in science.					
09. I am confident I will do well on science tests.					
10. Knowing science will give me a career advantage.					
11. I spend a lot of time learning science.					
12. Learning science makes my life more meaningful.					
13. Understanding science will benefit me in my career.					
14. I am confident I will do well on science labs and projects.					
15. I believe I can master science knowledge and skills.					
16. I prepare well for science tests and labs.					
17. I am curious about discoveries in science.					
18. I believe I can earn a grade of "A" in science.					
19. I enjoy learning science.					
20. I think about the grade I will get in science.					
21. I am sure I can understand science.					
22. I study hard to learn science.					
23. My career will involve science.					
24. Scoring high on science tests and labs matters to me.					
25. I will use science problem-solving skills in my career.					

Appendix C: RFCI

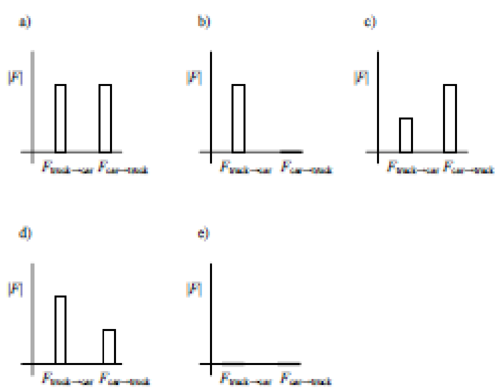
1. Two metal balls are the same size but one has mass twice as large as the other. The balls are dropped from the roof of a single story building at the same instant of time. The time it takes the balls to reach the ground below will be:

   a) about half as long for the heavier ball as for the lighter one.
   b) about half as long for the lighter ball as for the heavier one.
   c) about the same for both balls.
   d) considerably less for the heavier ball, but not necessarily half as long.
   e) considerably less for the lighter ball, but not necessarily half as long.

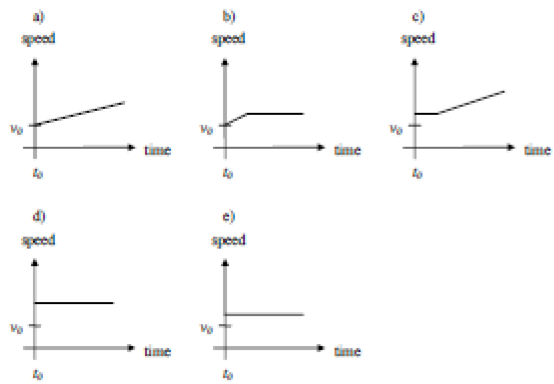
2. A large truck collides head-on with a small compact car.

   Let us denote the force exerted by the truck on the compact car as $F_{truck \to car}$ and the force exerted by the compact car on the truck as $F_{car \to truck}$.

   Which of the following alternatives best describes the magnitude of the average forces $|F|$ exerted on the truck and the compact car during the collision?

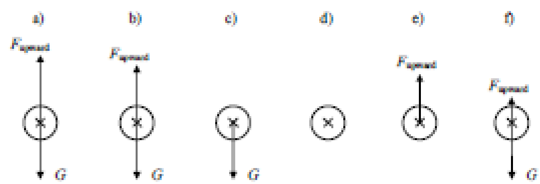


3. A woman exerts a constant horizontal force on a large box. As a result, the box moves across a horizontal floor at a constant speed v_0. At the instant of time t_0 the woman doubles the horizontal force that she exerts on the box to push it on the same horizontal floor. Which of the following alternatives best describes the speed of the box?



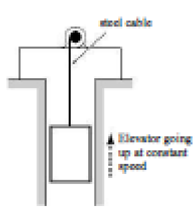
4. A boy throws a steel ball straight up. Assume that forces exerted by the air are negligible. Which alternative from a) – f) best describes the forces acting on the ball in the following situations?

i) The ball has left the boy's hand and is still ascending.
ii) The ball is at its highest point.
iii) The ball is descending but it has not yet hit the ground.



G = force of gravity
F_{upward} = upward force of the throw

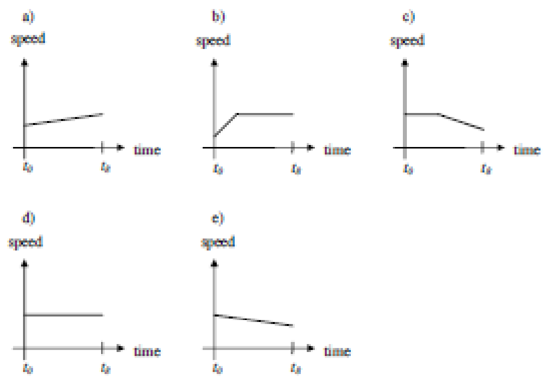
5. An elevator is being lifted up an elevator shaft at a constant speed by a steel cable as shown in the figure. All frictional effects are negligible. In this situation, forces on the elevator are such that:



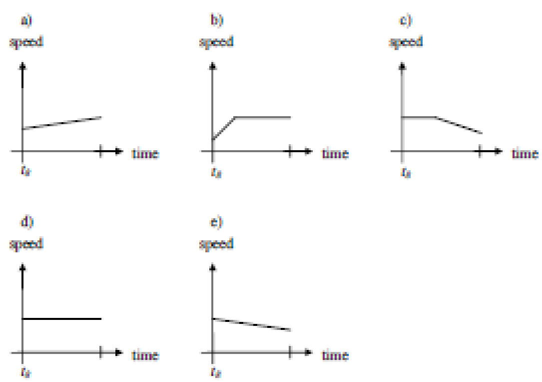
a) the upward force by the cable is greater than the downward force of gravity.
b) the upward force by the cable is equal to the downward force of gravity.
c) the upward force by the cable is smaller than the downward force of gravity.
d) the upward force by the cable is greater than the sum of the downward force of gravity and a downward force due to the air.
e) none of the above. (The elevator goes up because the cable is shortened, not because an upward force is exerted on the elevator by the cable.)

6. A spaceship drifts in outer space. The spaceship is subject to no outside forces. At the instant of time t_0, the spaceship's engine is turned on and produces a constant force on the spaceship. The force is in the direction of the motion. At the instant of time t_E, the spaceship's engine is turned off.

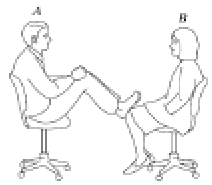
Which of the following alternatives best describes the speed of the spaceship in the time interval $t_0 - t_E$?



7. In the previous question, the spaceship's engine is turned off at the instant of time t_E. Which of the following alternatives best describes the speed of the spaceship after time t_E?



8. In the figure at right, student A has a mass of 75 kg and student B has a mass of 57 kg. They sit in identical office chairs facing each other. Student A places his bare feet on the knees of student B, as shown. Student A then suddenly pushes outward with his feet, causing both chairs to move.

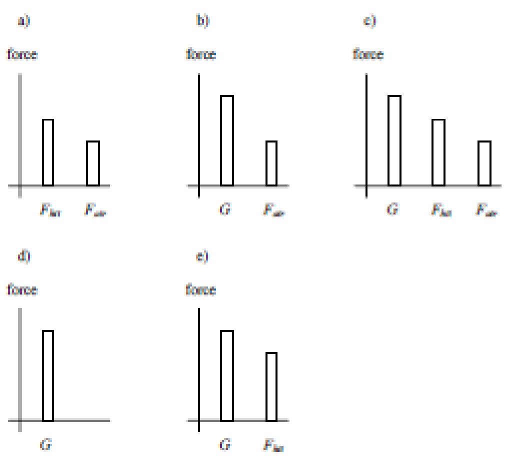


During the push and while the students are still touching one another:

a) neither student exerts force on the other.
b) student A exerts a force on student B, but B does not exert any force on A.
c) each student exerts a force on the other, but B exerts the larger force.
d) each student exerts a force on the other, but A exerts the larger force.
e) each student exerts the same amount of force on each other.

9. Despite a very strong wind, a tennis player manages to hit a tennis ball with her racquet so that the ball passes over the net and lands in her opponent's court.

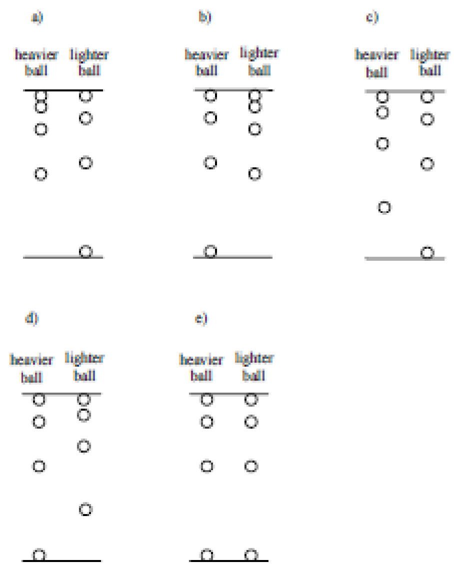
Which of the following alternatives best describes the magnitude of the forces acting on the tennis ball in an instant of time after it has left contact with the racquet and before it touches the ground?



G = force of gravity
F_{air} = force exerted by the air
F_{hit} = force by the hit

10. Two metal balls are the same size but one has mass twice as large as the other. The balls are dropped from the roof of a single story building at the same instant of time.

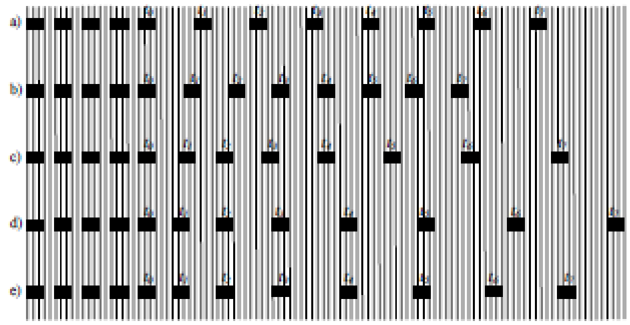
During the fall a photograph is taken from both balls at the same instant of time and again after a short time interval four times altogether. Which of the following alternatives best describes the fall of the balls from the top of the building to the ground?



11. A large truck collides head-on with a small compact car. During the collision:

a) the truck exerts a greater amount of force on the car than the car exerts on the truck.
b) the car exerts a greater amount of force on the truck than the truck exerts on the car.
c) neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck.
d) the truck exerts a force on the car but the car does not exert a force on the truck.
e) the truck exerts the same amount of force on the car as the car exerts on the truck.

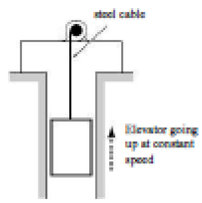
12. A woman exerts a constant horizontal force on a large box. As a result, the box moves across a horizontal floor at a constant speed v_0. At the instant of time t_0 the woman doubles the horizontal force that she exerts on the box to push it on the same horizontal floor. A photograph is taken from the box at even time intervals from t_0 to t_7. Which of the following alternatives best describes the speed of the box in the time interval $t_0 - t_7$?

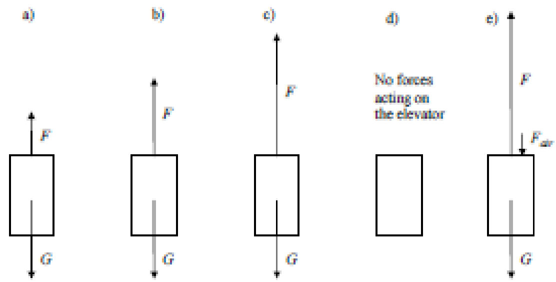


13. A boy throws a steel ball straight up. Consider the motion of the ball only after it has left the boy's hand but before it touches the ground, and assume that forces exerted by the air are negligible. For these conditions, the force(s) acting on the ball is (are):

a) a downward force of gravity along with a steadily decreasing upward force.
b) a steadily decreasing upward force from the moment it leaves the boy's hand until it reaches its highest point; on the way down there is a steadily increasing downward force of gravity as the object gets closer to the earth.
c) an almost constant downward force of gravity along with an upward force that steadily decreases until the ball reaches its highest point; on the way down there is only a constant downward force of gravity.
d) an almost constant downward force of gravity only.
e) none of the above. The ball falls back to ground because of its natural tendency to rest on the surface of the earth.

14. An elevator is being lifted up an elevator shaft at a constant speed by a steel cable as shown in the figure. All frictional effects are negligible. Which of the following alternatives best describes the forces in this situation?





F = the force exerted by the steel cable
F_{air} = the force due to the air
G = gravitational force

15. A spaceship drifts in outer space. The spaceship is subject to no outside forces. At the instant of time t_0, the spaceship's engine is turned on and produces a constant force on the spaceship. The force is in the direction of the motion. At the instant of time t_e, the spaceship's engine is turned off.

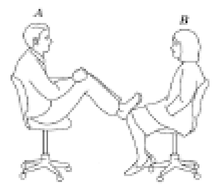
During the time interval $t_0 - t_e$ the speed of the spaceship is:

a) constant for a while and decreasing thereafter.
b) increasing for a while and constant thereafter.
c) continuously decreasing.
d) continuously increasing.
e) constant.

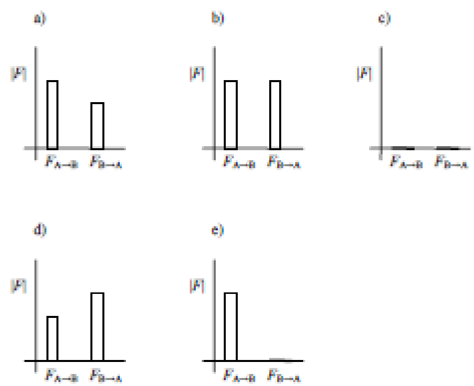
16. In the previous question, the spaceship's engine is turned off at the instant of time t_e. After this the speed of the spaceship is:

a) constant for a while and decreasing thereafter.
b) increasing for a while and constant thereafter.
c) continuously decreasing.
d) continuously increasing.
e) constant.

17. In the figure at right, student A has a mass of 75 kg and student B has a mass of 57 kg. They sit in identical office chairs facing each other. Student A places his bare feet on the knees of student B, as shown. Student A then suddenly pushes outward with his feet, causing both chairs to move.

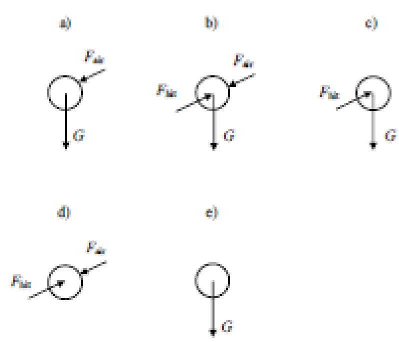


Let us denote the force exerted by student A on student B as $F_{A\to B}$ and the force exerted by student B on student A as $F_{B\to A}$. Which of the following alternatives best describes the magnitude of the average forces $|F|$ exerted on the students A and B?



18. Despite a very strong wind, a tennis player manages to hit a tennis ball with her racquet so that the ball passes over the net and lands in her opponent's court.

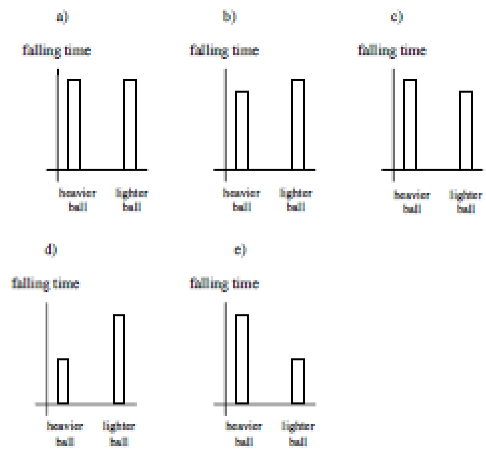
Which of the following alternatives best describes forces acting on the tennis ball in an instant of time after it has left contact with the racquet and before it touches the ground?



G = force of gravity
F_{air} = force exerted by the air
F_{hit} = force by the hit

19. Two metal balls are the same size but one has mass twice as large as the other. The balls are dropped from the roof of a single story building at the same instant of time.

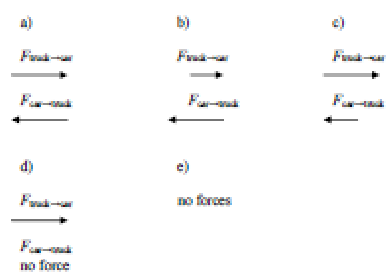
Which of the following alternatives best describes the falling times of the two metal balls?



20. A large truck collides head-on with a small compact car.

Let us denote the force exerted by the truck on the compact car as $F_{truck \to car}$ and the force exerted by the compact car on the truck as $F_{car \to truck}$.

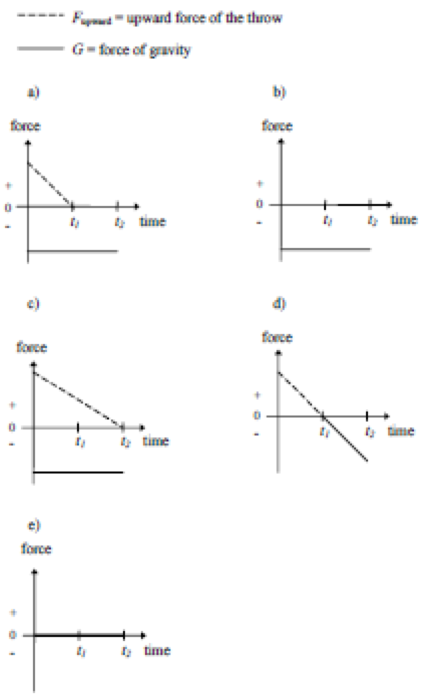
Which of the following alternatives best describes the average forces exerted on the truck and the compact car during the collision?



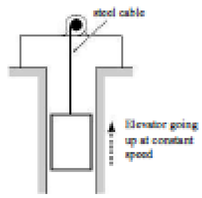
21. A woman exerts a constant horizontal force on a large box. As a result, the box moves across a horizontal floor at a constant speed v_0. If the woman doubles the horizontal force that she exerts on the box to push it on the same horizontal floor, the box then moves:

a) for a while with a constant speed that is greater than the speed v_0, then with a speed that increases thereafter.
b) for a while with an increasing speed, then with a constant speed thereafter.
c) with a continuously increasing speed.
d) with a constant speed that is greater than the speed v_0, but not necessarily twice as great.
e) with a constant speed that is double the speed v_0.

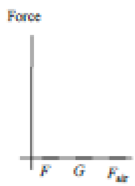
22. A boy throws a steel ball straight up. Consider the motion of the ball only after it has left the boy's hand but before it touches the ground, and assume that forces exerted by the air are negligible. At instant of time t_1 the ball is at its highest point and at instant of time t_2 the ball hits the ground. For these conditions, what alternative best describes the force(s) acting on the ball?



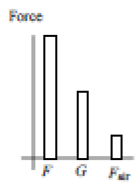
23. An elevator is being lifted up an elevator shaft at a constant speed by a steel cable as shown in the figure. All frictional effects are negligible. Which of the following describes the forces in this situation?



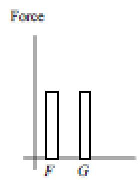
a)



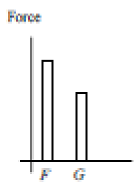
b)



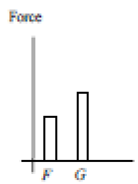
c)



d)



e)



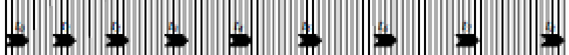
F = the force exerted by the steel cable
F_{air} = the force due to the air
G = gravitational force

24. A spaceship drifts in outer space. The spaceship is subject to no outside forces. At the instant of time t_0, the spaceship's engine is turned on and produces a constant force on the spaceship. The force is in the direction of the motion. At the instant of time t_8, the spaceship's engine is turned off.

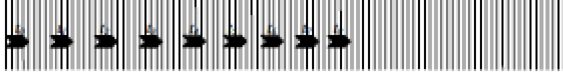
A photograph is taken from the spaceship at even time intervals from t_0 to t_8. Which of the following alternatives best describes the speed of the spaceship in the time interval $t_0 - t_8$?

a) 

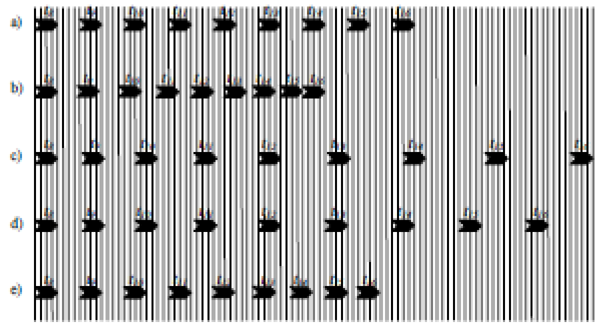
b) 

c) 

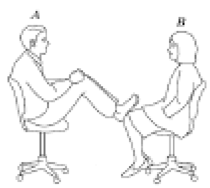
d) 

e) 

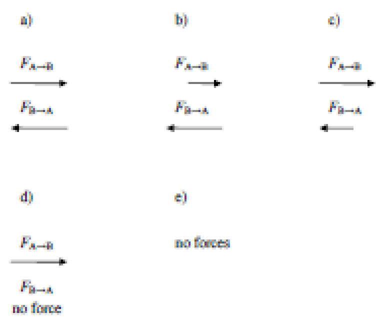
25. In the previous question, the spaceship's engine is turned off at the instant of time t_8. A photograph is taken from the spaceship at even time intervals from t_8 to t_{16}. Which of the following alternatives best describes the speed of the spaceship after time t_8 (i.e., after the engine is turned off)?



26. In the figure at right, student A has a mass of 75 kg and student B has a mass of 57 kg. They sit in identical office chairs facing each other. Student A places his bare feet on the knees of student B, as shown. Student A then suddenly pushes outward with his feet, causing both chairs to move.



Let us denote the force exerted by student A on student B as $F_{A\to B}$ and the force exerted by student B on student A as $F_{B\to A}$. Which of the following alternatives best describes the average forces exerted on the students A and B?

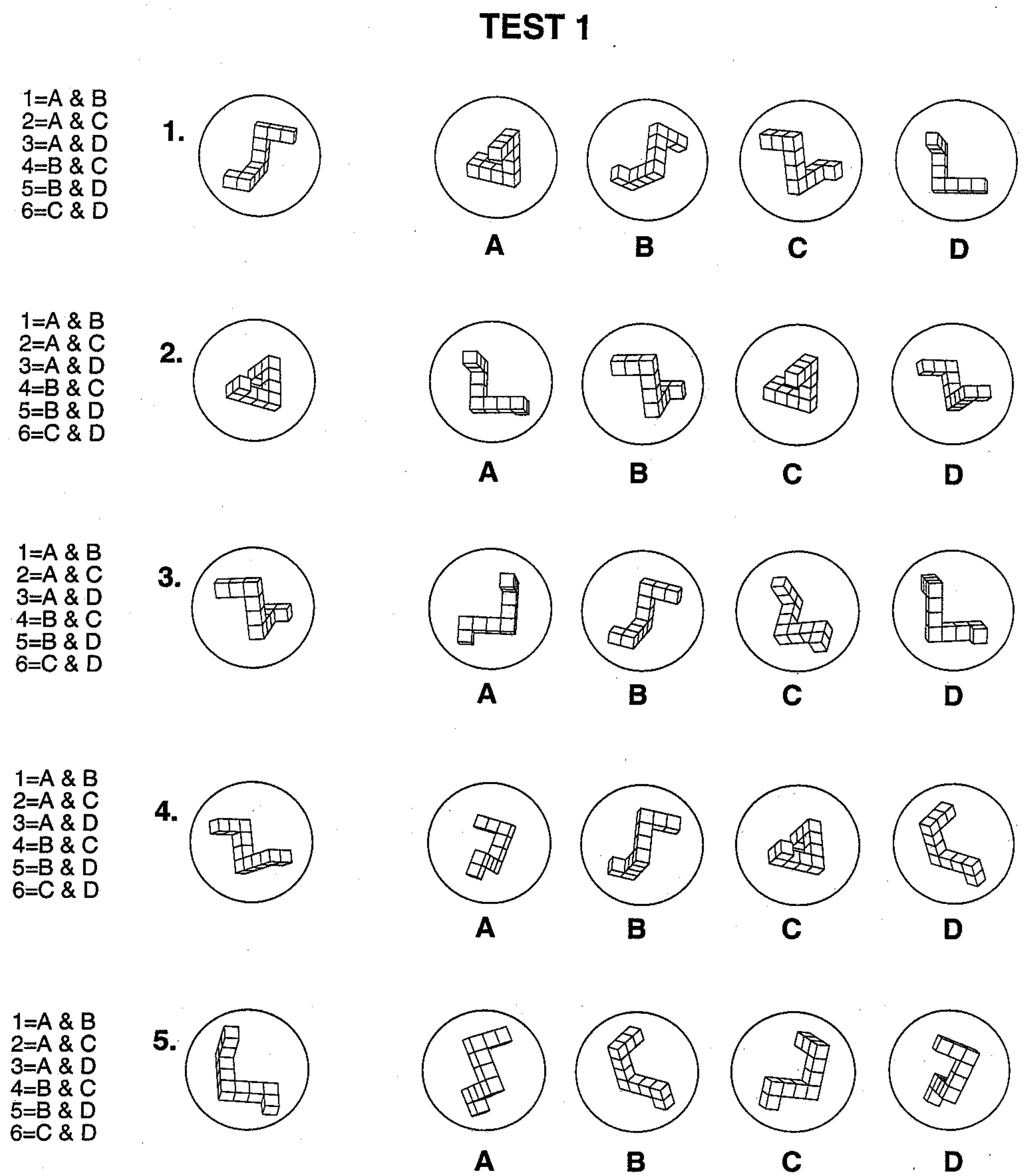


27. Despite a very strong wind, a tennis player manages to hit a tennis ball with her racquet so that the ball passes over the net and lands in her opponent's court.

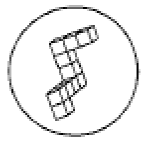
Which of the following forces is (are) acting on the tennis ball after it has left contact with the racquet and before it touches the ground?

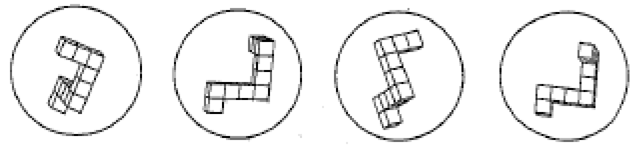
a) only a downward force of the gravity
b) a downward force of the gravity and a force by the "hit"
c) a downward force of the gravity and a force exerted by the air
d) a force by the "hit" and a force exerted by the air
e) a downward force of the gravity, a force by the "hit" and a force exerted by the air

Appendix D: Mental Rotations



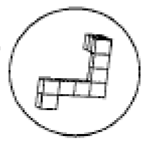
1=A & B
2=A & C
3=A & D
4=B & C
5=B & D
6=C & D

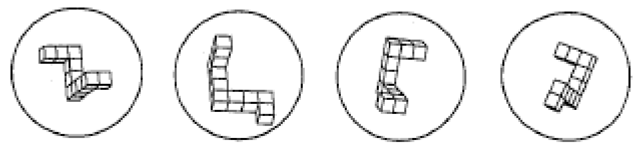
6. 



A B C D

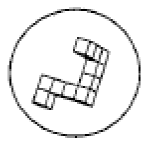
1=A & B
2=A & C
3=A & D
4=B & C
5=B & D
6=C & D

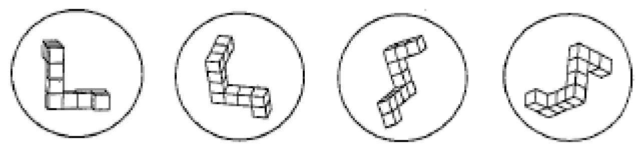
7. 



A B C D

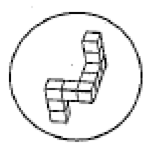
1=A & B
2=A & C
3=A & D
4=B & C
5=B & D
6=C & D

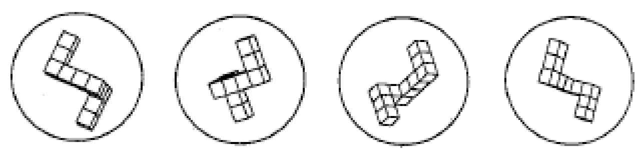
8. 



A B C D

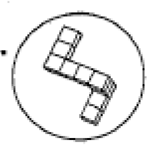
1=A & B
2=A & C
3=A & D
4=B & C
5=B & D
6=C & D

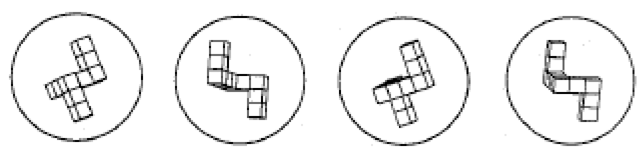
9. 



A B C D

1=A & B
2=A & C
3=A & D
4=B & C
5=B & D
6=C & D

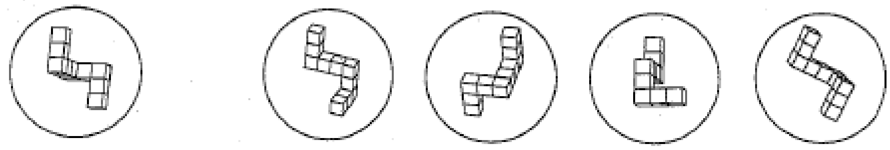
10. 



A B C D

1=A & B
2=A & C
3=A & D
4=B & C
5=B & D
6=C & D

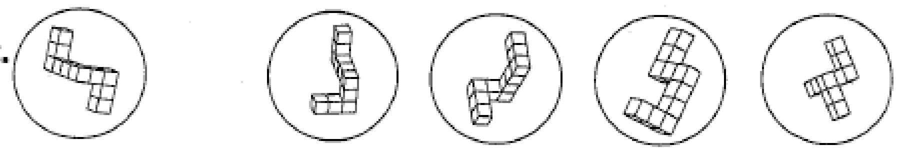
11.



A **B** **C** **D**

1=A & B
2=A & C
3=A & D
4=B & C
5=B & D
6=C & D

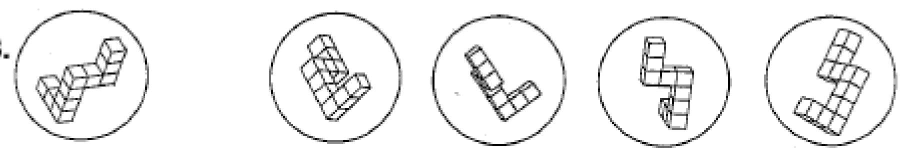
12.



A **B** **C** **D**

1=A & B
2=A & C
3=A & D
4=B & C
5=B & D
6=C & D

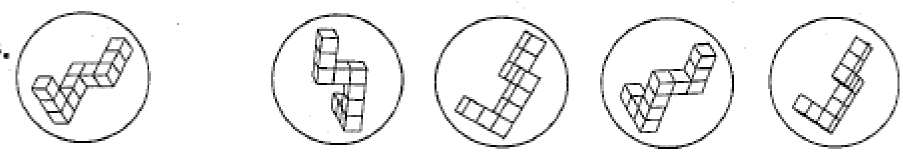
13.



A **B** **C** **D**

1=A & B
2=A & C
3=A & D
4=B & C
5=B & D
6=C & D

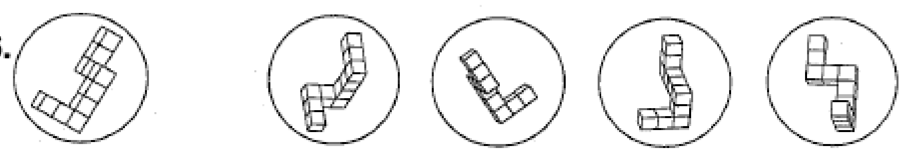
14.



A **B** **C** **D**

1=A & B
2=A & C
3=A & D
4=B & C
5=B & D
6=C & D

15.



A **B** **C** **D**

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Biography

David Bruce Vallett graduated from Williamsville North High School, Williamsville, New York in 1996. He received his Bachelor of Arts from the University of North Carolina Wilmington in 2000. He was employed as a teacher in Brunswick County (North Carolina) for four years, Wake County (North Carolina) for three years, and received his Master of Arts in Teaching (Science) from the University of North Carolina Wilmington in 2007.