Science Teachers' Conceptual Understanding of a Critical Rationalist Stance in Science and a Proposed Learning Module to Enhance Their Professional Knowledge

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Submitted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
under the Executive Committee
of the Graduate School of Arts and Sciences

COLUMBIA UNIVERSITY

2015

ABSTRACT

SCIENCE TEACHERS' CONCEPTUAL UNDERSTANDING OF A CRITICAL RATIONALIST STANCE IN SCIENCE AND A PROPOSED LEARNING MODULE TO ENHANCE THEIR PROFESSIONAL KNOWLEDGE

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The history of science is rich in examples of the importance of theories and hypotheses. Among the various disciplines of science, theories and hypotheses have been important in guiding research, including such large ideas as the atomic theory, theory of evolution, laws of motion in physics, and plate tectonics. One of the major ways science progresses is to gather evidence in relation to theories and hypotheses and to refine our explanations of how natural events occur both at very small scales of space and time or at the level of the universe. This dissertation research focused on understanding science teachers' conceptual models about theories, and the use of corroborating evidence based on a critical rationalist stance in science. The study explored a sample of science teachers' level of understanding of critical rationalism, and issues in modeling science within a ‘critical rationalist’, post-positivist framework. During the initial phase of the research, a pilot study was done to gather contextual evidence obtained from a sample of teachers’ views on the nature of science (NOS) who responded to an online questionnaire. Subsequently, a more comprehensive study based on the findings from this initial pilot study was done. In the subsequent more comprehensive study, an online learning module on NOS, containing core concepts within a critical rational stance, was presented to a second sample

of pre- and in-service teachers. This module specifically focused on how theories are initiated and rigorously tested under the highest risk conditions within a critical rationalist model. It also explained why this is a more productive approach than an exclusively verificationist cognitive framework underlying some logical positivist approaches. The results of a pretest, and post-test assessment, following the completion of the online learning module, provided robust evidence that the teachers who initially demonstrated significantly weak understandings of a critical rational stance improved to a level where they reached a preset benchmark level of accomplishment established by the researcher prior to the online intervention. The pretest results of the comprehensive study also aligned well with the results of the pilot study. That is, science teachers' pre-learning views on scientific theories and experimentation fall mostly within inductive verification-based models, more closely aligned with a positivistic worldview, outside of a contemporary critical rationalist view of a hypothetico-deductive or falsification approach. In this study, a convenient and reliable method of online learning and associated assessment instruments regarding critical rationalist understanding of NOS is presented and evaluated. The evaluation of the pre- and post-learning assessments, and analyses of questionnaire responses by the participants, showed that the use of the online learning module significantly improved science teachers' cognitive understandings of the nature of science, and that the learners generally reported favorable responses about the learning experiences based on quantitative and qualitative evidence. Based on this initial evidence, the online learning module and related assessment instruments appear to be a valuable resource for assessing teacher understanding of a modern critical rational view of science, and as a potentially productive way to introduce pre-service and in-service teachers to these modern views of NOS through application of the online learning module.

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ACKNOWLEDGEMENTS

First and foremost I am ever thankful to my thesis and research advisor, Professor O. Roger Anderson. He inspired me with his guidance and this research would not have been possible without his brilliance and patience. I am thankful to my thesis committee who generously gave their time for the review. I also want to thank the external science education expert panel and the participants. In particular, a special note of thanks goes to Dr. Fernand Brunschwig for helping me with reaching out to PhysicsTeachersNYC organization at a most crucial stage of my experimentation.

Many others helped me in this long journey over many years throughout my education. I am most grateful to my family, especially to my aunt G.D.L. Dassanayaka and my uncle D.D.M. Karaputugala for the wonderful parental roles they played, and also to my mother G.A. Dassanayaka, who nurtured my academic focus in those early years – without this foundation and their love, none of this work would have been ever imaginable. I am thankful to my grandmother P.M. Jayasekara for her influencing role in providing a creative inspiring environment, and my father W.A.H. Wijesooriya who gave me a unique 'only one of its kind experience' – early exposure and an opportunity for intellectual discourse in science and western philosophy, which helped foster my interests in scientific thought, art, creative imagination and rational thinking; it definitely crafted a shift in my worldview at a very young age. Among many excellent teachers, I must thank Mr. P.D.N. Dayananda for his extraordinary role, who nurtured my childhood enthusiasm and a passion for search in a scientific worldview. I am most fortunate to have my wife Keiko's caring support, who cheered, loved, encouraged and helped me cross this finish line throughout these hard years, and of course my little children Saya and Kai who gave me a joy and comfort during the difficult stage of final writing.

DEDICATION

To my mother Ambrosia Dassanayaka & my aunt Luxsmi Dassanayaka

for our time together

Chapter I

INTRODUCTION

Statement of Purpose

In this dissertation research, the focus was on understanding science teachers' perceptions of the nature of science (NOS) in relation to a critical rational stance (CRS), and consequently to create a teacher learning module to improve science teachers' critical rationalist perspectives of the nature of science. Briefly, CRS is a post-positivistic perspective on NOS that emphasizes rigorously testing the accuracy of scientific theories and hypotheses based on falsifiable evidence as opposed to a more inductive logically positivistic approach that largely emphasizes verification. Prior (largely preliminary) published research has focused on finding whether the beliefs, cognitive models and attitudes of science teachers are consonant with the principles underlying some currently accepted models of NOS. The specific focus of this dissertation research has been on assessing the teachers' level of understanding of a critical rationalist stance in science, notably including the importance of the falsifiability criterion of scientific inquiry. As a consequence of the contextual evidence gathered from the feasibility study, the researcher proposed and developed an instructional module to enhance the teachers' awareness of specific fundamental implications of a critical rationalist viewpoint. The extent of understanding of testability of scientific theories by the science teachers, as a rigorous effort towards falsification as compared to verification, and their in-depth comprehension of the implications of such nature of science understanding was assessed in the research by applying a rationally and critically discussed and agreed upon definition of the nature of science. In constructing such a definition, a thorough analysis of contemporary viewpoints on the nature of science, its philosophy and the most rigorous methodology in modern practices of science were examined and taken into account. This included viewpoints of eminent modern scientists and philosophers of science such as Feynman, Hawking, Gould and Karl Popper.

The researcher proposed that science teachers' modern understanding of the nature of science should be evaluated against this thorough understanding of the nature of science within a critical rationalist perspective. A thorough understanding of critical rationalist perspectives may help science teachers to be more effective in demarcating science from non-science, and as a consequence, avoid unfruitful approaches to science teaching that often mitigate students' understanding of the fundamental principles of modern practices of science. This assessment effort, based on questionnaire responses by a sample of in-service teachers, also provided evidence, of some of the erroneous or non-scientific explanations that teachers possess, and no doubt may share with their students during their teaching. An analysis of the science teacher's ability to view science within a "Critical Rationalist Stance," and thus to more clearly demarcate science from non-science, could be an important criterion for assessing the effectiveness of science teacher education. This is especially relevant given an ever increasing demand for teachers to use inquiry approaches, valid methods of argumentation based on evidence, and a thorough knowledge of modern practices of science in their planning and delivery of science lessons (National Research Council, 2013).

Central Ideas of Critical Rational Stance

Critical Rational Stance provides a structure for reasoning, an essential foundation for science, across all disciplines of natural sciences and beyond such as the fields of engineering and medicine. It is the epistemological framework of modern science addressing what constitutes reliable and valid knowledge, recognizing human imagination as the paramount creative origins of our thinking and reasoning in understanding the Universe. CRS underlying structure of reasoning emphasizes the need for critical examination of our theoretical explanations of the Universe or a part of the Universe. CRS necessitates that our creatively imagined new explanations should be highly general and make definite testable new predictions. Especially, the explanations should yield new predictions that are potentially capable of being refuted, not only supported by positive evidence. A good theory must clearly guide our thinking towards what new evidence would potentially refute it, if the predicted new observation is absent in nature. To illustrate this structure of reasoning, for example, analytical prediction of a new planet by Urbain Le Verrier before it was directly observed led to the sensational discovery of Neptune. Verrier was known as a scientist who “discovered a planet with the point of his pen.” First observers of Neptune, Johann Gottfired Galle and Heinrich Louis d’Arrest, made the discovery relying on the predicted position, i.e. theoretical calculations of Verrier who considered the aberrations in the path of Uranus and the theory of Newtonian Gravitation. This calculation of mass and orbital path of an entirely new planet positioned Newtonian Gravitation at the risk of refutation as is required by a CRS perspective for hypothesis testing. If the predicted new planet (observation) was absent in nature, this definite and previously unobserved prediction would have refuted the theory of gravitation, then, it could have required modification or search for a new theory. This type of careful analytical risking of a theory via daring and stringent falsifiable predictions is an essential aspect of modern scientific inquiry. CRS structure of scientific knowledge, creating new explanations and attempting to risk and disprove them, is a contrasting approach to a major dependence only on already known evidence that verifies the theory, as contained in most logical positivistic views about science. It is also an important point that teachers need to emphasize more fully when teaching science as inquiry and addressing students’ misconceptions.

Organization of the Thesis

This first chapter provides an overview of the purposes of the research study and establishes a context for the research in summary. In the Second Chapter an overview of the research is presented including a relevant review of the literature, and a broad perspective on the philosophical and pedagogical rationales for the study. Chapter III contains a general overview of the methods of the research, and provides a context for the more specific report of the methodology used in each study presented in the Results chapters. The Results are presented as two publishable papers chapters IV and V, representing the Results section of the thesis, in keeping with current policies of the Graduate School of Arts and Sciences for scientific and cognate theses at Columbia University.

The first study (Chapter IV) reports the results of an initial feasibility or pilot study. During the feasibility phase of the research, the pilot study provided valuable contextual evidence of a sample of teachers' current understanding of a critical rational stance. This assessment involved fifty in-service physics teachers. It also provided evidence if the strategy and instruments developed for the research plan were feasible. Moreover, this pilot phase allowed the researcher to obtain evidence of the reliability of the measurement instruments to be used subsequently in a more comprehensive study where an online learning module was developed and presented to a second sample of teachers. The results of implementing this module are presented in the second publishable paper (Chapter V). This module provided a concise introduction to the principles of modern science practices from a critical rational perspective. It also included a pretest and post-test to determine gains in understanding of the critical rational stance by the teachers. Quantitative and qualitative evidence is presented supporting the conclusion that the online learning module can be successfully used with preservice and in-service teachers to enhance their understanding of NOS from a modern critical rationalist perspective. The Discussion (Chapter VI) provides a reflective perspective on the findings from the Results chapters and includes a cross-cutting analysis and synthesis of the findings presented in the two papers presented in the Results section.

Chapter II

OVERVIEW

Review of the Literature and Related Research

Given the significant questions confronting science educators about what should be included in science teaching and what our future citizens should know about science, it is essential to consider a clear definition of the nature of science. Within this section, a definition of science is presented that collectively draws from the writings of some modern, selected authors. Among these are:, Stephen Hawking (1988), Carl Hempel (1966), Henry Margenau (1977), Charles S. Peirce (1994), Michael Polanyi (1958), Karl Popper (1992), David Hume (1900), Stephen Toulmin (2001), Albert Einstein (1936), Richard Feynman (1965b), Ludwig Wittgenstein (2001) Bunge (1964) etc. Recent research within contemporary Philosophy of Science by Miller (1994), Agassi and Jarvie (1987) , Radnitzky, Bartley, and Popper (1987) and Lakatos (1976) provides a strengthening case of this epistemology discourse and further consolidates the influence of critical rationalism in the nature of science. The discussion presented here is from a natural science perspective and based on contemporary philosophical standpoints that are consistent with modern practices of science and the canonical views of the nature of science as a way of knowing, where theories and hypotheses are critically examined based on evidence gathered from the natural environment. These views include definitions of science as a way of knowing based on theory, but also rooted in the use of evidence from the natural environment as means of explaining natural phenomena. It is also important to note that the definition of scientific methodology adopted in this study is closely aligned with the characterization assumed by the U.S. Supreme Court in the landmark case, Daubert v. Merrell

Dow Pharmaceuticals, Inc., 509 U.S. 579, 593 (1993), and consonant with the recommendations in the Next Generation Science Standards (National Research Council, 2013). This section will also discuss certain consensus perspectives among leading science educators and researchers, with particular reference to education researchers concerned with the Nature of Science: e.g., Fouad Abd-El-Khalick (2000), Richard Duschl (1990), Norman Lederman (1992), etc. It includes recommendations for good science education practice presented by these educators and researchers. Within science education research, however, there are only a few publications directly addressing critical rational stance. Some selected science education research authors who discussed CRS include: Adúriz-Bravo (2013), Blackie (2012), Erduran and Dagher (2014) and Matthews (1998). This review also provides references to the existing definitions recommended by authorities in science education and the position papers of the National Academy of Science on the Nature of Science. This characterization of scientific methodology is based on selected works that the author found most compelling and informative. Consequently, the theoretical framework represents a particular view that arises from the writer's analysis and findings of the Nature of Science as gleaned from the selected sources.

To have a clear view of Nature of Science, it is important to clearly understand how the scientific inquiry originates and progresses. Even among the scientific community, some consider that observations lead to conclusions, arriving at scientific theories, while others oppose this view saying that observations cannot arise alone without a theoretical model, a set of rules, to begin with. This section of the paper attempts to address the confusion and provide an account of how scientific thought process progresses.

Scientific Inquiry in many cases begins when an inquirer chooses a question. This occurs initially as a part of the human experience of nature based existing theoretical understandings.

During the initial stages, the inquirer may evaluate potential elementary explanations as answers to a question by observing the phenomena with the five senses in combination with the process of intellection in the brain. Sensation and the intellectual synthesis of percepts with prior knowledge are brain functions that help us to construct meanings of experience. Intellection is the process of using the human mind to consider these percepts carefully and creating a set of rules or a model that can be described as "conceptual modeling". This type of conceptual modeling is common to all forms of human inquiry. Some of these conceptual models involve describing of events in nature and some other models may be developed through imagination and non-natural phenomena that people learn outside the natural experience. These can be various models involving historical accounts, enforced belief systems, religion, art and music.

Science specifically progresses by creating hypotheses and testing them based on a given set of rules described, in part, within the hypothesis. Hypotheses are educated guesses, often stated by a careful logical deductive derivation from theory (a hypothetico-deductive process) about what the answer might be to the question framed by the investigator. These hypotheses also need to be formulated as a statement of prediction of some kind related to natural events. Some thinkers would say that science always begins with some conceptual model of varying sophistication that guides observation, question formulation and hence occasions the hypothesis(es). It is important to recognize that hypotheses do not simply arise de novo, even directly from observations – since observations do not occur on a blank slate. Given that observations and predictions are grounded in existing frames of reference or mental models, the process of making observations and forming hypotheses has been called "abduction" by some researchers, who also claim, therefore, that there can be no true process of "induction" as any given observation is made in relation to a specific cognitive construct.

Therefore, science begins with some form of hypothesis (Feynman, 1965a). This hypothesis may or may not be based on previous theory as stated above. Often, scientists tend to start from some kind of previous theory, scientifically valid or otherwise. The progress of science depends on the procedures used at the testing of the hypothesis. Michael Polanyi (1958) has been attributed as saying “Science is an interrogation of nature but nature can only respond in the way the question is asked.” Nature leaves much information hidden until questioned by an experiment designed to elucidate it. If a question is asked by the inquirer, for example, is the molecular structure of DNA a sphere; then, an experiment designed for this may show that it is not. On the other hand that particular experiment will not show that it is a double helix, either. While we have a clear consensus on the methodology to do hypothesis testing, the process of arriving at the original question and developing a hypothesis is influenced by human creativity, imagination, curiosity and personal experiences of the investigator. This is an important issue that will be discussed in detail in this dissertation.

General Research Questions

1. To what extent does a sample of teachers possess some of the most desirable understandings within a Critical Rational Stance, and what are the present understandings that the teachers have about the nature of science in relation to a critical rationalist approach?
2. What are the present conceptual models that the science teachers have about the nature of science in relation to a critical rationalist approach?
3. Can science teachers' understandings of the nature of science be enhanced through using an e-learning module designed to improve their knowledge of a critical rationalist viewpoint?
4. How effective is the proposed online NOS instructional approach?

Chapter III

METHODS

This chapter presents a summary of the overarching research strategy and planning, its methods and protocol of data collection. More detailed description of the specific methods presented here can be found in the following two results chapters, Chapter IV and V.

Overview

This is a mixed methods research where the researcher has adopted both quantitative and qualitative approaches to critically examine the validity of major results of this study. The methods used in examining the research questions presented below have been selected with careful consideration of the research setting, characteristics of the participants needed and access to tools and instruments in analyzing data (Fig. 1).

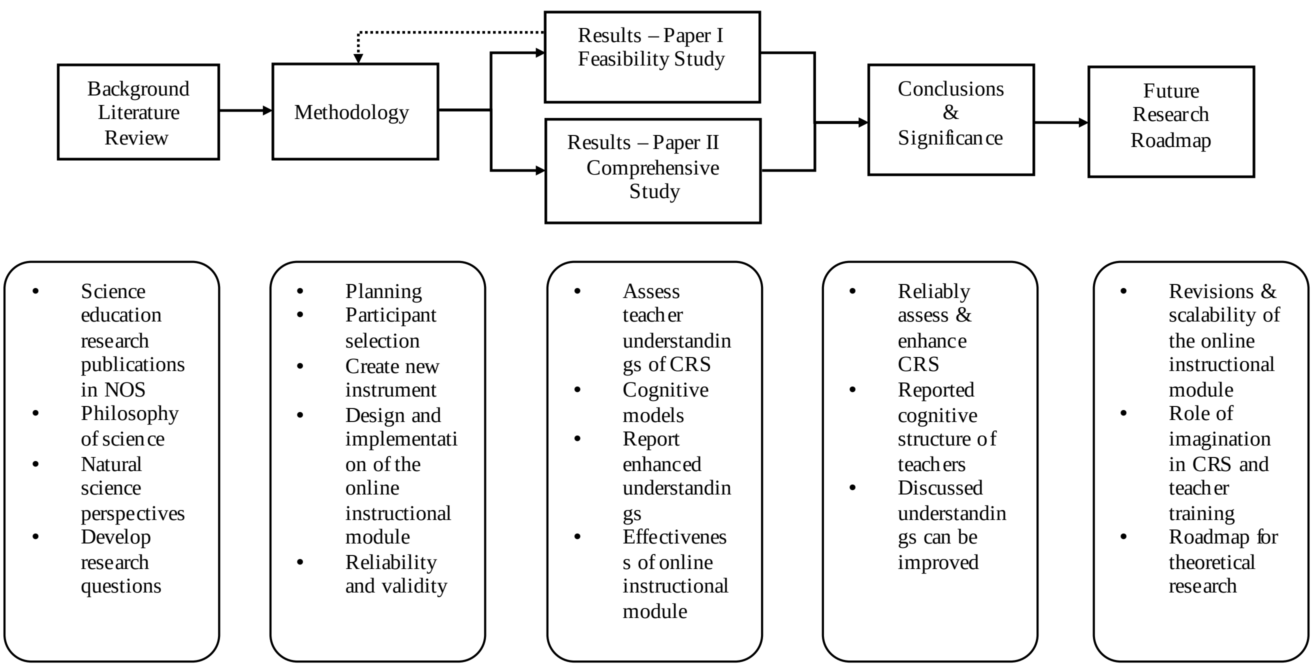

Figure 1

Structure of the study to assess in-service teachers' understanding of the CRNOS and to experimentally examine to what extent an online learning experience can enhance teachers' understanding of CRS. The dashed recursive arrow indicates that the results of the feasibility study were used to inform and revise the methodology.

Research Setting, Participants and Their Selection

The study includes in-service science teachers who are subscribers to a listserv and pre-professional science teachers enrolled in the graduate level courses of the Science Education Program at Teachers College, Columbia University. The first phase of the study, the pilot program, included only the in-service science teachers who currently subscribe to a mailing list at PhysicsTeachersNYC, a non-profit organization for physics teachers' professional development. At the moment of data collection, this listserv had approximately 180 subscribers in total. Among these total subscribers to the listserv, 50 participants anonymously responded to the new CRNOS questionnaire. Demographic data from participants was not gathered in the feasibility study, although it was reported by the list administrator that the subscribers are known to be active in-service science teachers with a diverse background. Feasibility study data collection continued for approximately two weeks and more than 90% of responses came in during the first five days. The comprehensive study (Chapter V) included 17 in-service and pre-service participants in total with a wide distribution of demographic data. There were five female and 12 male participants. Their education background was spread within suburban (12) and urban (5) settings. Ten participants had a physics background in college or university education as the major or main area(s) of study, and three participants were from biosciences. The rest of the participants' majors included chemistry, earth science, science education and economics – one participant each. The grade level they taught or career expectation was largely focused on high school teaching (13) and middle school (3) and one at the university level. Most of the participant teachers (15 of 17) had less than 10 years of experience. Among this group, eight teachers had 0-5 years and seven teachers had 5-10 years of teaching experience. Only one teacher each came from the groups of 10-15 years and 20-25 years of experience. Age groups included two teachers under 25, six from 25-29, one from 30-30, and four each came from 40-49 and 50-59 groups.

Selection of a sample of science teachers to assess their level of epistemological understandings of critical rationalist stance is based on convenience, availability and access through the departmental instructors of the courses. Thus, all participants in this study consist of a convenience sample of volunteers, presently enrolled in the teacher certification programs and other in-service teachers who are likely to benefit from enhanced professional development.

Contacting Participants

Potential participants were contacted in coordination with the faculty of the science education department. Students were invited to participate in this study via emails and in person communication during the weekly lectures. This was done after discussions with the faculty members who teach the science education classes in the science teacher certification programs. The researcher attended the class with the instructor of the course to meet the potential participants at a time and date that was convenient to the course instructor. This initial introduction to the study and request for participation was communicated in the presence of the course instructor during the normal class hours at a convenient time selected by the instructor.

Interviewing Participants

The interviews with a selected number of participants were arranged at a convenient time for the interviewee outside of class. This communication was done based on the participants' responses indicating their willingness to participate in an interview after the pretest is completed.

Communications with Participants

After the initial introduction to this study, all potential participants were contacted via email with an online survey URL to access the online instruments and instructional module. The participants who decided to volunteer would then have the option to either continue the online survey or decline participation with no response to the survey instrument.

The participants for the post-test interview component were selected based on the pretest scores and post-test scores of willing participants. Three interviews were conducted based on the available participants who already completed the instructional module and the post-test questionnaire.

Instrument

The instrument to gather data addresses the following question:

> How accurately do science teachers understand critical rationalist principles as compared to logical positivistic ones based on a multiple response test?

Instructional Module

A web based instructional module has been designed to enhance the critical rationalist views of science within the participants. This was delivered after the participant completed the pretest data collection. Instructional module is intended to help them better understand the core foundations of critical rationalist stance, and how such views can be integrated to widely known principles of science that are commonly found in science classroom settings.

Instructional module includes the following:

1. Using a few widely known theories in science and considering respective experiments as examples, help them become familiar with the terminology and scientific language they would need to understand the module.
2. Develop a sharp contrast between positivist vs. critical rationalist views of science.
3. Starting with a textbook explanation, suggest that the participants examine the given theory and evidence critically, and see what is appropriate and acceptable about it.

Discuss that it has verifications of the theory – science is verifiable, and then consider what can be improved or enhanced in this explanation, leading toward a more critical rationalist approach.

4. Then, using this same textbook explanation, interpret how this is shown as a logical positivist perspective. Afterwards, show that a critical rationalist framework can enhance the understanding of the same theoretical explanation.
5. Address and explain the seven implications of critical rationalist stance that were used in developing the pretest questionnaire.

Method of Delivering the Instructional Module

The research participants who successfully completed and submitted the pretest questionnaire were emailed again requesting them to complete the online instructional module located in the website where the questionnaire is located. The instructional module consists of reading assignments and instructional multimedia components.

Data Collection

Instrument for collecting data is listed in Chapter IV, Appendix, with its analysis. The instrument was a multiple choice item instrument. The data was recorded using web based secure database.

Data Analysis

Initial studies and informal data collection prior to the feasibility study in the form of quasi-pilot studies started with surveys and interviews including a questionnaire on the nature of science in post-positivist perspectives. Based on this evidence, the questions were adjusted to be more understandable and appropriate, while consulting with the faculty advisers in the Science Education Program.

Qualitative Approaches

A phenomenological research based data analysis was used to analyze text based feedback for pretest and post-test and interview responses following procedures such as those of Creswell (2012), Colaizzi (1978) and E. H. Anderson and Spencer (2002). Significant statements from the questionnaire feedback and recorded voice data were analyzed to find out the themes that may align with the theoretical framework of this study, and to understand the cognitive underpinnings behind these responses. The statements were read several times and voice recordings were repeatedly reviewed for significant statements to understand the cognitive models elucidated by the participants. The researcher assigned each significant statement to a mainstream cognitive and epistemological framework, primarily focusing on two schools of thought: logical positivism and critical rationalism as primary classifications. This was based on prior studies on critical rationalist epistemological framework of science and published research on the nature of science. This assignment of significant statements to two mainstream cognitive interpretations helped make clear how science is perceived by the participant, and how a science teacher may teach science to the students in a classroom. Understanding such teacher perceptions may help find out if the science teacher will utilize to a large extent the recommended critical rationalist paradigm over logical positivist argumentation in their own world view, and how they will likely present it in their science teaching. In addition to significant statements analysis, major cognitive themes clusters were developed once all the participants' responses are analyzed. This yielded a qualitative summary analysis of the teacher's epistemological views.

Quantitative Approaches

The teachers' responses to the questionnaire, were evaluated by using a scoring rubric and an overall score was assigned based on the scoring rubric. The median scores obtained from the application of the scoring rubric for the pretest questionnaire and the post-test questionnaire was compared using a non-parametric test to determine statistical significance. Accuracy of answers to multiple-choice questions was established as stipulated in the methods section of the publishable papers presented in greater detail in Chapter IV. Post-test data was compared to pretest data to determine if there was improvement in understanding and to what degree by using a paired t-test of the means (level of significance, $p \leq 0.05$). Cronbach's alpha, which measures the degree of internal consistency, was used to report the reliability of the new instrument. Cronbach's alpha is a function of the number of test items (N) and the average inter-correlation among the test items. The formula for the standardized Cronbach's alpha is as follows:

$$\alpha = \frac{N \cdot \bar{c}}{\bar{v} + (N - 1) \cdot \bar{c}}$$

Here N is the number of test items, $\bar{c}$ is the average inter-item covariance among the items and $\bar{v}$ is the average variance.

Chapter IV

A New Questionnaire-based Instrument for Assessing Teacher Understanding of a Post-positivistic Conception: "Critical Rational Stance" as a Significant Component of a Thorough Understanding of the Nature of Science and Scientific Theory Testing

Abstract

The main contribution of this paper is the introduction of a highly reliable, readily accessible and user-friendly online instrument that assesses science teachers' understanding of a critical rational stance inherent in post-positivistic explanations of the nature of science. The new instrument was designed to determine if in-service science teachers' views of the nature of science align with contemporary, post-positivistic perspectives about the role of critical rational thought in the practices of science, especially theory development and evaluation. The instrument is a multiple-response questionnaire that was administered to 50 in-service science teachers in a feasibility study. In addition to feasibility of use, additional evidence of the strengths and possible weaknesses of the new instrument was obtained. Construct validity of the instrument was obtained by report of a panel of four science education experts. The Cronbach reliability was 0.8. The results of administering the instrument showed that a highly significant percentage (84%) of participating teachers possessed only a weak understanding of the analytical reasoning underlying current perspectives on a critical rational stance in the practice of science. The statistical results, and a reflective analysis of the teacher's responses to the items, suggest that there may be a need to improve science teacher education to enhance understanding of the seminal role of critical rational thought in the nature and practices of science.

Keywords: Nature of Science, science teacher education, critical rationalism, critical thinking, falsification, refutation, scientific theory, scientific evidence, cognitive models, scientific reasoning, scientific method

Introduction

The nature of science and teachers' understanding of it has been a major focus among science education researchers; e.g., Abd-El-Khalick and Lederman (2000), Duschl (1990), Niaz (2011), Akerson, Morrison, and McDuffie (2006), Abell and Smith (1994), Irez (2006), Lakin and Wellington (1994), Mellado (1997), American Association for the Advancement of Science (1993). However, less attention has been given to some emergent ideas in post-positivistic thought about how theories arise and are tested in science based on critical rational thought. The critical rationalist worldview includes a robust challenge that our claims of credible knowledge shall withstand the most rigorous empirical tests that have the highest imaginable risk of falsification (Feynman, 1965a; Hawking, 1988; Popper, 1989). In this paper, a new multiple response online questionnaire designed to assess teachers' understanding of critical rational thought and theory testing in science is described and its feasibility examined by administering it to 50 in-service teachers. Based on the evidence gathered in this study, the instrument is sufficiently valid and reliable to assess teacher's fundamental understandings of the role of critical rationale thought in scientific theory testing. Hopefully, this new instrument may be useful to teacher educators and science education researchers to more fully assess a teacher's understanding of some of these emerging, post-positivist ideas about the role of theory and theory evaluation in science.

The specific focus of this research was on assessing teachers' level of understanding of a critical rationalist stance in science, notably including the importance of the falsifiability criterion of scientific inquiry (Hawking, 1988). This includes assessing teachers' knowledge of the importance of a rigorous and careful effort towards refutation of hypotheses as compared to an exclusive emphasis on verification (Feynman, 1965b). In constructing such a definition, a thorough analysis of contemporary viewpoints on the nature of science, its philosophy and the practices of science are examined and taken into account.

This assessment was an initial effort to determine whether a teacher's understanding of such critical rationalist perspectives regarding the nature of science could eventually help avoid the difficulties experienced by science teachers to demarcate science from non-science, and avoid unfruitful approaches to science teaching that often mitigate students' understanding of the fundamental principles of the scientific enterprise of inquiry.

Review of Pertinent Literature

Given the significant questions confronting science educators about what should be included in science teaching and what our future citizens should know about science, it is essential to consider a clear definition of the nature of science. Within this section, a definition of science is presented that collectively draws from the writings of some modern, selected authors. Among these are: David Hume (1740), Stephen Hawking (1988), Carl Hempel (1966), Henry Margenau (1977), Charles S. Peirce (1994), Michael Polanyi (1958), Karl Popper (1992), Stephen Toulmin (2001), Richard Feynman (1965b), Carl Sagan (1995), Ludwig Wittgenstein (2001), etc. The framework presented here is drawn from a natural science perspective and based on contemporary philosophical standpoints that are consistent with canonical views of the nature of science. These views include definitions of science as a way of knowing based on theory, but also rooted in the use of evidence from the natural environment as means of explaining natural phenomena (e.g. Duschl, 1990). It is noteworthy to mention that the definition of scientific framework adopted by the U.S. Supreme Court in the landmark case, 509 U.S. 579, 593, ("Daubert v. Merrell Dow Pharmaceuticals, Inc," 1993) with a majority opinion of the court, is also well aligned with the definition adopted in this research. Briefly the court asserted, with references to Green and Nesson (1983), at 645 and Hempel (1966), Philosophy of Natural Science at 49, that "scientific methodology today is based on generating hypotheses and testing them to see if they can be falsified; indeed, this methodology is what distinguishes science from other fields of human inquiry." This review also reflects certain consensus perspectives among leading science educators and researchers, with particular reference to education researchers concerned with the nature of science, neurocognitive theory and constructivism in science education: e.g., Fouad Abd-El-Khalick (2000), Richard Duschl (1990), Norman Lederman (1992), O. R. Anderson (2009; 2014), Niaz (2011) and the position papers of the National Academy of Science on the Nature of Science, American Association for the Advancement of Science (1993), among others.

Defining Critical Rational Stance in the Nature of Science

Scientific Inquiry in many cases begins when an inquirer chooses a question. This occurs initially as a part of the human experience of nature based on existing theoretical understandings. During the initial stages, the inquirer may evaluate potential elementary explanations as answers to a question by observing the phenomena with the five senses in combination with the process of intellection in the brain. Sensation and the intellectual synthesis of percepts with prior knowledge are brain functions that help us to construct meanings of experience. Intellection is the process of using the human mind to consider these percepts carefully and creating a set of rules or a model that can be described as “conceptual modeling” (O. R. Anderson, 2009). This type of conceptual modeling is common to all forms of human inquiry. Some of these conceptual models involve describing of known events in nature and some other models may be developed through imagination that people learn outside the natural experience. These can be various models involving historical accounts, enforced belief systems, religion, art and music.

The critical rationalist view specifically emphasizes the need for testing of theories based on predictions of new evidence that can potentially refute the theory rather than a major dependence only on already known evidence that verifies the theory, as contained in most logical positivistic views about science. Key implications of critical rational stance stated in the cited articles in this review stands as the foundational framework in assessing teachers' understanding of a thorough knowledge in the nature of science via the newly designed questionnaire.

General Research Questions

1. To what extent does a sample of teachers possess some of the most desirable understandings within a Critical Rational Stance, and what are the present understandings that the teachers have about the nature of science in relation to a critical rationalist approach?
2. What are the present conceptual models that the science teachers have about the nature of science in relation to a critical rationalist approach?

Methods

Participants

Prospective participants were invited via a subscriber's listserv of teachers in the Greater New York area, or by invitation to students in a graduate class of in-service teachers. There were approximately 180 total subscribers in the listserv. It is possible that more teachers received this invitation through subsequent forwarding of email, and additional volunteers may also have participated although it was not possible to characterize such participation, because the responses were obtained anonymously to encourage participation.

Instrument

The questionnaire, designed to measure science teachers' conceptual understanding of a critical rationalist view of the nature of science (Appendix), has been modified here to indicate the categories of response options for each item that were used in evaluating the respondents' choices. Bold letters are used to indicate critical rationalist view responses emphasizing the testing of theories based on new predictions of evidence that could potentially falsify the theory. This is in contrast to a major dependence only on evidence that verifies the theory, as contained in most logical positivistic views about science. Italic font is used for responses that are mostly positivistic in nature. Response items printed in normal font are mixed (partially positivistic), or one of the most inaccurate views. These were collectively classified as misconceived views.

An interactive online version of the questionnaire as administered in this study is available at the following URL: https://sites.google.com/site/hemanthawijesooriya/test-labs/test10 . The questionnaire is presented in the Appendix of this paper.

Administration of the Questionnaire

The online questionnaire was presented to the volunteer participants via email in a website link using Google Docs online forms software. With this online service, text based multiple responses were automatically recorded to a spreadsheet database for subsequent data analysis.

Analysis of Results and Statistical Procedures

Responses to questionnaire items (Appendix) were scored as 0 or 1 point, 0 (not critical rational) or 1 (critical rational), with no partial credit. In addition to the total score (CRS score) in a possible the range of 0 to 10, there were two other categories of responses that were obtained based on the percentage of responses, i.e. Logical Positivistic Category, and Mixed Category. A respondent who selected 70% or more of the logical positivistic responses was placed in the Logical Positivistic Category. A respondent who had a mixture of responses from among those identified as critical rational stance, logical positivistic and misconceptions options was placed in the Mixed Category. That is, mixed category participants fall in the middle range with scores less than 70% in both critical rational stance and logical positivistic response choices.

Reliability and Validity

Cronbach reliability was 0.8. Construct validity was established via an external expert panel consisting of four senior level science educators presently actively engaged in science teacher development programs who commented on the validity of each item. In overall review, the panel of experts stated that the test items aligned with the questionnaire objectives and that the questionnaire was well designed. Among the comments made by the panel were the following: "…the test items for the multiple-choice items align well with the learning objectives. The test items explicitly address content from the objectives. All the objectives are dealt with in the test items." Another panel member stated: "The project, in general, has reached the researcher's goal and objectives with well-designed test questions…" A few comments were made about possible future additions and/or modifications, but overall the assessment of the panel supported the validity of the questionnaire.

Descriptive and Inferential Statistics

Descriptive statistics were used to present breakdown data for the respondents' scores on each questionnaire item and the overall mean score of responses. A one-Sample t-Test for the Mean of CRS Scores (verified to be normally distributed) was used to compare the sample mean against a preset benchmark target minimal CRS competency score of 7 (out of a total CRS score of 10) based on the criterion that at least 70% of the responses should be of a critical rational stance to be passing.

Results

Evidence is presented to address each of the research questions.

Research Question 1: To what extent does a sample of teachers possess some of the most desirable understandings within a Critical Rational Stance, and what are the present understandings that the teachers have about the nature of science in relation to a critical rationalist approach?

With respect to the first aspect of competency in understanding the critical rational stance, the sample population of 50 science teachers had a significantly low mean critical rational stance (CRS) score of 3.72 (S. D. = 2.51) on a scale of 0 to 10 (Table 1). Table 1 provides descriptive statistics for the entire population of 50 participants (Row 1) including the 42 teachers who scored below the benchmark score of 7 (Row 2). The teachers who scored below the benchmark score (shown as < 7) had a mean CRS score of 3.02 (S.D. = 2.08) and a median score of 3.0. The participants who met the preset benchmark CRS score of 7 or greater are shown as ≥ 7 (Row 3). These results suggest a serious deficiency when compared to the expected benchmark performance standard of 7.0. Eighty four percent of the total sample population had a score less than the benchmark score.

Table 1

Summary of descriptive statistics for entire sample population

CRS Score	Total test responses	Accurate view answers	Maximum score	Lowest score	Mean	Median	Standard Deviation	(%) score	Total participants
0-10 (All)	500	186	9	0	3.72	4	2.51	37.2	50
< 7	420	127	6	0	3.02	3	2.08	30.24	42
≥ 7	80	59	9	7	7.38	7	0.74	73.8	8

Teachers' views and degree of their understanding of a critical rational stance are shown in Figure 1, including a breakdown of the total number of individuals who chose the desirable critical stance response for each questionnaire item, and a graph showing the cumulative subtotals in an ascending order.

Question	Total Desirable Responses	Desirable response rate %
Q10	1	2
Q4	8	16
Q3	10	20
Q6	11	22
Q9	17	34
Q5	20	40
Q7	22	44
Q2	30	60
Q8	32	64
Q1	35	70

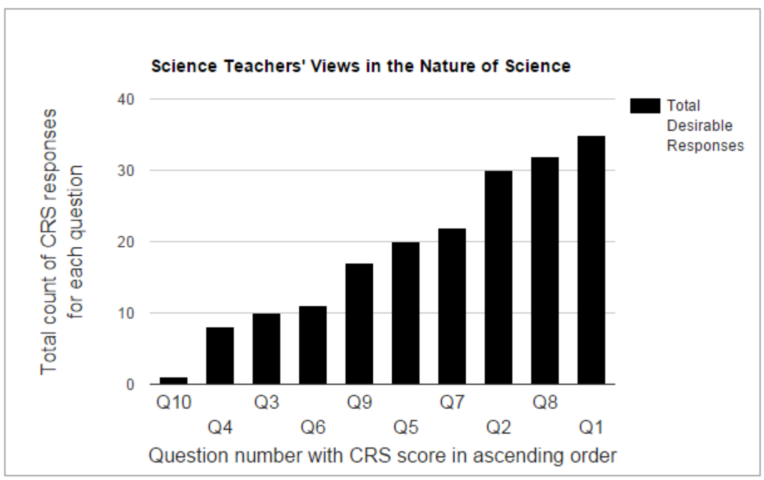

Figure 2
Science teachers' expressed views in the nature of science understandings representing a critical rational stance

In relation to the conceptual models held by the teachers, the results in Figure 1 suggest sixty to seventy percent of teachers were aware of the tentativeness of scientific knowledge. Questions 1, 2 and 8 (among the most frequently selected as shown in Fig. 1) were designed to be the easiest, or most likely chosen, distractors relative to the optimal critical rational view options in each question. However, all of the remaining seven questions with more difficult understandings, that are implications of critical rational stance, were chosen significantly less frequently (< 50%). Question 10, which was the most difficult, requiring the most discriminative understanding by test design, was selected much less frequently by this sample of teachers. Questions 3 and 4, that tested important and distinguishing implications of the critical rationalist view of science, also were among the least frequently selected.

Research Question 2: What are the present conceptual models that the science teachers have about the nature of science in relation to a critical rationalist approach?

The conceptual model assigned to each respondent was based on the three categories as cited in the Methods section, i.e. 1) Critical Rational Stance, 2) Logical Positivistic, and 3) Mixed Views. Eight of the teachers (16%) who achieved a CRS score equal to or greater than 7 (≥ 70 % accurate critical stance responses) on the questionnaire were categorized as possessing a Critical Rational Stance. Twenty-eight of the teachers (56%) held Mixed Views, and 14 (28%) who chose at least 70% of the logical positivistic options on the questionnaire were categorized as Logical Positivistic. Some detailed analyses of teachers who exemplified each of these categories are presented in the next section containing case studies.

Case studies

Five case studies are presented to illustrate the three main categories of conceptual models of science teachers. These case studies were selected targeting individual teachers whose responses to the questionnaire fell into each of the three categories: 1) participants with most evidence of a critical rational view (CRS score of 70% or above), 2) most positivistic participants (positivistic responses of 70% or above), and 3) the remainder of the participants with mixed views. As a context for the five case study narrative analyses, Table 2 presents an overview of the selected participants' scores. Participant C.S.1 demonstrated the most outstanding record of responses in this sample population with a CRS score of 9 and only one positivistic response. This participant did not select a single instance of inaccurate, mixed or misconceived views. In contrast, participant C.S.2 consistently selected positivistic options; all ten responses were logical positivistic. Three participants (C.S.3, C.S.4, and C.S.5) were categorized in the mixed group. Their responses present very complex and mixed perspectives. In general, their responses indicated a mixture of views spanning across perspectives categorized as critical rational stance, positivistic understandings and misconceptions. Hence these three case studies are reported in more detail, because they may represent the kinds of complicated and inconsistent views that some teachers possess. Their lack of a consistent perspective may present a primary challenge for science teacher professional development, because essential attention may be needed to initially bring some coherence to the logical structure of their understandings in addition to helping them attain a more modern understanding of the nature of science grounded in a critical rational stance and other post-positivistic views likely to promote effective inquiry teaching and learning.

Table 2

Case studies representing cognitive models of selected participants

Case study number	**Categorization**	**Case selection criteria**	**Number of CRS responses**	**Number of positivistic responses**	**Number of misconceived views responses**
C.S.1	Group 1 – CRS	Most outstanding CRS score	9	1	0
C.S.2	Group 2 – Positivistic	Most positivistic	0	10	0
C.S.3	Group 3 – Mixed	Logically incoherent	3	3	4
C.S.4	Group 3 – Mixed	Leans to CRS	6	1	3
C.S.5	Group 3 – Mixed	Leans to positivistic	3	6	1

Case Study 1: Participant C.S.1 with the most outstanding CRS score (9 of 10) selected no responses containing clear misconceptions. The only positivistic response (Question 10 – response 3, Appendix) contained a distinguishing implication underlying the CRS stressing that our new theories in science often aim at improbable or highly unlikely explanations; although, they are rigorously tested via falsifiable definite predictions. Question 10 was also the most difficult item in terms of test design intent and the degree of understanding demonstrated by all the participants (Q10, Figure 1).

Case Study 2: Participant C.S.2 represents a most noteworthy participant from the Group 2 category with the highest positivistic view score (10 of 10) and no selection of CRS or clear misconception options. It is a striking observation to note that this participant clearly avoided all the inaccurate popular misconceptions presented in all of these test items as shown in Appendix answer options (normal font).

Case Study 3: Participant C.S.3 exhibited a highly mixed cognitive structure in reasoning, a multidimensional most challenging scenario for professional development. This participant demonstrated the highest frequency of misconceptions (4 out of 10) and selected a mixture of CRS and positivistic views (3 each) indicative of a logically incoherent reasoning and cognitive structure, relative to the theoretical framework used in this study. Also, when the participant chose designated CRS options, they were largely among the least difficult items in the questionnaire (Questions 1, 2 and 8 – Appendix) based on test design. Moreover, these were deemed to be among the least difficult based on the high frequency they were chosen by all participants (Figure 1). The most distinguishing CRS constructs presented by this respondent are evident in the particular options chosen among the most inaccurate responses. For example in Question 6, the respondent chose option 4, which demonstrates a lack of appreciation of instrumentality in scientific inquiry. For Question 7, the respondent chose option 5 (*Credible evidence that can test a theory requires looking for verifications, or confirmations*). For Question 3, the respondent chose option 5 (*A new theory gains higher explanatory power and more value* *to us when the theory appears most likely, and prior theories support it as well*), indicating a leaning toward positivistic views. For Question 10, the option chosen was 5 (*Theories aim at most likely explanations that describe what we have already observed but had no prior explanations*). While these are not among major misconceptions, they are among some of the options that are partially logically positivistic or non consistent with current practices of science.

Case Study 4: Participant C.S.4 responses represent a mixed view pattern leaning toward a critical rational stance, with three misconceptions and one positivistic response. The three misconceptions chosen by this participant are: Q3- response 5; Q9- response 2; Q10-response 3 – Appendix. All these three selections are mixed with partially positivistic and inaccurate views, outside of the clear most positivistic two answer options that were included in each of the ten questions. One response however was selected from the second most positivistic view choices for Q4- response 1. Unlike the C.S.3 participant who had chosen responses all over the place in terms of cognitive models of interest, this participant carefully avoided the positivistic answers of test items and preferred CRS choices in a greater consistency (6 of 10). The participant carefully avoided 9 of 10 instances of the most positivistic category responses offered (Appendix). When the participant did not choose the most desirable critical rational stance response in four test items, there were no selections that were within the most inaccurate misconceptions either. Additionally, the four inaccurate responses came from the most difficult set of five questions based on response frequencies on Figure 1. These observations may possibly support an inherent deficiency in the deeper understandings and an inability to identify the vital nuances in the more non-intuitive aspects of key implications of CRS constructs tested.

Case Study 5: Participant C.S.5 characterizes a logical positivistic leaning participant who selected three CRS responses and one misconceived view. The three appropriate CRS view options were in response to questions 2, 4 and 8. Two of these questions, 2 and 8, are among the three least demanding questions as discussed earlier for participant C.S.3. However, the participant's response pattern indicated a high inclination to favor a positivistic view over a critical rational view of science.

Discussion

Summary of results and implications for science teacher professional education

The instrument administered in this study is based on a model containing a synthesis of modern post-positivistic ideas in science, including published scholarly works of scientists and science educators. The feasibility study using the instrument indicates that it can be an appropriate means of assessing the status of in-service and possibly pre-service teachers' understanding of critical rational stance in modern science epistemology.

The results of the study along with high reliability assessments point toward a severe deficiency in the foundational understandings in the epistemological basis in scientific thinking and reasoning with only a small group of teachers meeting or exceeding the preset benchmark standard. Target selected case studies from the main categories of cognitive models presented a corroborative insight in to the highly positivistic views of teachers and most importantly, the very complex multidimensional cognitive structure in the teacher participants with the mixed views, a most challenging scenario for science teacher professional development. The highly positivistic views of science expressed by a large portion of teachers may also raise concern on present instructional practices prevailing in science education and opportunity to consider effective approaches to enhance contemporary epistemological understandings of science within teacher professional development.

The CRS instrument could provide an easy to use, readily accessible, inexpensive and relatively rapid tool to obtain an almost instantaneous assessment of the initial understandings of a group of prospective or in-service teachers about the critical rational stance in science. Moreover, if used as a pre- and post-assessment in teacher education courses, it can provide evidence of the students' gains after appropriate CRS learning experiences integrated into professional teacher education. Also, the results obtained from administering this instrument as at the beginning of a course, could allow a professional developer to better estimate what particular aspects of the nature of science within the context of critical rational stance are most likely to need attention; and/or most likely to be good beginning points in a constructivist approach to enhancing teacher understanding of the nature of science. Unlike some of the well-established nature of science questionnaires that have only open-ended questions, a highly reliable multiple response approach as demonstrated here could provide a robust user-friendly assessment platform that can be easily automated. This is evidenced here by the use of a Google online assessment platform.

The results of this research could lay the foundation for further research to help identify erroneous or non-scientific explanations that may arise from unscientific notions that sometimes can occur in the classroom. An analysis of the science teacher's ability to view most desirable views of science within a "Critical Rationalist Stance," and thus to demarcate science from non-science, could be a productive criterion for assessing the effectiveness of science teacher education, especially relevant to an ever increasing demand for teachers to use inquiry.

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Appendix

Multiple Response Questionnaire

Bold letters are used to indicate critical rationalist view responses. Italic font is used for responses that are mostly positivistic in nature. Response items printed in normal font are mixed (partially positivistic), or one of the most inaccurate views. These normal font items were collectively classified as misconceived views.

Answer Option	**1. A good theory should have certain characteristics. Which of the following is the most desirable quality of a good theory?**
1	A good scientific theory is so sound, that it is not potentially disprovable, falsifiable or refutable with evidence
2	**A good scientific theory is potentially disprovable, falsifiable or refutable with evidence**
3	*A good scientific theory is so sound because it is conclusively verified by obtaining many repeatable confirmations*
4	*A good scientific theory is proven true with a large number of confirmations presented by many scientists*
5	A good scientific theory is so sound because it is mathematically proven true while supported by many precise confirmations

Answer Option	**2. A good test should have certain characteristics. Which of the following is the most desirable quality of a test?**

1	A good test should conclusively prove the theory true with obtained positive confirmations
2	*A good test is aimed at obtaining as many repeatable positive confirmations, or verifications as possible by many scientists*
3	*A good test is aimed to show known observations positively confirm or verify the theory*
4	**A good test is a serious attempt to falsify the theory, or a test of refutation of the theory**
5	A good test is aimed at obtaining a collection of reproducible confirmations, or verifications by many scientists

Answer Option	**3. Which of the following is the most desirable statement to describe the explanatory power or value of a new theory?**
1	*A new theory gains higher explanatory power and more value to us when the theory appears most likely, where supporting confirmations are easily found in large numbers*
2	**A new theory gains higher explanatory power and more value to us when the theory appears least likely, and unknown observations are predictable**
3	*A new theory gains higher explanatory power and more value to us when the theory appears most likely and all known observations support the new theory*
4	A new theory gains higher explanatory power and more value to us when the theory appears least likely, and predictions are currently not observable with our instruments

5	A new theory gains higher explanatory power and more value to us when the theory appears most likely, and prior theories support it as well

Answer Option	**4. Which of the following is the most desirable statement to explain the credibility of a new theory?**
1	*A theory gains higher level of credibility, when it least restricts, prohibits or constrains certain predicted observations; the least it prohibits, the better the predictive power*
2	A theory gains higher level of credibility, when the restrictions, prohibitions or constrains make the predicted observations not accessible with the available instruments or our senses
3	*A theory gains higher level of credibility, when the fewer restrictions, prohibitions or constrains afford all the imaginable observations to agree with the theory; the fewer the prohibitions, the greater the predictive power*
4	**A theory gains higher level of credibility, when the theory heavily restricts, prohibits or constrains its predictions accessible by observations; the more it prohibits, the greater its predictive power**
5	A theory gains higher level of credibility, when the theory restricts prohibits or constrains a specific number of predictions accessible by observations

Answer Option	**5. Which of the following is the most desirable statement that describes testing of predictions of a theory?**

1	*To test a theory, it is essential that already known positive observations are precisely measured and repeatedly verified by many scientists*
2	*To test a theory, it is essential that the outcome or observation is already known to many scientists*
3	To test a theory, it is essential that the outcome of testing is not predictable
4	**To test a theory, it is essential that the outcome of testing such a prediction be currently unknown, or previously unobserved**
5	To test a theory, it is essential that the outcome of testing such a prediction be currently known, or previously observed by others

Answer Option	**6. Which is the most desirable statement to characterize good observations that arise from a good test of a theory?**
1	Evidence or observations from a test should provide a large number of positive confirmations or verifications with no conflicting evidence
2	**Evidence or observations from a test would count only if the observation puts the theory at great risk of disproof, refutation or falsification**
3	*Evidence or observations from a test would count only if those observations lead to the construction of a new theory, or verify a theory known to us before*
4	Evidence or observations from a test would count only if those observations are directly observable with our senses or experience
5	*Evidence or observations from a test would count only if all known confirming observations are reproducible by many others*

Answer Option	7. Which one of the following statements is the most desirable to describe 'credible evidence' that can genuinely test a theory?
1	*Credible evidence that can test a theory includes positive confirming observations or other repeatable verifications*
2	*Credible evidence that can test a theory requires reproducibility of exactly the same known verifications published by the original authors*
3	**Credible evidence that can test a theory must require searching for a previously unknown observation that could potentially refute the theory**
4	Credible evidence that can test a theory require looking for those previously known observations that were used to confirm the theory by its discoverers
5	Credible evidence that can test a theory requires looking for verifications, or confirmations, that have the highest precision

Answer Option	8. Which is the most desirable statement to characterize the scientific status of a theory?
1	A theory which is not refutable or non-falsifiable by any conceivable observation can be scientific
2	**A theory which is refutable or falsifiable by any conceivable observation can be scientific**
3	*A theory which can provide most number of confirmations, or verifications without contradictions is scientific*

4	*A theory which is mathematically proven to be true and confirmed by evidence is scientific*
5	A theory which is refutable or falsifiable by any conceivable event is always non-scientific

Answer Option	**9. Which is the most desirable statement to describe 'confirming evidence' of a valid test of a theory?**
1	*Confirming evidence should count only when it can be presented as a repeated verification by others*
2	Confirming evidence should count only when we manage to verify our laws and theories by seeking to apply them and to confirm them
3	Confirming evidence should count only when it can be presented as certainty that would help prove the theory or justify the theory
4	**Confirming evidence should count only when it can be presented as a serious but unsuccessful attempt to falsify the theory**
5	*Confirming evidence should count only when it can be presented as a successful confirmation, or verification of the theory with no observable disagreements*

Answer Option	**10. What may be the most desirable description of a goal, or aim of scientific theories?**
1	*Theories aim at highly likely explanations, where observations we initially make lead to their construction, or discovery, and subsequent verification*

2	**Theories aim at improbable or highly unlikely explanations where observations are difficult to be made or previously unknown**
3	*Theories aim at highest likelihood where many observations confirm and justify our explanation without contradictions*
4	Theories aim at conclusive ultimate explanations where mathematical certainty is essential for proof of our explanations
5	Theories aim at most likely explanations that describe what we have already observed but had no prior explanations

Chapter V

A New Digital Learning Module Capable of Enhancing Teacher Understanding of a Post-positivistic View of the Nature of Science and Scientific Theory Testing

Abstract

This is a report of the design and initial implementation of a readily accessible digital learning experience integrated with learner assessment tools that can enhance teacher understanding of fundamental constructs in a post-positivistic view of a critical rational stance in the nature of science (CRNOS). This new learning module was developed with the goal of providing a self-guided and self-paced e-learning experience that can be adopted as an adjunct to classroom instruction, or used in other settings where direct face-to-face instruction may not be possible. A mixed method approach (including qualitative and quantitative data) was used. The main finding is that this relatively concise, online instructional module can effectively increase teacher understandings of CRNOS with an overall mean gain in pretest, post-test scores of 30%. Moreover, the weakest performing teachers had a final mean score of 62% correct, relative to a low 24% correct pretest mean score. Interview evidence was used to gain a more in-depth understanding of the gains by participants who showed the greatest improvement on the CRNOS post-test. A panel of four professional science educators provided feedback on the validity and practical merits of the new e-learning module.

Keywords: Enhance views on Nature of Science, Improve science teacher education, conceptual change, critical rationalism, critical thinking, falsification, refutation, scientific theory, scientific evidence, science teacher professional development, scientific reasoning, scientific method

Introduction

Science education research in recent years has focused substantially on ways to generate highly effective and consistent improvements in teachers' understanding of the nature of science (NOS). Among these are contributions related to the following broad categories: teacher education enhancement efforts by Abd-El-Khalick (2005), Holbrook and Rannikmae (2007), Akerson and Hanuscin (2007), Schwartz, Lederman, and Crawford (2004), understanding teacher views and beliefs by Lederman (1992), Lakin and Wellington (1994), Mellado (1997), Waters-Adams (2006), Clough and Olson (2008), neurocognitive perspectives, cognitive psychology and constructivist models of learning science by O. R. Anderson (2009), Duschl and Hamilton (1992). Position papers of the National Academy of Science on the Nature of Science, American Association for the Advancement of Science (1993), strongly urged the need for teachers' focus in the nature of science. Substantial work has been published in recent decades. More than 24 assessment instruments published during 1954 through 1995 aimed at evaluating NOS understandings. These instruments were extensively reviewed and critiqued by Lederman, Wade & Bell (1998) including an analysis of reliability and validity. Recently, more effective methods to assess learning gains in NOS include the *Views of Nature of Science Questionnaires* (*VNOS*) constructed by Lederman, Abd-El-Khalick, Bell, and Schwartz (2002). Among all these many important contributions, less attention has been given to emergent ideas in post-positivistic thought about how scientific theories arise (Einstein, 1936), and the kind of rigor in experimental evaluation needed for new scientific theories to gain highest credibility. This is especially the case relative to recent emerging views about critical rational thought in the practices of science. Moreover, there are few instructional approaches that have been reported that aim to improve teacher understanding of the ways scientific knowledge grows based on a critical rationalist worldview.

The critical rationalist worldview includes a robust challenge that our claims of credible knowledge must withstand the most rigorous empirical tests that are designed to have the highest imaginable risk of falsification (Feynman, 1965a; Hawking, 1988; Popper, 1989), thus establishing the highest confidence and utmost credibility in our accepted scientific explanations. However, with all the recent opportunities in digital learning, there has not been an extensive interest in exploring how digital media can be effectively designed to improve teachers' understandings of complex newer interpretations of science practices, such as CRNOS. To address this need, this study presents a first trial and critical evaluation of a potentially useful e-learning module, and associated learner assessment instrument, in a format that can be readily adopted in science teacher education.

Research Questions

1. Can science teachers' understandings of the nature of science be enhanced through using an e-learning module designed to improve their knowledge of a critical rationalist viewpoint?
2. How effective is the proposed online NOS instructional approach?

Methods

Participants

Prospective participants were invited via a subscriber's listserv of teachers in the Greater New York area, or by invitation to students in three graduate classes in science education at a major northeastern university. There were 180 total subscribers in the listserv. The demographics of the participants were broad in terms of variation in the years of teaching experience (0-22 years) and age (21-59). Approximately three quarters of all participants were male. Subject matter major included biosciences, chemistry, physics, earth science, mathematics, social sciences and science education. However, 59% had a physics undergraduate background, partially due to the preponderance on the listserv.

Learning Module

The learning module is a self-guided and self-paced electronic learning environment that is intended to enhance understandings of the foundational conceptual constructs underlying a critical rationalist stance in science, notably including the importance of the falsifiability criterion of scientific inquiry (Hawking, 1988). The module addresses these issues in a context that may promote science teacher adoption of these ideas in their teaching. More particularly, the emphasis is on a constructivist approach to foster student understanding of the importance of a rigorous and careful testing hypotheses by refutation as compared to an exclusive emphasis on verification (Feynman, 1965a). Inquiry learning often emphasizes experimental verification of hypotheses. While this is an important part of establishing accepted theories in the scientific community, it is also important to understand that the most robust and epistemologically critical requirement is to show that a theory and derived hypotheses are refutable, and that evidence should be gathered that can refute as well as verify explanations in science. This is a central tenet of a modern critical rational stance in science theory design and testing. The learning module implemented, and evaluated here, is intended to guide a teacher towards the central epistemological constructs and cognitive framework underlying this modern critical rational stance in NOS. The learning module is accessible at the URL reported in the next section.

Administration of Intervention and the Pre-post Test Design

The online questionnaire pretest was presented to the volunteer participants via email in a website using Google Docs online forms software. With this online service, text based multiple responses were automatically recorded to a spreadsheet database for subsequent data analysis. At the end of the pretest, the URL to the online learning module was given to the participants. After completion of the online learning, each participant received the URL for the post-test evaluation questionnaire.

The pretest questionnaire is available at the following URL:

https://sites.google.com/site/hemanthawijesooriya/test-labs/pretest

Online Instructional Module is accessible at:

https://sites.google.com/site/hemanthawijesooriya/courses/nos/oim

The post-test questionnaire as administered in this study is available at the following URL:

https://sites.google.com/site/hemanthawijesooriya/test-labs/posttest

Analysis of Results and Statistical Procedures

A summary of criteria for scoring the online questionnaire is presented as follows:

Each of the ten questions in the multiple response questionnaire contained evidence of the five following evaluative dimensions, where the first dimension was considered the most consistent with CRNOS perspectives: 1.) Critical Rational Stance, 2.) Most positivistic view, 3.) Second answer with a highly positivistic view, 4.) Partially positivistic and/or misconceived mixed response, and 5.) Most inaccurate popular misconceptions. All four distractor options in the questionnaire (dimensions 2 to 5) were designed to be as attractive as possible to avoid biasing the participants' responses. The questions 1 – 10 addressed the following aspects of CRNOS: 1.) the most desirable quality of a good theory; 2.) The most desirable quality of a scientific test of an hypothesis or theory; 3.) The best example of the explanatory power or value of a new theory; 4.) What best explains the credibility of a new theory; 5.) The most acceptable statement that describes testing of predictions of a theory; 6.) Characteristics of good observations that arise from a good test of a theory; 7.) Most 'credible evidence' that can genuinely test a theory; 8.) Best qualities that characterize the scientific status of a theory; 9.) Best description for 'confirming evidence' of a valid test of a theory; 10.) Most acceptable description of a goal, or aim of scientific theories.

A paired t-test was used to assess if there was a significant gain in pretest to post-test mean scores for the thirteen participants who were initially least proficient and who did not meet the designated benchmark score on the pretest. The statistical criterion level of confidence was $p < 0.01$.

Methods of Qualitative Analysis

Two sources of qualitative evidence were included in this analysis: 1.) Participant responses regarding the NOS instructional approach consisting of, a.) participants' perceptions of the e-learning experience based on submitted comments about the learning module and also feedback included in the questionnaire associated with the post-test, b.) Interview-based evidence on the effectiveness of the CRNOS instructional approach obtained from the participants who had the highest pretest, post-test gains. 2.) A detailed analysis of interview evidence for three participants who showed the greatest pretest, post-test gains, as they reflected on their learning experiences from the perspective of conceptual change. Each response was examined in relation to three categories: 1). Evidence of a critical reflective NOS stance as emphasized in the learning module, 2.) Positivistic kinds of perspectives, and 3.) Statements that evidenced mixed or misconceived views, as erroneously taken from the theoretical framework presented in the module.

Reliability and Validity

The Cronbach's reliability of the instrument determined with a sample of fifty in-service science teachers was 0.8. A panel of four expert professional science educators reviewed the questionnaire and the learning module. Their critical reflective judgments indicated that they deemed the e-learning module to be valid, it sufficiently addressed the major objectives designated for the learning experience, and the pretest and post-test items were appropriate and aligned with the stated objectives of the learning experience. There were only some relatively minor recommendations for follow-up corrections and revision.

Results

Evidence is presented to address each of the research questions:

Research Question 1: Can science teachers' understandings of the nature of science be enhanced through using an e-learning module designed to improve their knowledge of a critical rationalist viewpoint?

The mean pretest questionnaire critical rational stance score (CRS) for this sample of teachers was low; i.e. 3.65 (S. D. = 3.0) on a scale of 0 to 10 (Table 1). Of the seventeen participants (Row 1), thirteen participants had particularly weak scores, with a mean of 2.46 (S.D. = 2.3). This is substantially below the preset benchmark score of 7 out of a total score of 10 (Row 2, 'Pretest < 7'). The post-test scores for the groups in Row 1 and Row 2 are shown in Row 3 and Row 4 (Table 1). The paired t-test results for the mean gain scores are statistically significant. The rather substantial gains in post-test scores by the weakest participants, who scored below 7 on the pretest, provide encouraging evidence that the e-learning module can be an effective means of improving teacher understanding of the critical rational stance perspective. The data for the mean pretest, post-test gain scores for this group are presented in Row 5; i.e. a gain of 3.77 score points.

Table 1

Test scores of participants against preset benchmark

Row Number	**CRS score**	**Answers submitted**	**Accurate Answers**	**Maximum score**	**Lowest score**	**Mean**	**Paired t Test P value**	**Median**	**Standard Deviation**	**(%) score**	**Total participants**
1	Pretest (ALL)	170	62	9	0	3.65		4	3	36.47	17
2	Pretest<7 (13)	130	32	6	0	2.46		1	2.3	24.62	13
3	Posttest (ALL)	170	113	10	2	6.65	P=0.001	7	2.26	66.47	17
4	Posttest of Pretest<7 participants (13)	130	81	9	2	6.23	P=0.001	7	2.35	62.31	13
5	Posttest Gain (13)					3.77				37.69	

Overall, the results indicated that 65% of the sample population in this study met or exceeded the benchmark score on the post-learning evaluation, while only 24% of this population met benchmark on the pretest evaluation.

As additional evidence of the effectiveness of the e-learning module, qualitative evidence is presented to address Research Question 2. There are two subsections: 1.) Respondents' views of the learning experience, and 2.) a detailed analysis of interview data for three participants who showed the greatest pretest, post-test gains.

Research Question 2: How effective is the proposed NOS instructional approach?

1.) Participant Responses Regarding the NOS instructional approach.

Two sources of qualitative evidence were analyzed: a.) Participants' perceptions of the e-learning module and their comments in the questionnaire associated with the post-test evaluation, and b.) Interview responses gathered from the three participants who had the highest gains in CRS score.

a. *Participants' perceptions of the e-learning experience*

As an optional task, the seventeen participants were asked to provide feedback as part of the post-test questionnaire to help further improve the learning module and learning assessment instrument. Eleven participants submitted comments and suggestions after completing the learning experience, and ten participants commented after submitting responses to the post-test questionnaire evaluation. The responses were qualitatively assessed to understand the effectiveness of e-learning.

Overall, the participants found the contents of this learning module to be interesting and helpful in understanding the core concepts established in CRNOS. For example, a participant commented, "This was a most interesting exercise". Additionally, some statements provided reflective criticism identifying areas needing development. These included comments on merits and skepticism on long-term changes such as, "…Then I was forced to rethink my concepts. Not sure if just presenting these ideas without jarring the audience enough to abandon their naive models will be enough."

While the feedback was highly positive, in general reflecting effectiveness, the introductory CRNOS concepts presented in the learning module seemed particularly challenging, even for some of the most outstanding learners who achieved the highest learning gains. For example, the participant with the highest pretest, post-test gain score (pretest score of 0 and post-test score of 9) commented as follows:

> I have not yet internalized some of the concepts presented in Section 2; I fully comprehend and understand the reasoning behind them, but I have yet to completely "buy into them." However I felt the need to be somewhat "correct" with my answers this time around. Given more time, I would be more certain about my answers.

In general, students also made positive and critically reflective comments such as the following:

> I thoroughly enjoyed the content and its simplicity in conveying the characteristics of good science and what makes something a scientific theory.
>
> This was a most interesting exercise, solidifying a number of concepts about theories that I had learned during this semester. The examples were helpful. The repetition within the exercise was also useful to reinforce the ideas.

Some participants simply appreciated the general experience as a “Great job!” or “This is Great” without further elaboration, while other participants gave detailed accounts of reflection on the content they admired in the module including the following:

> I like how you use the word "imagine" where I use the "guess." I love the Einstein quote about limiting cases. Very illuminating. I love that you address Darwin's falsifiability. I'd have preferred any of his numerous suggestions in The Origin of Species for how to falsify his theory--a little more hard-hitting, and shows how thorough and humble he was.

Two participants contributed to some extent indirect appreciative remarks attributing to overall effectiveness and positive outlook, including the following: “I think that I learned some new points about the nature of scientific theories from the materials provided…" "It was good for me to review some of the aspects of Darwin's theory through this module, as I am not a bio teacher and haven't studied it for a long time."

Some constructive criticism was also presented, reflecting on certain limitations in the instructional design or areas requiring fine-tuning, including, "There was a lot of text, even in the videos, not enough concrete visuals that relate to specific theories. This might be especially important since terminology and concepts related to theories are inherently abstract in its nature and hard to understand textually without visual examples." No entirely negative remarks were submitted. It can be concluded from this evaluation that the participants gained the benefits of enhancing their perceptions, while recognizing the limitations of the module. The extent of constructive criticism presents further support to the overall effectiveness of the learning experience and also provides very useful insight to the significant development areas. Most participants' critique largely focused on e-learning instructional design areas in the graphical user interface along with the back-end database server limitations on e-learning interface design and user experience improvement. They are collectively summarized.

One participant's remarks recognized this learning as an opportunity to help rethink certain prior conceptual understanding, but raised a considerable level of skepticism over long term downstream benefits of this learning as means to help teach these concepts in a science classroom setting to enhance CRNOS among students. This participant questioned and highlighted the viability and possible complexity of adopting these intricate ideas and concepts in a classroom with the following comment.

Response: In my experience, just having people READ this stuff isn't going to convince them.

And if they haven't really developed the concepts on their own, they may not

> understand how this is different from their existing view. Unfortunately, I can't really think of an inquiry-based way of teaching this in an Internet module that would force people to come up with these ideas on their own. The way I learned this is being presented with examples from the history of science that clearly didn't fit the hypothetico-deductive or positivist or pure induction model of scientific thinking. Then I was forced to rethink my concepts. Not sure if just presenting these ideas without jarring the audience enough to abandon their naive models will be enough. Similar to teaching science itself!

Another participant expressed appreciation of short videos and review questions inserted in the learning module, although appeared to have expected a broader scope, greater depth and breadth from the video content delivered. “I liked the video interjections between readings and questions after every different section. However, to me, I think the message was very similar throughout the module and had a difficult time distinguishing uniqueness of each video.”

Apart from these comments that directly addressed the effectiveness, several others commented on technical limitations in the database, and less satisfaction with, or diminished utility of, the Google Apps framework used for the e-learning and assessment interface. These responses are collectively summarized as follows. A small number of users pointed out certain incompatibilities of the web platform with their mobile devices and mobile operating systems, improvements to audio-video editing, database design improvement for ease of navigation, data retention for returned users, accommodate further flexible time management and improve ease of navigation. While some highly appreciated the textual repetition of video content as an opportunity to revisit and rethink their prior concepts, review and reflect on the video content already presented, some others found this approach taken in instructional design leads to an excessive amount of text contained in the module. One participant particularly expressed more focus and further attention to concepts distinguishing between theory and hypothesis stating students have a lay interpretation of law versus theory versus hypothesis, and highlighted there was no mention about law versus theory versus hypothesis in sufficient detail.

Some participants particularly emphasized the need for more graphical visualizations and use of examples to illustrate concepts. A representative example is presented for this category of responses:

> Try to use more visuals to show concrete examples of theories, modifications, exemplars and predictions. Use Newtonian mechanics; visualize what these would be in light of velocity, acceleration, gravity experiments. There was a lot of text, even in the videos, not enough concrete visuals that relate to specific theories. This might be especially important since terminology and concepts related to theories are inherently abstract in its nature and hard to understand textually without visual examples.

b.) Interview-based Evidence on the Effectiveness of the NOS instructional approach

Three participants (A, B and C) who reported the highest gains in score (i.e. 9, 6, 9 respectively) volunteered for an optional interview after completing their post-test questionnaire.

Participant A

This participant commented, particularly, on the utility of the module as preparation for teaching a specialized class on the nature of science:

> I was just going to say, you know, actually really got a good bit out of this… I am teaching a class at Columbia, at the Double Discovery Center at Columbia for high school students, and one of the classes I am teaching is a science inquiry class… so my

> lesson on Saturday I am actually going to talk about… you know, science as inquiry… what is the difference between theory in everyday terms and theory in scientific terms. A lot of things, I kind of got out of here. This was actually really helpful for me when studying to teach… actually, it was good.

Later as a final remark, the participant reaffirmed, "…I really got something out of it."

Participant B

Participant B was particularly interested in the relevance to her/his teacher education coursework and the consequent merits for teaching NOS related topics, especially the nature of theory:

> I found it very interesting, because it was relevant to what I was learning as a teacher, as a science teacher. We are all about Nature of Science, and if I don't really learn and can't explain it to the students… what if they ask a question, like, why is this a theory? Why is general relativity a theory, what's so great about it? "What's so great about it, it explains the Universe"…Yeah, like, Theory vs. Evolution Theory, just another theory, or for some bad luck, I have to teach it in the (in a region in the USA where evolution is highly politicized)… I have to get my answer ready.

Moreover, Participant B was eager to ask about the aims of this study and wanted to know more about the future roadmap for the research study and the potential of this research, for example: "Where do you see this study going in terms of helping science teachers with it? As a final comment the participant said: "I am interested in the progression of your work, because it's dealing with fundamental questions."

Participant C

Participant C was a graduate student in a teacher certification program who was a biology major, a former physician and a pharmaceutical researcher with a significant experience currently undergoing a transition in to a career in science teaching.

> Moving over to Teachers College…and then, taking your course gave me the more pedagogic perspective, or the more current terminology to understand the perspectives about scientific theories, theories vs. laws, it was enlightening and quite helpful. But that in a nutshell, probably why my substantial difference between before and after.

2.) A detailed analysis of interview evidence for three participants who showed the greatest pretest, post-test gains

A qualitative assessment of three participants with highest gains in their understandings is presented as more comprehensive evidence of the effectiveness of the CRNOS e-learning module. These participant interview scripts were evaluated for more detailed examination of their performance in relation to their pretest cognitive constructs, degree of conceptual change and their post-learning reflections.

All three participants came from the same pre-service science teacher certification program. Participant A and B both had undergraduate degrees in physics, and participant C was a biology major, a former physician and a pharmaceutical researcher with significant experience in the practice of science. Participant A and C had the highest gains in this study with a 90% gain from pretest to post-test. Participant B had a 60% gain.

Participant A had no correct responses on the pretest with a correct score of 9 on the post-test. Pretest responses had a positivistic score of 6 of 10 and an inaccurate or misconceived views score of 4. In the post-test, the only positivistic response came from the most difficult test item by design intent, ‘Question 10: what may be the most desirable description of a goal, or aim of scientific theories’. The participant selected answer option 1: ‘theories aim at highly likely explanations, where observations we initially make lead to their construction, or discovery, and subsequent verification’. Participant B had one CRS response on the pretest, while a correct score of 7 on the post-test. Pretest contained zero inaccurate or misconceived views; however, positivistic score remained among the highest at 9 of 10. Post-test responses carried three positivistic views. They are, ‘Question 6: Which is the most desirable statement to characterize good observations that arise from a good test of a theory?’ Participant responded with option 5: ‘Evidence or observations from a test would count only if all known confirming observations are reproducible by many others.’ Next positivistic response came from ‘Question 9: Which is the most desirable statement to describe 'confirming evidence' of a valid test of a theory?’ for which participant selected option 5: ‘Confirming evidence should count only when it can be presented as a successful confirmation, or verification of the theory with no observable disagreements.’ The last item was the most difficult question by design intent, ‘Question 10: What may be the most desirable description of a goal, or aim of scientific theories?’ for which the participant selected option 3: ‘Theories aim at highest likelihood where many observations confirm and justify our explanation without contradictions.’ Participant C had no correct responses on the pretest, while a correct score of 9 on the post-test. Pretest responses were a highest positivistic score of 9 of 10 and one inaccurate mixed view response. Post-test responses had only one positivistic answer, ‘Question 4: Which of the following is the most desirable statement to explain the credibility of a new theory?’ with option 1: ‘A theory gains higher level of credibility, when it least restricts, prohibits or constrains certain predicted observations; the least it prohibits, the better the predictive power.’

Qualitative Evaluation of Responses

Based on the analysis of the respondents' follow-up interview responses, two emergent categories were identified that characterized the participants' orientation to the learning experience and their understanding of CRNOS: 1.) Pre-learning Cognitive Models (related to the initial understandings assessed on the pretest), 2.) Reflections on Post Learning Gains (particularly their conceptual-change-specific reflections related to their learning gains on the post-test). Examples of participant responses representing each of the two categories are presented. In some cases, the question presented by the interviewer is cited in addition to the response made by the participant.

1. *Pre-learning Cognitive Models (related to the initial understandings assessed on the pretest)*

Significant statements from each of the three participants taken from their interview scripts demonstrating CRNOS, positivistic views or mixed cognitive models are presented. The categories were adopted from the theoretical framework in this study as described in the methods section.

Participant A

Participant A portrayed a highly positivistic cognitive framework in the pretest hybridized with misconceived views. These traits of reasoning were probed in-depth during the interview to further understand pre-learning percepts.

Question: Regarding pretest – Is it possible to capture some thoughts on your previous view of a theory? Can we capture your previous thoughts about this…?

Response: I was thinking along the lines of, when I thought of theory, I thought of, like, theory of evolution or theory of universal gravitation, things that are very well established,

> you know that is why I have ‘years of data’. My initial thought was that it didn’t start as a theory, and after we accumulate enough confirming evidence, it becomes a theory.

Further clarifications to this positivistic view leaning statement followed during the interview discussion. Participant’s additional statements elucidating preconceptions supporting a positivistic view are listed as taken from the responses to demonstrate such views on scientific reasoning.

> My Initial idea was that for something to be a theory it needs evidence to support it…more evidence, stronger the theory…
>
> If theory doesn’t work with some of the evidence, then we modify it to agree to those observations. More evidence for the enhanced one, we confirm the theory.

The next segment provides further evidence of a participant’s acknowledgement that the pre-learning concepts on experimental verifications of a theory were aligned mainly within a positivistic view.

Question: We were talking about the theory of gravitation… Can you tell why you thought it was a good theory, during your pretest? Participant was informed clearly to make sure the responses depict preconceptions at the time of pretest.

Response: For example, you can make some calculations about the force between earth and sun, and then predict the earth’s motion. If it agrees with your observation, it is good.

Response: I think here, verifiable means you must be able to make observations based on predictions.

Response: Confirmation, would generally be, you make a prediction, and then you make some observations and you see if they match, if they do that, it’s a confirmation.

Question: What level of confirmation is necessary?

Response: I don't think any set number. I think it is important for confirmations to come from different people and different examples. Different people will predict different examples.

And they will build the theory to match the patterns. And then, may be they would take the theory and setup some new experiments, make predictions with the theory and then check with your observations. That's kind of what I was getting at.

In the context of gravity: Theory would be that objects with mass attract each other, and the law would be the actual mathematical relationship – of how they attract.

And looking back on this, my conception of theory and law was muddled…Theory is supposed to be applied in every permutation.

As a concluding remark, this participant stated, "I guess I did not have a concrete idea…" Then, the participant explained prior conceptions on how to enhance credibility of a theory,

> I think here what I was trying to say is that… once I have confirmed the prediction, I will get other people to do it, you know, first to see if may be test my methodology is accurate and then have other people test it in their own ways in other situations, like that. Every time it confirms it enhances the credibility.

In the pretest multiple-response questions, referring to the first question, (1. A good theory should have certain characteristics. Which of the following is the most desirable quality of a good theory?), participant choice was option 4: 'A good scientific theory is proven true with a large number of confirmations presented by many scientists.'

The participant explained pre-learning uncertainties using cognitive understandings as follows.

I think it was intersection of observations as most likely, you have all these observations, you might be thinking two or three possibilities, then you go with the most intuitive one as your explanation.

This viewpoint highlights a highly positivistic attitude in pretest reasoning. However, the participant was aware of the need to have highly specific constraints that restricts observable predictions.

If a theory can explain everything, I have this idea that a theory should be specific. You wouldn't, I would be vary of a theory that would explain photosynthesis and plate tectonics.

To sum up, in relation to positivistic pre-learning cognitive framework during the pretest, participant remarkably clarified the way of thinking and said,

And again, this is because my idea that observations come first. Then, you kind of go back. To further clarify if a theory contained natural phenomena should be directly visible in our senses --- so here, I didn't mean that we had to be able to see. Something whatever tools we have, x-ray diffractions of crystals; you are not able to see. Based on patterns we can. Indirect observations would still be Okay.

The participant, however, made it clear how prior conceptions leaned towards observation driven theory formulation and building of 'most likely' explanations as scientific theories… insight to this inductive worldview is evident by,

Response: I think my initial thought was that since we gathered all these observations, you know, we see a pattern, then we formulate the theory. Reason the theory is most likely, is because we have all these observations.

When further asked about this direction of 'going from observation to theory'…, and how scientific statements may be conclusively verifiable…. Can you explain further?

Response: I think just the idea of falsification, I just was not exposed to it at that point. So, I think that's why. This was much more familiar to me.

General sentiment and the degree of enthusiasm of this participant remained very high during the interview, with a keen interest in understanding presented NOS constructs and discussed the difficulties faced during pretest providing a lucid account.

Participant B

Question: I wanted to find out more about your pre-learning views and post-learning change of views. Can you elaborate these changes, if you can go back and reflect on your pre-learning…? Let's look at a couple of questions… First Question, 1.) A good theory should have certain characteristics. Which of the following is the most desirable quality of a good theory? After review of chosen response, 'A good scientific theory is proven true with a large number of confirmations presented by many scientists',

Response: …Especially for physics it's very hard, because theories are laws, and laws you can't really test, except when it goes to crazy fields like Astrophysics. That's the only way where you can actually prove or disprove some kind of theories. And, once again... keeps proving that Einstein was right. Theories are laws… They are really difficult to distinguish. But, all I kept remembering was that the core of scientific theory is evidential based; so when I think of proven, I think that they are reaffirmed within the scientific community that it is actual evidence from that… Accepted evidence based on confirmations.

Question: Can you clarify your understanding of the word 'proof'?

Response: A theory is proven means, accepted evidence based on confirmations.

Next was a brief discussion on the fifth multiple response question. Question 5, ‘Which of the following is the most desirable statement that describes testing of predictions of a theory?’ Participant’s choice in pretest: ‘To test a theory, it is essential that already known positive observations are precisely measured and repeatedly verified by many scientists.’

Response: So, the question is asking, what best fits how to test predictions of a theory. That word in itself was confusing to me, I remember. Because, am I testing, and then applying it to another test…like a theory and then applying to a new test? Referring to choice of answer in the pretest,

Response:, So, I picked that one, because that seems like what we learned in science, I drew from what I learned in science from elementary school, high school, that experiments are valid if it’s repeated, yeah.

In the post-test participant shifted this answer to the most desirable choice. Regarding this change she said, “So, something influenced me…” This change is discussed later in detail in the post-learning views evaluation.

Participant C

Question: If you can give a single statement explanation, stating what prior idea lead to the change of your view of a scientific theory…?

Response: Over my prior career, looking at, you know, building a body of evidence for a particular view of things, I guess I was equating that with a somewhat colloquial term of theory. And, in understanding what constitutes a scientific theory in terms of… evolution for an example, or other examples that you gave, it obviously is a different entity. That understanding went from, you know, helped me to more clearly understand what the generally accepted view of what a scientific theory is.

2. *Reflections on Post Learning Gains (particularly their conceptual-change-specific reflections related to their learning gains on the post-test)*

Participant A:

Participant provided concise statements addressing certain important changes in cognitive understandings. Referring to the first multiple response question,

Response: You can come up with a theory from the start.

Response: I think it is much more difficult to come up with falsifiable predictions, predictions that could falsify a theory.

Question: How this learning will be useful in your teaching science?

Response: I thought, you know, The structure of the actual program (referring to student teaching assignment at Double Discovery Center at Columbia College), it's ten classes every week on Saturday, it's kind of an enrichment thing, and so, I figured out take one of those periods and explicitly trying to clear some of these up. Because after going through this it was very obvious to me nobody explicitly tells these things, you probably never going to … so I thought, you know, I am not kidding myself, in one of my classes, on a Saturday with a bunch of high schoolers, I am not going to get hundred percent… at least I can help a little bit… If I can at least clear up the misconceptions, no it's not just a theory, explain to them you know, how the strength of calling a scientific theory and all of that, you know, a lot of people have theories and laws backwards, and things like that. So, going through this got me thinking about it, inspired me to take it in exclusively and talk about this.

Response: … Actually, just last night, kind of typing up a preliminary lesson plan. And, so my first idea was that, I was going to have the students as a group come up with some terms that have meaning in science and everyday language. I was going to let them on their own come up with a chart for everyday definition and what the scientific definition is. And we were going to come back together and discuss these things as a class and get an informal pretest. After that I would kind of set them on the right track… Then, I wanted to, I would take a theory and discuss during a class…

Participant B:

The post-test explanation for the same question asked earlier in the pretest, Question 5, was correct this time around. Question 5: To test a theory, it is essential that the outcome of testing such a prediction be currently unknown, or previously unobserved.

Response: At this point I think this answer made more sense to me. Because, I was just like for some reason, I was stuck on the example of relativity. And, just current fascinations after I learned Astrophysics, with all these new evidence they are collecting, from advancing technology of course, you know, more telescopes. And then, all of a sudden, these things are proving relativity right. I think it was the dual white blinking star, somehow proved that the speed it blinks, and the gravitational pull towards each other, proved that general relativity is correct. And that was just that a very recent finding. [Participant referred to new and previously unknown observations that agreed with the predictions; these observations could be predicted by general relativity and successfully observed] So, nothing was necessarily repeated, you know what I am saying… And, I realize that in order to test those grand physical theories, one discovery is actually enough. But it is not just that, all the other observations fit with that too. So, I was like, may be repeated is like too narrow, I don't know…

[Reflecting back on giving prominence to 'repeatability' and reproducibility in the earlier pretest answer] … it's what we learned [in school], and I spit it back out.

Response: It is just like a slight tweak in thinking, and what I was looking at… Because, I could be looking at a different experiment in a classroom where it has to be repeated, and then that would fit the theory.

General comments on the post-learning views:

Response: I think the video module did a really good job in emphasizing the point that, I think it had to do something was interesting … It started out with a social perspective …it's just a theory, what do you mean by just a theory... Actually, I took a little bit of my classroom learning into how charged that word is in the whole dialogue within America. So, actually the video seems to be addressing that. Theory of Evolution is not just a theory; we are using theory completely differently than what other people think. So, it did a good job addressing that. Scientific Theories based on, evidentially based, and it's made, so that it can incorporate, like a very big phenomena, enough so that, if you test that, then it can be refuted. That's what's the difference. And, to me, that highlights the key difference between social use of theory and the other…

Response: And, as emotionally charged as you can be about your own theory… and then all of a sudden, oh, wait there may be another component… It can still be added on, it can still be modified, at the same time, it's there to explain that phenomena. And it's going to be there until something refutes it. I think that's how I applied it later on.

Because, theories are once again… The concept of perfect theory, it does not exist in science community…

As explained earlier, participant B answered 3 questions in the post-test with positivistic responses. One such response was Question 6, and participant clarified what has gone through her thinking as follows,

Response: I think I reverted back to reproducibility. What is a good observation? And, a good test of theory? (after reviewing the question and her response given at post-test)… I was playing with the idea that good observations…, and validity of it. It is only valid if people can actually reproduce it, which is the way how it gets accepted by the scientific community…Those answers were very drawn in… for me… If evidence is reproducible, and people do reproduce it, like I feel that it gains credibility.

Response: And at the same time, I feel like, nature of science takes a back stage because students are going to have to perform to science textbooks that we give them. So, they are going to have to perform in the standardized testing – to them, that's all facts. This is what I am going to take for granted. For them it is all about facts…. Scientific theories are really weird, I don't know if you would agree with my statement….Yes, theories explain universal phenomena, but how explains it is very specific. We all know the gravitational theory… gravity between the planets; we predict that all planets, going to act like that within the gravitational field. …. But, that also limits our predictions to go around our predictions. It is generally applied, but really specific at the same time. Still I may not have the skills to grasp that.

Response: We are asking them in a sense about these in a way to read between the lines, you can observe it, but there are phenomena behind it. That behind it, we require imagination... Application to other phenomena... That might be a cognitive process for students that they are not exposed to it before, that's going to be a completely new field. I can only imagine, because I unfortunately learned scientific theory like, you know, repeatable, or, step one hypothesis, step two prediction, step three testing. All we did was like, almost like filter the water, or like… it was very micro environments.

Response: I feel like, me being a physics major made a difference than itself. Because it is so prevalent there in making different observations, and refuting theories. I think physics…and stuff…, I wouldn't be sure if this was chemistry, I wouldn't be sure if it was biology. Even though evolution is…: Evidence itself is… I mean the genetic evidence is getting more and more valid…But then at the same time, the evidence itself is heavily observations…

Similar to other two participants, this participant showed great enthusiasm during the interview and requested to have a copy of responses hoping to reuse the content in classroom teaching.

Participant C

Similar to earlier questions raised with participants A and B, participant C was asked to reflect on the conceptual change.

Response: And I certainly, I think that the idea of falsifiability, and you know, constantly challenging a theory or a set of data is something that I was familiar with, and, you know, that there are times in medical research, where it seems things are very clear, and then something comes along and disproves it. Participant then gave an example on how our understanding of the causes of a certain stomach ulcers changed with new evidence that falsified previous understanding.

Response: What seems to be a solid set of data turned out to be wrong. And, the idea of testing that as false and subjecting it to an experiment where there was falsifiability was very useful.

Response: I guess briefly, what made me change from one to the other was a clear understanding of what one needs, what it takes to actually to have become a scientific theory. There aren't that many that I can name where you have such an overwhelming body of evidence that supports something. But when they are there, it's important that they are still be subjected to questioning and testing and… to falsifiability…. That approach makes very good sense to me and it seems like an appropriate way to advance scientific knowledge."

Participant was asked to reflect on the Question 10, the most difficult question in the questionnaire.

Question: What was your previous understanding vs. post learning understanding? First question being the easiest and the last question being the most difficult…

Response: I thought that was an interesting one. I think that, I was going from sort of the view of that the more data supports something, the better. , which often is the case, but... often you also have to look at the quality of data, such that, if a, …you know, have you been…, have the data being generated really from a rigorous point of experiment that are looking to, you know, trying to disprove that theory, or are they really sort of designed to trying to be one of the crowd and further support it. And, you can see how sometimes the herd mentality, and sometimes takes somebody with a contrarian view to really design the experiment that put the theory to a real test.

Conceptual change of participant C,

Response: I noticed I changed substantially. I recognized that when I took the post-test. And, you know, a lot of it is from what I learned and as I was explaining earlier. I had a greater clarity of it, and I appreciate the opportunity to learn something. And you know it is interesting because I do in general, you know, before I took your little course here or before coming to TC, I think it is good to have a healthy skepticism about any set of data and subjected to continued scrutiny, and thoughtful scrutiny, and yet I think that I did have a, as you were describing it, I certainly portrayed a positivist view of the world; and how I described things in the pretest. And to me, part of it, I think I did not clearly understand the significance of falsifiability. But it was also a really good reminder to me that one does need to continually have that healthy skepticism and willing to do the work to keep challenging and doing thoughtfully design rigorous experiments to really find out what is there in the truths in nature. And, in that sense, I think this exercise was a good reminder for me.

Discussion

The objective of this study was to evaluate the effectiveness of an online teacher education and professional development module to teach some fundamental principles of a critical rational stance in the nature of science. Overall, there was substantial evidence supporting the effectiveness of the implementation. For example, teachers who initially showed a very low 36% mean pretest score had an encouraging gain of 30% to reach a desirable 66% mean post-test score. This post-test score was established by the author as a reasonably proficient threshold or benchmark level of teachers' understanding of CRNOS. More specifically, the high gains in post-learning understandings by the weakest participants, who scored below the benchmark of 70% on the pretest, provide additional evidence to support that this learning and evaluation program can be an effective means of improving teachers' CRNOS. The study showed that initially a very large group, 76% of total teachers, did not meet the benchmark in the pretest. These weakest participants had an extremely low mean of 24% on the pretest, a somewhat disturbing indication of possible limited knowledge by this sample of teachers. However, after using the CRNOS online learning module, they improved to reach a relatively high 62% mean score, representing a 38% gain. Teachers within such a weak performing cluster represent one of the major challenges that science teacher professional developers face. The significant gains made by this sample of teachers indicate that an online learning module of the kind implemented here can be a useful resource in teacher professional development. In particular, 65% of the sample population in this study met or exceeded the benchmark on the post-learning evaluation compared against only 24% on the pretest evaluation. In total, this evidence provides encouraging evidence that the online learning module and related assessment instrument can be effectively implemented for teacher training related to CRNOS, and also serve as a productive model for further development of online learning modules.

Additional supportive evidence comes from the analysis of the conceptual change data. All of the participants who demonstrated the highest learning gains in this study, initially leaned toward a highly positivistic view, or inductive worldview, before using the online module. Interview evidence obtained from participants who made substantial gains after use of the online module suggested that their initial, highly positivistic orientation could be attributed to a lack of sufficient exposure to these fundamental concepts during their prior formal science education instruction. For example, the following participant's comment supports such an interpretation, "After going through this it was very obvious to me nobody explicitly tells these things, you probably never going to…" Reforming K-12 teachers' understanding of the CRNOS perspective may help to better prepare students to enter college with a much more sophisticated understanding of modern practices of science, and thus provide a stronger foundation for their professional teacher education prior to entering the classroom as a science instructor.

The interviews also provided evidence that the teachers found the online learning experience enlightening and interesting. Some selected comments are presented. "This was a most interesting exercise", "I thoroughly enjoyed the content and its simplicity" and "it was enlightening and quite helpful." One participant in particular expressed elucidating comments of gratitude for having the opportunity to participate in this study. "I was just going to say, you know, actually really got a good bit out of this…A lot of things, I kind of got out of here. This was actually really helpful for me when studying to teach… actually, it was good." Another interviewee said, "I found it very interesting, because it was relevant to what I was learning as a teacher, as a science teacher. We are all about Nature of Science…" The third interviewee addressed how the experience contributed to her/his conceptual change, "I noticed I changed substantially. I recognized that when I took the post-test." The qualitative evidence in general complements the quantitative test results and supports the conclusions made about the participants' positive conceptual change.

The study also complements well-known nature of science studies and assessment instruments such as *Views of Nature of Science Questionnaires* (*VNOS*) by Lederman et al. (2002) that contained open-ended items, allowing the respondent to make more reflective and revealing insights into their understanding of NOS. In some respects, there are similar characteristics and constructs shared by the *CRNOS Questionnaire* used in this study and the *VNOS*, particularly in focusing on general conceptual understanding of NOS and modern views on the practices of science. Among other new dimensions, the CRNOS questionnaire and the learning module address such topics as how we establish enhanced credibility of our theoretical understandings and achieve a higher level of rigor and critical analysis in evaluating research data and testing hypotheses. CRNOS brings attention to our deep reliance on human imagination as the primary driving force of credible knowledge generation. Imagination has been a central force in both the creative process of devising new theoretical explanations and in the design of experiments to gather data that can withstand the most rigorous falsifiable tests, thus adding a major new dimension beyond solely using verification.

Future research within this program could begin with additional improvements in the assessment questionnaire items to improve reliability, and additional studies using larger sample sizes. A revision of the CRNOS learning module to address some of the constructive but critical reflections offered by the participants would be helpful to further sharpen its clarity and conciseness. The broader long term vision and growth of this research program however can include new research and development efforts to create assessment tools and curriculum materials for K-16 grade level students, thus better preparing students for more advanced studies in science. Transforming current science inquiry teaching and learning practices to focus more on encouraging students' imagination may contribute to more effective realization of learning CRNOS perspectives, given the close ties between falsification and imaginative theoretical thinking.

In conclusion, this research was an ambitious attempt to find out to what extent a complex idea such as CRNOS can be effectively introduced to a sample of pre-service and in-service teachers. The study provided a considerably effective, accessible and low cost digital learning system for teacher education in this newer vision of NOS. Evidence presented here shows that the CRNOS questionnaire can be used to reliably assess teachers' understanding of CRNOS. The qualitative analysis of the teachers' conceptual change further attests to the efficacy of learning gains using the online module. Gains in learning of the weakest participants demonstrated that this online instructional module can effectively bring significant enhancement in teachers understanding of Critical Rational Stance in the Nature of Science.

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Chapter VI

DISCUSSION

Two papers included in this thesis address a common objective; i.e., to find out to what extent teacher understandings of a post-positivistic view of NOS, namely the critical rational stance in the nature of science (CRNOS), can be assessed and enhanced. The first paper introduces a new instrument, consisting of a multiple response questionnaire, to assess teachers' understanding of fundamental constructs underlying CRNOS. The second paper presents an analysis of the efficacy of an online learning module intended to improve teacher understanding of CRNOS. It utilizes the assessment instrument presented in the first paper to measure teacher gains resulting from their use of the online learning module.

Common Theoretical Foundation of These Two Papers

The common conceptual framework for these two papers is the CRNOS theoretical framework (Einstein, 1936; Feynman, 1965a; Gould, 1998; Hawking, 1988; Hume, 2011; Popper, 1989; Sagan, 1995). The design and development of the assessment instrument and intervention were founded on some basic tenets of the CRNOS viewpoint. Because the assessment instrument was utilized in both of the papers, it represents a common methodological linkage between the results of these two studies. Each test item in the CRNOS instrument examines a participant's perception of a uniquely defining logical implication of the CRNOS perspective that can elucidate whether the epistemological viewpoint of the respondent is clearly consistent with a CRNOS view vs. a logical positivistic view (Bacon, 1850; Newton & Thayer, 2005; Richardson & Uebel, 2007). It also provides evidence of some commonly held misconceptions. Each test item in the multiple response questionnaire contains a desired CRNOS (target) response and four non-CRNOS distractors. The distracters were written to be likely attractive choices to a participant who isn't well informed about the CRNOS viewpoint. Given that the instrument was used in the design of the research in each of the two chapters; the distractors, representing logical positivistic and misconceived views, also are a common source of evidence about the respondents' varied interpretations of NOS, and more specifically CRNOS. Hence, from an assessment viewpoint, the evidence on positivistic or misconceived views, detected as a result of utilizing the assessment instrument, is also a consistent source of evidence used in the analyses in both papers, thus contributing further to their compatibility. Within the common CRNOS theoretical framework that characterizes the test items and the online learning module, a final recommendation in the second paper contains some proposals for how to more effectively utilize these new learning materials to enhance teacher professional education, especially relevant to modern views of NOS.

The New Instrument to Assess Teacher Understanding of CRNOS and its Feasibility

The new CRNOS assessment instrument, presented in the first paper, was designed and evaluated in a preliminary study as an essential step in gaining evidence of its reliability (Cronbach alpha = 0.80) and validity. Construct validity of the instrument was established via comments obtained from a panel review by experts in science education. Based on the favorable evidence from the first study, the assessment instrument was used as the primary assessment device in evaluating the efficacy of the online learning module in improving teachers' understanding of a CRNOS perspective. Additionally, the results of the first study point to the need for teacher improved understanding of post-positivistic views - at least based on the sample of teachers available for this initial trial use of the instrument.

In general, the feasibility study reported in the first paper achieved the intended major goal of gaining a comprehensive understanding of the cognitive structures of the opportunistic sample of teachers in relation to the CRNOS theoretical framework (Einstein, 1936; Feynman, 1965a; Gould, 1998; Hawking, 1988; Hume, 2011; Popper, 1989). The teachers' cognitive representations of NOS, based on the results of administering the CRNOS assessment instrument, were assigned to three categories: 1) a CRNOS-congruent perspective, 2.) a positivistic or inductive worldview, and 3.) an incoherent mixed cognitive perspective combining aspects of CRNOS, some positivistic aspects, and NOS misconceptions. The findings, including the above categorical evidence, of the first paper support the claim that a detectable major deficiency exists in some teachers' perceptions underlying the CRNOS. Moreover, it is probably indicative of the challenges that teacher educators may face in improving the preparedness of prospective and in-service science teachers to better achieve the recommendations of the Next Generation of Science Standards to more validly represent the *Nature and Practices of Science*.

To highlight the summary of major results, this feasibility study using a sample of in-service teachers detected that an extremely high percentage of the teachers (84%) possessed a very weak understanding of CRNOS, with a particularly low mean score of 30%. Among the more notable findings, are the detection of some consistent cognitive structures inherent in the teachers' responses to the CRNOS questionnaire items. These cognitive structures based on assignment to the three categories cited in the previous subsection are as follows: 16% CRNOS, 28% positivistic and 56% mixed or highly multifaceted incoherent cognitive structures. Highly positivistic participants (28%) are potentially among those of substantial interest in science education research, because they consistently selected the most positivistic views of science, clearly avoiding CRNOS options and the popular misconceptions. The reasons for their exclusive selection of logical positivistic views remain to be determined. Among this large positivistic group were some particularly interesting examples. For instance, C.S. 2 (Table 2 in

Paper One) was among the most logically positivistic, and chose 100% of the positivistic distractors. Equally interesting for further research are the respondents who had a mixed perspective, partially positivistic and partially CRNOS. It is not clear how they maintain these two contrasting world views, and additional research may be profitably directed to elucidating how such respondents rationalize the apparent inconsistencies in their thinking.

Although many well known scientists in various major disciplines of science (Einstein, 1936; Feynman, 1965a; Gould, 1998; Sagan, 1995) emphasized the theoretical significance of CRNOS, in contrast to popular inductive or logical positivistic approaches, the science education establishment appears to have largely overlooked the scientific philosophical and educational significance of CRNOS. DeBoer (1991), for example, emphasized the paucity of interest in presenting modern NOS perspectives, “Science educators were slow, however, to apply this new view to science teaching”. His “new view of NOS” and his conceptual framework is similar to that of CRNOS, where he called attention to Einstein’s critique of “excessive faith on the part of nineteenth-century scientists in the inductive method” stressing a possible end result as, “ Failure to understand this fact constituted the basic philosophical error of so many investigators of the nineteenth century” (Einstein, 1956).

Duschl (1985) expressed similar views as well, suggesting that the science educator community which is answerable for timely inclusion of important changes in to the curriculum did not account the new understandings gained in NOS. He said when the epistemological perspectives of NOS changed within philosophy of science community towards a new definition in the twentieth century, the new curriculum development programs of the 1960s “effectively ignored [these] developments” (p. 551).

Additionally, Finley (1983) commented on popular inductive or positivistic approaches to inquiry learning by stating, “If we fail to recast our view of the nature of science, and continue to overemphasize a discovery approach to instruction, we are likely to continue to expect that students will inductively formulate concepts and generalizations. It is unlikely that a child would ever inductively discover the full meaning of science concepts – even a concept as fundamental as mass.” This deficiency in an emphasis on modern perspectives, such as CRNOS, along with a highly inductive worldview or logical positivistic perspective that may be emphasized by teachers, should be recognized as a central problem in science education.

The finding of a low mean score (30%) among 84% of the participants in the first study, is alarming, because the ratio of positivistic to CRNOS options in the questionnaire selected by teachers in this sample also remained very high. It was close to almost double the size compared to teachers who were categorized as largely CRNOS-oriented. These teachers with a positivistic structure in logical reasoning will be more likely to emphasize only an inductive logical positivistic worldview when teaching their students. Consequentially, downstream these teachers will more likely emphasize science concepts and inquiry learning within the limits of a largely inductive, interpretive approach (Finley, 1983).

In summary, the results of the first paper strongly supported the need for enhanced teacher understanding of the epistemological principles underlying modern science, such as the CRNOS perspectives. The newly designed CRNOS assessment instrument, and the first feasibility test of it, may provide a foundation for further development of instruments of this kind, and in the meantime provide a reliable and valid method to assess teacher understanding of CRNOS.

The Intervention and the Extent of Enhancement Achieved in Teacher CRNOS Understandings

The implementation of a new learning experience (the online module) presented in the second paper, including quantitative and qualitative examination of the effects of the implementation on teacher conceptual change relative to CRNOS, provided encouraging evidence for the value of this new approach. Quantitative results from a paired t-test and the qualitative evidence, analyzed in relation to relevant published prior work [e.g., Creswell (2012) and Merriam (2014)] presented in the second paper, provided encouraging evidence of the successful application of the online learning module. Among the main results supporting effectiveness of the learning experience are as follows. Although only 24% of the teachers met the benchmark at the time of the pretest, 65% of teachers met or exceeded the 70% benchmark target at the time of the post-test following the online learning experience. The overall sample mean test score raised from a low of 36% to a high of 66%, demonstrating a 30% gain. More importantly, the weak participants who fell below the benchmark of 70% in the pretest showed a significant 38% gain in understandings at the time of the post-test. Going from a 24% pretest mean to 62% at the time of the post-test.

Based on the qualitative evidence, the participants who demonstrated the most outstanding gains made highly positive and appreciative comments about the effectiveness of this learning module. While the overall comments are highly supportive, it is important to note, however, that this exploratory study provides only an introduction of the most elementary foundational understandings of CRNOS. A more extensive learning experience may be necessary, distributed appropriately over a longer time, to fully help teachers grasp the larger view of CRNOS that they may require to fully employ it in teaching.

This intervention, although only a prototype, turned out to be a successful trial experiment. Encouraging results may be largely ascribed to the adopted instructional design strategy. First, instructional contents and design were geared towards explicit focus on the core constructs of CRNOS contained in the test questionnaire. The interactive review questions and suggested answers delivered in the module were targeted to encourage reflective thinking in the participants to help grasp and internalize those core ideas. Learning module design attempted to differentiate and contrast the CRNOS concepts from familiar positivistic views and misconceptions using well-known examples from the history of science, hence favorable results in the post-test. Secondly, and most importantly, the key constructs were adopted from prominent authors' CRNOS publications referenced in the theoretical framework. Limiting this lesson only to the most fundamental implications helped present a comprehensible but succinct account in its presentation. Additionally, a thorough faculty critique and review followed by several rounds of reworking of the learning material contents further helped achieve effective learning.

Alignment of CRNOS with the Next Generation Science Standards (NGSS)

Recent introduction of NGSS (National Research Council, 2013) sets a long term vision and consensus among science educators in the USA to bring a foundational epistemological framework in NOS directly to the K-12 classrooms. NGSS recognized the need for explicit instruction of NOS concepts, "…there is a strong consensus about characteristics of the scientific enterprise that should be understood by an educated citizen" (National Research Council, 2013). As clarified in the NGSS Appendix H, the new standard is well-aligned with CRNOS epistemological views. For example, NGSS requests that the teachers address explicitly the foundational epistemological concepts in the nature of science as follows: "Epistemic knowledge is knowledge of the constructs and values that are intrinsic to science. Students need to understand what is meant, for example, by an observation, a hypothesis, an inference, a model, a theory, or a claim and be able to distinguish among them" (National Research Council, 2013). It highlights the overall NOS goals in proper alignment with the CRNOS approach, "One fundamental goal for K-12 science education is a scientifically literate person who can understand the nature of scientific knowledge…"

Integration of CRNOS in Teacher Education and Professional Development within a NGSS Context

The restructuring and reforming expectations contained in the new science standards will very likely influence teacher education and professional development strategies in the USA in the years ahead, supporting the recommendation that CRNOS should be included in professional development and teacher education programs. Teacher training programs will need redesign to address NGSS – Appendix H of the NGSS stipulated goals could indeed benefit by an inclusion of CRNOS principles. The new standards support NOS enhancements to improve teaching practices, "The nature of scientific explanations is an idea central to standards-based science programs. Beginning with the practices, core ideas, and crosscutting concepts, science teachers can progress to the regularities of laws, the importance of evidence, and the formulation of theories in science." In such a view, adopting a CRNOS framework across the various disciplines of sciences holds promise of being highly productive toward improving citizens' understanding of modern science practices. The standards also provide a suggested guideline "a series of concepts and activities important to understanding the nature of science as a complement to the practices imbedded in investigations, field studies, and experiments." To achieve overarching expectations from these activities, professional development and teacher education may need to refocus on adequate integration of introductory concepts in deductive formal logic on how to construct logically consistent valid argumentation within these activities. An integration of creative capacities and imagination to brainstorming, wondering and 'daydreaming ideas' to imagine most remarkable new explanations is central to CRNOS. The ability to critically assess logical arguments to test and examine validity and fallacy of theories and ideas will be a major part of such a new endeavor. Teachers being able to distinguish valid and invalid arguments in a scientific context will be important. Identifying quasi-science or pseudoscience including popular myths, while also emphasizing the central tenets of CRNOS in critically analyzing evidence to either support or refute the claims of these alternative views to scientific understanding is centrally important.

Overall, there is only a modest amount of learning tools and training material in these areas in terms of quality and quantity for professional development and teacher education. Further research, and curriculum and learning resource development efforts, will be needed in a new direction for such future training programs, including training the professional developers in science education to have a deeper understanding of CRNOS and its educational implications. Some of this new approach can be enhanced by revisiting what Duschl (1990) proposed in his book on *Restructuring Science Education: the Importance of Theories and Their Development*, and to maintain a relentless focus on "Inquiry as Content" as Rutherford (1964) proposed. By amplifying these previous recommendations by incorporating CRNOS as a central tenet should significantly improve future teacher training programs toward increasing public scientific literacy.

Recommendations for future research

Although the sample size in the second paper was sufficient to obtain statistically significant findings, this study - and others like it - should be replicated with a larger sample population to more fully verify and refine the findings reported here. Long term retention of conceptual change experienced by the teachers who used the online module was not examined in depth. Detailed studies will be needed to fully examine the degree of cognitive internalization of the conceptual understandings and the ability to recall and transfer the learning in new situations, especially problem solving situations. Downstream effects on students were not addressed in this study, and further research is needed to examine how the teacher's percepts about CRNOS affect their teaching and student science learning. Appropriate curriculum materials are also needed to provide support for teachers who want to incorporate the CRNOS perspective in their classrooms. Presently, many of the inquiry-based learning materials are not fully exemplary of the new post-positivistic perspectives. One participant commented cogently about this problem, "Unfortunately, I can't really think of an inquiry-based way of teaching this in an Internet module that would force people to come up with these ideas on their own." Although the gains reported here are highly significant for an introductory effort such as this study, the realization of deeply sustained understandings, demonstrating a thorough knowledge, would need further research studies with a much broader scope, larger sample size, and more detailed analysis of the findings.

The intervention is structured to introduce only the essential key foundational implications of CRNOS at an introductory level. It did not cover the important nuances or fine distinctions a teacher will likely need to teach CRNOS-integrated science. Understanding of the core principles however is a first step to start recognizing the major implications and demonstrate knowledge.

Future research roadmap

Three potential pathways for future research are suggested, including: 1) refinement of the research instruments used in this study to better support teacher professional development, 2) production of grade-level appropriate curriculum materials for school science learning related to CRNOS, and 3) theoretical research on the basic paradigms of CRNOS.

First, incremental enhancements with essential revisions of the assessment instrument geared towards a higher Cronbach reliability and expansion of the new online intervention for higher effectiveness are needed. Revision of the module should include refinements to address the limitations and enhance the clarity and conciseness of the learning experience as recommended by the expert panel of reviewers and those of the participants gathered during the qualitative phases of the study. A more refined online learning module may yield an increase in the post-test mean from 6.6 to a more desirable target of 8.0, also using a relatively larger sample size. Back-end database and software engineering improvements can yield a more user-friendly digital learning platform; including, perhaps, a cloud-based, software application. Introducing this learning platform as a robust engineered learning tool to a global audience of science teachers and science teacher professional development programs can be highly beneficial.

Second, a long term research, instructional design and development strategy centered on CRNOS learning materials is needed to cultivate grade-level appropriate curriculum applications of the CRNOS perspectives in classroom teaching and learning. A comprehensive and programmatic set of CRNOS learning materials, integrated with the school curricula and consistent with the Next Generation of Science Standards, beyond the online module used here, can be a significant contribution to improving NOS instruction in the schools. All grade levels and all major specialties in natural sciences can be included in such an initiative. Student assessment methods also should be developed for all the grade levels and subject specialties. This will likely require a broader vision and commitment from the secondary and postsecondary educational establishment coupled with sufficient collaboration among philosophers of science, science educators and practicing scientists to realize this goal. In conjunction with the development of a school-based curriculum, a comprehensive teacher development program will be needed to provide teacher education in the implementation of such a science learning program.

To productively and strategically move education in this new direction of CRNOS, the importance of fostering students' imagination and passion for learning science should be a major conceptual core of the new curricula. History tells us that each major discovery in science originated with contributions from many varied and imaginative sources (Feynman, 1965b). No single methodological approach was adopted by the highly imaginative scientists working in their various specialties and no simplified methodological procedural prescription has been devised to satisfactorily produce these major advances in scientific discovery. There are known methodological approaches to stimulate imagination (Feynman, 1965a; Osheroff, 2001, 2010), although there is no deterministic method driving successful innovation and discovery. Fostering students' imagination in a generative thought process conducive to scientific discovery towards CRNOS can be gained with lesson plan development combining critical thinking and creative imagination as some of the major learning goals. Research is needed to further analyze how some of the well known strategies to encourage students' creative thought can be incorporated with CRNOS principles to design more effective curricula consistent with modern views of the practices of science. Investigating what factors may promote student enthusiasm, intellectual passion and their motivation to inquire more deeply into unknown dimensions of our natural environment, as they better comprehend CRNOS perspectives, can be one of the additional merits of greater emphasis of CRNOS in school-based learning. Emphasis on experimental design to help students understand how to test their own new hypotheses and propositions within a CRNOS theoretical framework would be a logical culminating part of such new science curricula.

A third approach to additional research on CRNOS could include philosophical and psychological studies to examine the role of creativity and imagination in the cognitive processes involved when researchers and science learners incorporate more explicitly the CRNOS perspectives in their practice of science. Potential research objectives within a broad scope can include a new synthesis of theoretical explanations of human imagination with CRNOS cognitive perspectives and neurophysiology of the brain. Human imagination is at the central core of new CRNOS epistemological views of modern science; it is the principal human neurological phenomenon that drives new scientific theory generation in conjunction with a deductive logical thought process needed for a critical examination of emerging new predictions in scientific discovery. It will be profoundly important for future research to attempt to establish a grand unifying theoretical understanding of how human imagination, and creative thinking more broadly, is related to CRNOS cognitive skills and potentially in relation to neurophysiological correlates of such higher level thinking processes. The consequences of a successful synthesis of new theoretical understandings can help to advance creativity and imagination beneficial to science teaching and learning. Such a new undertaking can benefit from recent syntheses of constructivist learning approaches as explained by neurocognitive learning theory (e.g., O. R.

Anderson, 2009; 2014) where traditional strands of research from neurophysiology, cognitive science and learning theory have been combined. With respect to such a newly proposed CRNOS synthesis, it will be interesting to additionally focus on evolutionary biology of human intelligence (Deugo & Oppacher, 1993; Parker & McKinney, 2012; Plotkin, 1988; Sagan, 2012; Shettieworth, 1989; Sternberg & Kaufman, 2001) and how higher level thinking such as embodied in CRNOS may have had adaptive value in the rise of human civilization, including modern science, and the selective adaptive features of brain function mediating these higher cognitive skills. A grand theoretical synthesis in this direction may provide a more sophisticated grounding for further research on the nature of science in general, and a more substantial theoretical framework to guide science education inquiry in the area of CRNOS learning.

Understanding the theoretical foundations of CRNOS through mathematical formulations and modeling of these cognitive information processing constructs may have greater implications extending beyond the field of science education to support other specialties such as machine learning (Goldberg & Holland, 1988; Langton, 1997; Nolfi & Floreano, 2001)founded on evolutionary learning algorithms and artificial intelligence research in engineering (Fogel, 2006). Although some of these futuristic research proposals are highly speculative at the present moment, some of these seemingly idealistic goals could be achieved by a more dedicated interdisciplinary approach to explore the multifaceted way that CRNOS thought processes interrelate with other established formal disciplines.

Conclusion

In the contemporary professional organization of K-16 education, science teachers are accountable for fostering students' understanding of a scientific worldview. Researchers generally agree, of the school factors affecting student achievement, teachers are probably the most important determinants that contribute to the largest variation in student learning (Goldhaber & Brewer, 1999; Rivkin, Hanushek, & Kain, 2005; Sawchuk, 2011). Hence it is important that science teachers are highly skilled and trained in achieving learning goals consistent with the best wisdom and understanding of NOS from a modern perspective (Abd-El-Khalick & Lederman, 2000; DeBoer, 1991; Duschl, 1985; Lederman, 1999). Success in cultivating a scientific attitude, and a more scientifically defensible NOS cognitive framework in students' thinking, should help them avoid some of the non-scientific, and mistaken understandings that may be presented by their social traditions, particular culture, and established less-scientifically accurate primitive explanations about the natural environment. Science teachers are the vanguard in leading this effort, to ensure that the younger generations are not just knowledgeable about the most remarkable and powerful scientific understandings developed by our previous generations, but also well prepared to engage in scientific reasoning and critical thinking consistent with our best modern understanding of these higher cognitive processes (J. R. Anderson, 1990; Issa M. Saleh & Khine, 2009; Phye & André, 1986).

Students will need to develop a strong reasoning framework essential for their imagination of new and enhanced theoretical understandings with the highest explanatory power, including novel means to experimentally assess their theoretical deductions in the most imaginative and creative ways. This modern conception, and filtration of weak ideas through rigorous experimentation, relies heavily upon having robust cognitive structures such as the one underlying a critical rational stance. Consequently, a teachers' thorough understanding of a critical rational stance may be paramount in achieving these primary aims of science education – as was one of the major goals of this initial CRNOS research study. We know today that the progress and growth of human knowledge is inherently limited by our own limitations in imagination as we endeavor to construct new ideas and design the most imaginative and rigorously designed experiments to test our hopefully ground-breaking new conceptions. Understanding these fundamental CRNOS-specific science education research goals, and how to address effective research strategies to improve student critical reflective thought, may be one of the most significant movements enhancing science education reform in the twenty-first century.

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APPENDICES

Appendix A

Critical Rational Stance in Science – Contents of the Instructional Module

Introduction

The purpose of this learning experience is to provide some modern ideas about the nature of science, especially those that may help you teach your students about scientific theories. We will consider, especially, a particular view called the Critical Rational Stance. Critical Rational Stance is a way of scientific reasoning that is particularly helpful in analyzing how scientists create and critically test theories. It is a systematic way of carefully and rigorously testing a new theory in order to establish its credibility and enhance confidence in some of the remarkable new ideas that often are contained in scientific theories. Understanding the Critical Rational Stance can encourage students to develop a scientific mindset and foster an attitude of critical thinking when learning science; it also can increase the depth and breadth of a student's understanding about how scientific inquiry actually works and motivate students to engage in genuine scientific inquiry.

Scientists understand theories in a much more refined way than is often used by the public. This has become a notable problem in teaching, because some community leaders fail to understand that a theory is not simply a guess or an unfounded idea. Consequently, as shown in the next video clip, the teaching of some scientific topics such as the theory of evolution has come under unwarranted attack, especially by some school boards.

What is a Scientific Theory?

We will start with the video below to explore how scientific inquiry actually works, and look at how we may specifically define a theory from a scientific perspective. You may watch this on HD mode on Youtube in ‘Full Screen’, however please come back to this webpage afterwards to continue into the next section.

Please click the ‘play button’ to start.

Link 1: https://sites.google.com/site/natureofscienceinteaching/what-is-a-scientific-theory

Link 2: https://www.youtube.com/watch?v=omjdQDbNfK8

Let's review what we just learned:

From the video, we learned what a scientific theory is, and how theories can help us understand natural phenomena. Let's consider following two study questions to reflect on what was presented up to this point and see what understandings did we gain about theories in science?

There are two questions in this review. Please make sure to answer both of them before we move on to the next page.

Review Question 1

In this first question, we will reflect on the general character of a theory in science. Please pick an answer that you consider most suitable, and then click the 'continue' button to view the explanation.

A good theory in science should have certain characteristics. Which of the following is the most desirable statement to describe a good theory?

A. A theory in science is largely a guess, hunch or speculated idea. It is still debated as a possible explanation of some aspect of the natural world because it agrees with some of the observations to justify it.

B. A theory in science is never a hypothesis. A theory contains several universally proven laws that determine how nature works with perfect certainty. Theories are proven right unlike hypotheses.

C. A theory in science helps us understand nature and our Universe by testing our explanations against the natural world. If the explanations we come up with don't hold up when we test them, we abandon them.

Review Question 1 Answer: Neither A or B is acceptable. Let's review why they are not good explanations.

Review Question 1 Explanation:

A theory in science helps us understand relationships in nature and explain natural phenomena. We, humans come up with testable explanations to describe natural phenomena driven by our great creativity and imagination. Our acceptance or rejection of these explanations will depend on the testing of our explanations against the natural world - that's what makes science quite different from other claims of explanations. If the explanations we come up with don't hold up when we test them, we abandon them. In science, observations judge the acceptability of an explanation to determine if the theory is false. This is the foundation of Critical Rational Stance in science. A theory in science is accepted not simply because it agrees or verifies with some positively supporting confirming observations; a good explanation has to survive every rigorous experiment of a prediction that function as an attempt to reject it. A good theory can survive to explain a wide range of natural phenomena without disagreements in a highly consistent robust way. If our explanation holds up well against the most unlikely predictions based on the theory without disagreements, then we accept it tentatively with enhanced confidence.

Now, let's move to the second review question shown below.

Next, we will explore how to identify a good theory from what may not be scientific or pseudo-scientific.

Review Question 2

In this second question, we will use some of the understandings we gained earlier to identify what may be scientific and what may not be scientific. Please pick an answer that you consider most suitable, and then click the 'continue' button.

Which of the following approach may make it possible to separate a good scientific theory from a non-scientific one?

A. A good scientific theory should suggest explaining everything in nature and entire Universe with no conceivable way to abandon it by experiment or observation.

B. A good scientific theory can explain natural phenomena that can be tested against the natural world, so we may potentially abandon it if an expected observation is absent.

C. A good scientific theory suggests describing most of the already known observations with good agreement with the theory most of the time.

Review Question 2 Answer: Neither A or C is acceptable. Let's review why they are not good explanations.

Review Question 2 Explanation:

A theory in science helps us understand connected relationships in nature by testing our explanations against the natural world. If our explanations don't hold up when we test them, we abandon them. This critical approach to evaluate a theory requires a rigorous attempt to reject it by experiment beyond what we know as good verifying evidence that genuinely supports it. If the explanation disagrees with a good careful attempt at experimentation, then the theory will be rejected, and we will try to modify or improve that theory further. No matter how many good confirmations we have, we cannot ignore those observations that would disagree with our explanation. A theory is valuable if it can describe a large class of observations without failing in its explanatory power. However, it should be disprovable by observation at least in principle so we can test it to see if it is wrong. Explanations that fail in certain unpredictable ways in experimentation but shows agreement in some regions are not very useful to us. A theory that gives occasional agreement sporadically with observation, while failing at certain times is unscientific and not useful. Any theory that claims to explain everything in the Universe in a non testable way, or non-refutable way, where it is crafted to avoid possible disproof by experimentation is also unscientific.

Now we have completed both questions, let's move on to the next section.

Essential Character of a Scientific Theory

In the prior section, we considered what are some of the general qualities of a sound and productive scientific theory, including that it should explain a certain phenomena in nature based on the theory.

In our next journey, we will look at the fundamental characteristics of any theory which serve to distinguish a scientific one from pseudo-scientific or non-scientific ones.

You may watch the video in Youtube HD Full Screen mode.

Please click the play button to continue.

Link 1: https://sites.google.com/site/natureofscienceinteaching/essentials

Link 2: https://www.youtube.com/watch?v=FnfSSq-EhTU

A Good Theory Must Make Falsifiable Predictions

In the prior section, we considered what are some of the qualities of a sound and productive theory, including that it should be highly general, make testable predictions, and especially that it should yield explanations that are potentially capable of being refuted, not only supported by positive evidence. That is, a good theory should suggest ways of testing it that indeed may provide verification through gathering evidence, but also must clearly indicate what new evidence would potentially refute it, if the predicted observation is absent in nature. The Critical Rational Stance particularly emphasizes the importance of stating a sound theory in a way that makes clear what evidence could be gathered in an attempt to refute it. This is an essential aspect of modern scientific inquiry. It is also an important point that as teachers we need to emphasize more fully when we are teaching science as inquiry. That is, evidence that verifies a theory provides information about what aspects of a theory can be retained as we proceed forward in our quest to test its accuracy. But, also in our testing of the theory and its predictions, we must also clearly understand what evidence can be gathered at least in principle to refute it. Only then, can we have some confidence that our verifying evidence is sufficient to consider the theory acceptable as it stands at the current time. If a theory or hypothesis is to be most likely to contain refutable aspects, it should be a rather imaginative, and even "risky," novel way of explaining natural phenomena. For example, historically, some of the most productive theories in science were initially considered, sometimes, as remarkably unlikely, or even highly deviant from the accepted view at that time. So, in our inquiry teaching, we need to encourage students to initially think imaginatively about possible "theoretical" explanations and hypotheses that would explain the natural phenomenon they intend to test through inquiry and gathering of evidence.

In the process, of course, with the help of the teacher, they may need to refine their explanations both in terms of the logical consistency and in relation to data (positive and negative) gathered during their inquiry.

It is quite important to note that 'a theory is falsifiable' does not mean it is false. Also, it does not mean we can succeed in finding observations in nature that makes it false. It simply indicates the theory is defined in a definite way that we can make accurate and completely new predictions of observations that we haven't seen before, based on our theory under test. If these unknown predictions based on the theory are not found in nature, then only the theory is falsified. The ability to make unknown, entirely new and definite predictions that are potentially disprovable by observations makes a theory falsifiable, refutable or disprovable.

Section Review - Modern Perspectives on the Nature of Science and Theory Testing

Where are we now in our perspective on Critical Rational Stance?

At this point, we have emphasized that a scientific theory is an explanation about the natural environment, a kind of mental model of the natural environment that we invent. It is an explanation that we hope will allow us to make accurate predictions about events in the natural environment. Thus, a good theory is comprehensive; it logically explains a large number of natural events. It also must suggest predictions or hypotheses about the natural environment that can be tested by making observations of the natural environment.

A check on our progress:

Let's review what we learned from this video so far...

Using the information you have gained, which of the three following statements seems to be a good hypothesis that can be tested scientifically?

A. The complexity of life suggests it is directed by an unobservable intelligence.

B. Gases are composed of infinitesimally small particles of matter.

C. Our universe is unique and there is no other detectable universe beyond ours.

A check on our progress:

Review Question Answer: Neither A or C is acceptable. Let's review why they are not good explanations

A check on our progress – explanation:

A theory suggesting a gas is infinitesimally small particles of mass yields us testable logical consequences of this theory, or falsifiable definite predictions that can be compared against observations to see if it agrees or disagrees with our theory. For example, the prediction that at constant temperature, the product of an ideal gas's pressure and volume is always constant can be tested using a pressure gauge and a variable volume container. If the experiment disagrees with our prediction, the theory of invisible small particles of mass is falsified. If it survives, our confidence in the theory is increased.

The idea that complexity of life suggests it is directed by an unobservable intelligence cannot be tested to see if it is false in any conceivable way based on a new and definite prediction that only such explanation can provide.

Similarly, the idea that our Universe is unique, and there is no other detectable Universe beyond ours is not testable using our currently available explanations.

Let's move on to the next section.

Section Review: Theories are always provisional and must make predictions

As Professor Steven Hawking points out, a theory is actually a model that we invent in our minds about the universe, or a restricted part of it. Such an imagined model contains a set of rules that relate quantities or conceptions in the model to observations we make of our environment, or more broadly even of the universe. A theory is a good theory if it satisfies two requirements. First, it must accurately describe a large class of observations on the basis of a model that contains only a few arbitrary elements. Arbitrary elements are assumptions or conceptual ideas that are taken for granted, not necessarily supported by prior evidence. Secondly, it must make definite predictions about the outcomes or results of future observations we may make based on the theory. These predictions may be stated as deductions, or logical consequences, drawn from the theory.

From the last video we also learned, any physical theory is always provisional, in the sense that it is only a grand hypothesis (an explanation we invent about natural events): you can never prove it. But, you can gather evidence to either help support it, or more importantly, attempt to disprove it if it fails to make accurate predictions. No matter how many times the results of experiments agree with some theory, you can never be sure that the next time the result will not contradict the theory. On the other hand, you can disprove a theory by finding even a single observation that disagrees substantially with the predictions of the theory. As philosopher of science Karl Popper has emphasized, a good theory is characterized by the fact that it is not only a logically sound explanation, but it also makes a number of definite predictions that could in principle be disproved or falsified by observation. That is, a good theory must also make new or previously unknown predictions that can be tested by observations. If the prediction is absent and shown to be false through careful analysis of nature, we can abandon the theory. For example, each time the results of new experiments are observed to agree with the predictions the theory survives, and our confidence in it is increased. However if ever a new observation based on the theory is found to disagree with the theory, it shows a serious weakness of the theory, and we have to abandon or modify the theory. At least that is what should be done if the observations are accurate, but you can always question the competence of the person who carried out the observation. Hence, to be thoroughly tested, a good theory should provide logical consequences of predictions that are capable of being struck down, based on evidence. Otherwise, we are likely to only end up constantly proving our ideas as correct, and never really testing carefully if they are false.

Our current progress in exploring modern views of theories in science

Now, we have added another important aspect of a good theory. The predictions that are logically drawn from the theory must be capable of being tested and potentially shown to be false. If a theory is so airtight that its predictions are never able to be rigorously tested and no possibility of shown to be false, we can never be certain that we have fully tested the theory for accuracy. For example, suppose a scientist claims that the Universe is composed of an unobservable force that accounts for human actions. It may be a very clever set of ideas, and written up in very convincing language. But, if the supposed invisible force cannot be detected and analyzed via its new predictions to judge if it is false or not, then the theory is NOT a scientific theory. Theory cannot be fully tested based on already known confirming observations that it makes about the undetectable force supposedly in our natural environment. That is, no matter how much seemingly supportive already known observations you may find or suggest – it cannot challenge the theory to be shown to be false. Placing the new theory at the highest risk of disproof by testing the most rigorous, new and unknown predictions is characteristic of Critical Rational Stance.

What is your opinion?

Let's review what we learned from the last video...

Atomic theory assumes that there are infinitesimally small units of matter (atoms) that cannot be seen or detected directly by human senses. Why, however, has this theory remained acceptable?

What is your opinion?

Explanation:

Atomic theory suggests that there are small units of matter; they may be detected by evidence that is based on the use of physical evidence beyond direct human observation, including the scattering of protons by thin metal foil, etc. If there is no scattering and there seems to be a continuous structure to matter at all levels, the theory can be falsified.

Let's move on to the next section.

Major Summarizing Points for this Section of our Presentation

In summary, general characteristics of a good theory in science (e.g., biology, chemistry, earth-science, engineering or physics), are:

1. It makes definite predictions about the results of future observations. It not only explains what is already known, but makes testable predictions about future studies of the natural environment. In this view, showing verifying or agreeing observations that are already known to us is not a genuine good test of a theory. We need to go beyond those observations and search for still hidden consequences of the theory. Confirming evidence should count only when it can be presented as a serious but unsuccessful attempt to falsify the theory.
2. Previously 'unknown observations' or phenomena must be accurately predictable if a 'new' theory is to be tested and accepted. Why does it have to be 'unknown' observations, you may ask? If the theory doesn't tell anything new, and simply describes what is

already known to us in a descriptive way with no risk of refutation, then it has no predictive power, and yields no new insights.

3. A theory should carry only a few arbitrary elements. That is, as few assumptions as possible that are taken as given or true based largely on logic without prior evidence.
4. At least in principle, the new theory should be refutable, or falsifiable by observation. A theory that is non-falsifiable cannot be tested for its validity and therefore is considered unscientific. A theory that doesn't tell anything new, but agrees with all imaginable known observations is also non-refutable; such theories are also non-testable and unscientific. Such unscientific character is often visible in pseudoscience and mythological beliefs that pretends to be demonstrative as science by the use of 'pseudo-observations'. These are inferred observations that often cannot be reduced to any form of evidence in the natural environment.
5. A new theory that may seem 'least likely' or least probable, but successfully predicts previously unknown observations is of more value to us than a new theory that is 'highly likely' or highly probable, which only agrees with what is already known to us. Likewise, a theory that is verified by easily obtained or sometimes nearly obvious evidence, and thus does not challenge us to think creatively about the natural environment, is not as elegant as one that challenges us to think about extraordinary ideas.
6. A theory gains higher level of credibility, when the theory heavily restricts, prohibits or constrains its predictions accessible by observations; the more it prohibits, the greater its predictive power. A good theory should be as general as possible to describe a large class of observations; however it should not be vague and indefinite in its predictions. The

most clarity and conciseness is expected by clearly restricting its new predictions that we may observe.

7. A goal, or aim of scientific theories is to search for highly improbable or highly unlikely counter-intuitive explanations. We seek new explanations to natural events that dissent from 'common view', where supporting observations are difficult to be made, yet demonstrable with predictions in nature after evaluating logical consequences unique to a new theory. These unknown and hidden new predictions that we observe bring credibility to our 'unlikely' and improbable explanations.

Where have we arrived at this point in our discussion of theories?

At this point in our discussion, we have suggested that new theories as viewed in a Critical Rational perspective are new explanations that often are made by expanding on existing theories. This is in contrast to the strictly inductive view. In the inductive view all theories are invented by starting with observations, sometimes de novo, that we link together to create a new theory based on them. Also central to the Critical Rational perspective is the idea that it is the predictive capacity of a good theory that provides the insight to expand it through data that is gathered, both in support of it, but more importantly also by gathering data that may falsify it. In the latter case, motivating us to reformulate it or abandon it when critical predictions are falsified.

How do 'new' theories come about?

In this segment of our learning experience, we will try to find out what are some of the ways that a new theory comes about? In some instances, what often happens is that a new theory is proposed that is really an extension of a previous theory. That is, as we critically reflect on an existing theory and evidence gained from testing it, we may expand it to be more comprehensive in its explanation of the natural environment.

Critical Rational Stance takes the view that scientific theories are spawned as off-springs of the creative capacity of human imagination. Thus, theories may arise from the logical elaboration of explanations we have already invented in memory, or learned about from other scientists. Not, necessarily, by inductively building a new idea or model based on the cumulative evidence that we have collected and logically connected together to invent the new explanation. This is called the inductive synthesis of a theory based largely on a string of fundamental observations, not drawn from prior ideas. In much of what scientists do, highly creative ideas can lead us to expand on them and enlarge the scope of the idea, thus making new theories that are derived from prior existing theories. This is opposed to the inductive view of theories. The inductive view proposes that we create new theories by making many observations in the natural environment and then logically assemble them into some grand explanation, without necessarily using prior ideas or existing theories about the natural environment. As though we do this without the wisdom of ideas already known or presented by others. In contrast a Critical Rational Stance views theories as built from prior existing ideas, they are elaborated through testing using observations and critical reflective thought.

Next, we will look at how scientific inquiry progresses by imagining better and new explanations about nature.

Link 1: https://sites.google.com/site/natureofscienceinteaching/thought-map-video

Link 2: https://www.youtube.com/watch?v=MVX8B--d03k

Please click the play button to continue.

An Example of Critical Rational Stance: Theory of Evolution

Darwin's theory as he originally proposed it is that all living things have arisen under common ancestry by small changes in the adaptive characteristics of individuals from one generation to the next over very large geological time spans. Thus, evolution is an idea that the diversity of living things has arisen through gradual changes over millions of years as organisms have become more adapted to the particular environments where they lived. During many generations, through genetic changes from one generation to the next, and survival of the best adapted in a given environment, new species have arisen. Thus, the many existing species we see today are a result of this accumulative series of changes and the genetic diversity that has developed over very long time spans.

Why is this such a bold and novel (even "risky") idea?

First, when it was initially suggested it was very different than prevailing ideas of the time – namely, that existing species were fixed as given, not a result of gradual changes over long periods of time. Second, it was a very grand and general idea that all living things could be explained by the assumptions of the evolutionary theory. Third, because the theory addressed events that presumably occurred over many millions of years in the past, it was challenging to find evidence to test the theory, and thus there was always the threat that the theory was actually "too grand" to be tested. Moreover, from the perspective of a Critical Rational Stance, It was also a theory that could be submitted to the test of falsification as well as verification. Thus, it is a good example to illustrate the fundamental ideas of the Critical Rational Stance that we introduced in the preceding section of this learning module.

Your view on the theory of evolution

We learned that a good theory should make bold and risky predictions that are definite and falsifiable. These should be new and previously unknown predictions that can be made from the theory, so we can compare against nature to see if they are good or false.

Let's review if the theory of evolution demonstrates this character.

What do you think of falsifiability of the theory of evolution? In what ways do you think theory of evolution is capable of making falsifiable predictions?

Your view on the theory of Evolution

We will explore the explanation to this question in the next page.

Predictions of the theory of evolution can be potentially proven wrong.

As Darwin recognized, if there were even one proven case of a species that definitely did not arise from a pre-existing one, then the entire theory would be falsified. However, if there was evidence (as now has repeatedly been shown from fossil evidence, for example) that over geological time spans "new species" could be clearly linked to, and derived from, previous species, then the theory would be strengthened through positive evidence. As we mentioned previously, a good theory is one that makes predictions that can be potentially falsified, as well as predictions that may be tested by gathering positive evidence.

Darwin's some of the original ideas were unsupported suggesting further modifications

As with most theories, some parts of Darwin's original ideas (not the entire theory, but part of it) have been subjected to the test of falsification and found to be unsupported.

For example, Darwin's apparent idea that evolution is a gradual process, has been challenged by some fossil evidence that seems to show that at some time spans, rapid changes occurred over shorter geological time spans than would be predicted by gradualism. So, alternatives to Darwin's original theory have arisen, namely that in addition to gradual changes over long time periods, there are punctuated changes (relatively rapid evolutionary changes) that seem to have occurred during relatively shorter geological time spans. That is, the gradual diversification of species through inherited changes that Darwin initially envisioned seems to be too simplistic. More likely, during some geological periods of time, some species changed more rapidly, with new species appearing at a rate much faster than a very gradual idea would suggest. Hence, through evidence that falsified part of Darwin's original ideas, the theory of evolution, itself, has "evolved" as a result of incorporating changes as required by evidence that falsified some of the assumptions of the original theory.

Modifications were made to the Darwinian model of the Theory of Evolution

Another way of looking at this is through the perspective of falsification of hypotheses. Theory-based hypotheses, are predictions that can be logically derived from the ideas contained in the theory. A good hypothesis is clearly and logically linked to the initial ideas found in the theory that guides the derivation of the hypothesis. Here we consider an example of how one hypothesis logically derived from Darwin's original theory has been subjected to a test of refutation. Based on Darwin's original form of the theory, one would hypothesize that new species arise by small changes very gradually over very long time spans. This leads to a hypothetical prediction that as fossils are discovered in sediment layers, or in layers of rock, representing a history of geological time periods, there should be uniformly and only gradual changes in the forms of the fossils throughout the layers. However, as cited above, evidence has been gathered that the hypothesis of gradualism is false in some cases. That is some remarkably rapid changes have been observed in fossil forms of species in rather closely spaced strata in the geological fossil record. Thus, the hypothesis of uniform gradualism has been falsified.

Consequently, the theory also has been changed to acknowledge that evolution can occur very gradually for some species, but in relatively rapid spurts of change in some other cases, and during much shorter time spans than previously thought. Because the theory has been modified to account for the falsification of one of the hypotheses derived from it, the changed theory may yield new hypotheses to be tested.

For example, we can state a new hypothesis to test; namely, that evolution of life is both gradual in some cases and punctuated and relatively rapid over geological time spans in other cases. This example demonstrates the process of careful data gathering and critical reflection on our existing theories and hypotheses that characterizes the Critical Rational Stance, and is a major way scientific understanding of the natural environment progresses. Critical reflection about the merits of a theory requires that the theory be subjected to both tests of falsification as well as tests that yield positive, supporting evidence.

Highlights and Section Review: Biological Evolution

Theory Falsification – An example from biological evolution

Slide 1 text: An original hypothesis: Darwin originally theorized that new species evolve over many thousands of years by a gradual genetic change. This would account for the fossil evidence that showed gradual changes in some species that were discovered in rock formations that were formed over many millennia.

Slide 2 text: However, some recent evidence that has been gathered more carefully shows that some species changed very little for considerable time geologically, then showed a very rapid spurt of change. This evidence falsified the main assumptions of the original hypothesis of gradualism, and required a revision of the theory to include punctuated or rapid evolution stages in some cases.

Slide 3 text: →A revised hypothesis, but not a falsified theory! Although this one original hypothesis was not fully supported and was modified to include the rapid or punctuated evolution of some species, the overall theory has stood many tests.

Only a part of the theory was proven insufficient and that part, gradualism, was modified.

Slide 4 text:

A. An entire theory should be subjected to testing for falsification, not a part of it.
B. If a part of a theory is falsified, then the entire theory must be rejected.
C. If a part of a theory is falsified, the part can be revised and the theory still stands.

Which of the statements, A, B, or C is most correct based on your understanding of theory testing?

Slide 5 text:

A. An entire theory should be subjected to testing for falsification, not a part of it.
B. If a part of a theory is falsified, then the entire theory must be rejected.
C. If a part of a theory is falsified, the part can be revised and the theory still stands.

If you chose (C), that is the best choice. An appropriate part of a theory can be falsified and revised without necessarily jeopardizing the entire theory. (A) and (B) are too broad and sweeping to be accurate in all cases, although falsification of a major part of a theory (B) may seriously jeopardize the entire theory, in some cases

Conclusion

What did we gain from this learning experience?

We discussed that theories are not mere vague guesses or hunches though they do originate from great human imagination. We humans come up with explanations to describe observations in nature, however they are rigorously tested under highest risk conditions in our greatest effort to falsify them. If a good theory can survive all our attempts at disproof, we tentatively accept them.

A good theory can lead us to predict new observations that are previously unknown. Any scientific theory must be falsifiable, or testable. Falsifiable doesn't imply it is false; it simply means the theory is capable of withstanding disproof by making new predictions that can be tested against.

Understanding how theories work, how they are invented or imagined, how they are tested using highest risk experiments in our attempt to falsify them using predictions is important when we do scientific inquiry even at classroom level. We hope your time spent in this learning experience a productive and rewarding one.