Toward an Integrated Framework of Scientific Reasoning

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Abstract: This paper proposes an integrated framework, *PREP*, to capture the dynamic relationship among key influential factors of scientific reasoning, including prior knowledge (P), reading capacity (R), epistemic beliefs (E), and personal attributes (P). Empirical evidence from a qualitative study is presented as we elaborate and further develop this framework. In this study, twenty-six undergraduate students were interviewed to reason about competing arguments on global climate change. In-depth analysis of participants' interview responses demonstrated important characteristics of the cognitive processes and underpinning mechanisms of scientific reasoning. This work adds to ongoing discussion about the nature of scientific reasoning and provides a holistic approach to characterizing and evaluating scientific reasoning. Furthermore, by capturing important features of individuals' reasoning when faced with climate issues, this work has significant implications for classroom science teaching and learning.

Keywords: scientific reasoning, epistemic beliefs, prior knowledge, reading capacity, personal attributes

Introduction

Scientific reasoning is at the core of scientific inquiry, but is not just a vehicle that scientists are entitled to (Giere, Bickle, & Mauldin, 2006; Sinatra & Chinn, 2011). The ability to reason scientifically greatly affects how people understand and evaluate information from professional publications and public media (Sinatra, Kienhues, & Hofer, 2014). Hence, science educators have long been emphasizing the importance of teaching scientific reasoning in the classrooms so that students grow to be scientifically informed citizens (National Research Council, 2001, 2012; NGSS Lead States, 2013). However, obstacles abound in such efforts, one of which lies in the lack of theoretical consensus on what constitutes and affects scientific reasoning (Zeineddin & Abd- El-Khalick, 2010). To better inform teachers as they support students' development of reasoning skills, there is a call for more integrated frameworks to conceptualize the essence of scientific reasoning (Kind, 2013).

In this paper, we propose a framework to characterize the processes and mechanisms of scientific reasoning. Based on our work through two large projects that aimed to promote classroom instruction and assessment of scientific reasoning, we identified four key factors and investigate their dynamic interactions during reasoning processes. In the following, we first review relevant literature that informed our perspective. We then present our theoretical framework with findings from an empirical study and conclude with future directions of this work.

Theoretical backgrounds

Existing literature provides numerous perspectives toward what constitutes scientific reasoning and how to measure it. Here, we highlight previous research that has influenced our framework.

Reasoning is a process of drawing conclusions from principles and evidence so as to infer new conclusions based on what is already known (Wason & Johnson-Laird, 1972). As an important type of formal reasoning, scientific reasoning has drawn attention from scholars in different fields that hold distinctive perspectives (see Zimmerman (2005) for review), among which the main discrepancy falls in whether to focus on the cognitive processes during reasoning or the underpinning mechanisms that guide such processes. Chinn and Malhotra (2002) pointed out that more work is needed to unpack the complex mechanisms which underlie individuals' reasoning processes. They held that as the majority of previous studies tended to focus on exploring simplified aspects of scientific reasoning, such as the control-of-variable strategy, the epistemic nature of reasoning has been missing in not only scholarly research but also classroom teaching. Here, the epistemic nature mainly refers to how one evaluates evidence in authentic inquiry and coordinates theory and evidence when faced with complex science problems.

In the past decades, with growing concerns on teaching socioscientific issues-such as global climate change and genetic engineering-in science classrooms, the scope of research on scientific reasoning has been greatly extended (e.g., Mason & Scirica, 2006; Yang, Chang, & Hsu, 2008). For instance, Sadler and colleagues used the concept of *socioscientific reasoning* to explain how individuals process information about socioscientific issues to which there are no absolute solutions (Sadler, Barab, & Scott, 2007). In particular, they stressed that socioscientific reasoning, as a major type of informal reasoning, requires one to recognize the inherent complexity of ill-defined issues, examine them from multiple perspectives, appreciate that they are subject to ongoing inquiry, and exhibit them from multiple perspectives. Yet, while studies of socioscientific reasoning have greatly enriched our understanding of how people reason, it remains unclear whether individuals are able to reason formally through scientific means about competing arguments on socioscientific issues.

More recently, the growing body of studies on epistemic beliefs has imposed significant influence on investigation of scientific reasoning (Sinatra & Lombardi, 2013). Current research on epistemic beliefs has moved from mainly focusing on individuals' beliefs toward knowledge and the process of knowing (e.g., Hofer & Pintrich, 1997) to investigating how such beliefs guide individuals' cognitive and metacognitive processes (e.g., Muis & Franco, 2009). As a result, many scholars start to incorporate discussion on epistemic beliefs into studies of reasoning processes (e.g., Barzilai & Eshet-Alkalai, 2015; Chinn, Rinehart, & Buckland, 2014). Such research movement corresponds to educational reforms which suggest further development of students' skills of engaging in authentic inquiry and participating in scientific argumentation (NGSS Lead States, 2013). In all, the converging research interests from various lines of work have brought in a refreshing look on what affects scientific reasoning and calls for a revisit of existing approaches to investigating scientific reasoning. Further work is needed to move toward an integrated framework of scientific reasoning.

The PREP Framework

Building upon related literature, we identify four interconnected factors that critically contribute to individuals' scientific reasoning processes: *prior knowledge*, *reading capacity*, *epistemic beliefs*, and *personal attributes* (henceforth, ***PREP***) (Liu, 2014).

Prior knowledge

Prior knowledge is a double-edged sword in one's scientific reasoning process. On one hand, appropriate knowledge supports the selection of appropriate reasoning strategies (Schauble, 1996). The more content knowledge one has, the more likely they are to perform well in scientific reasoning about related issues (Mason & Scirica, 2006; Osborne, 2010). On the other hand, the prominent domain-specific approach to investigating scientific reasoning left it vague as to whether prior knowledge can place significant impacts on reasoning (e.g., Klahr & Dunbar, 1988). Thus, to maximize the positive effects of prior knowledge, more and more studies start to investigate the dynamic interactions between prior knowledge and other learner characteristics such as reading capacity and epistemic beliefs (e.g., Kendeou & van den Broek, 2007).

Reading capacity

Compared to prior knowledge, the effect of reading capacity on scientific reasoning is much less discussed. As research on scientific reasoning has been more and more embedded in contexts of argumentation, reasoning often involves comprehension and evaluation of written texts that include two-sided scientific arguments or multiple solutions in relation to controversial or ambiguous issues (Chan, Ho, & Ku, 2011). Hence, to reason about various arguments, it is critical that individuals have adequate reading capacity to coordinate the multiple sources of information presented. Bräten and colleagues held that individuals who could integrate information are more likely to process information in a way consistent with their epistemic beliefs (Bräten, Britt, Strømsø, & Rouet, 2011). At the same time, they also called for further research to specify the relationship between reading capacity and epistemic beliefs.

Epistemic beliefs

Epistemic beliefs entail "*individuals' beliefs about the nature of knowledge and the processes of knowing*" (Hofer & Pintrich, 1997, p. 117). People with limited reasoning abilities tend to find it difficult to process information from multiple perspectives, which in turn discourages them from endorsing sophisticated epistemic beliefs that acknowledge the tentative and complex nature of knowledge (Zeidler, Walker, Ackett, & Simmons, 2002). Conversely, naïve epistemic beliefs were found to be associated with withdrawal from in-depth reasoning (Sinatra, Southerland, McConaughy, & Demastes, 2003). Those who hold such beliefs tend to overlook the need to engage in scientific reasoning and are more likely to treat information that does not support their existing beliefs in a biased manner (Chan, Ho, & Ku, 2011; Kuhn, 2001; Weinstock & Cronin, 2003).

Discussion on the interaction of the above three factors adds an important lens to the study of scientific reasoning. It not only relates to constant debates on the domain-general and domain-specific nature of scientific reasoning, but also proposes alternative explanations of challenges one may encounter during reasoning.

The fourth factor: Personal attributes

With increasing emphasis on epistemic beliefs and other learner characteristics, research on scientific reasoning is demonstrating growing orientation toward capturing "warm cognition" (Dole & Sinatra, 1998). In particular, affective factors like motivations and beliefs are being paid increasing attention to in the investigation of reasoning processes. For instance, Lombardi, Seyranian and Sinatra (2014) have explored how emotions may relate to the level of scientific understanding students hold and their perception of plausibility of evidence regarding critical issues such as climate change. As early research on scientific reasoning mostly features the cognitive and metacognitive processes, the role affective factors play is a relatively under-studied area. Based on existing work on affective components of scientific learning, here we use "personal attributes" to refer to important aspects including one's belief system, attitudinal orientation toward certain topics, as well as personal interests and motivation.

The study

While existing research has taken various paths to reveal the relationships among some of the four factors above, to our knowledge, there is little work that devotes to capture in depth how they interact with each other. Therefore, in the present study, we employed a qualitative approach, *grounded theory (*Glaser & Strauss, 1967; Strauss & Corbin, 1990) to answer a critical question: *How the four factors proposed in the PREP Framework interact with each other to guide people's scientific reasoning processes?* Grounded theory research allows an exploratory development of theory grounded in data from the field (Glaser, 1978). Researchers conduct iterative data collection and analysis to allow an analytic, substantive theory to emerge from the phenomenon. Thus, following the principles of grounded theory, this work enables a more "naturalistic" insight into the nature of scientific reasoning.

Participants

Twenty-six undergraduate students (20 females and 6 males, M_{age} = 19.65 years, SD_{age} = 1.06) at a major university in the Midwestern U. S. were recruited through theoretical sampling (Glaser & Strauss, 1967). Theoretical sampling is a key feature of grounded theory: it requires the sampling process to be guided by the need for understanding the phenomenon of interest (Glaser, 1978). Following this principle, participants were purposefully recruited from a wide range of majors to increase the diversity of the sample in terms of their content knowledge and personal beliefs about climate change. Data collection was complete after 26 participants were interviewed when saturation of theoretical categories was reached and no new categories emerged.

Study design

An interview protocol was developed, including a 606-word reading document and 13 open-ended questions. The topic of interest is global climate change. Despite the ongoing educational efforts, students at all levels still experience difficulties in processing the multitude of perspectives and evidence regarding climate change (e.g., Braasch et al., 2013; Gil, Bräten, Vidal-Abarca, & Strømsø, 2010). Analyzing individuals' reasoning processes on this topic can help reveal a more well-rounded view of the nature of reasoning and its influential factors. The reading document consisted of two opposing perspectives: climate change is human caused versus climate change is due to natural changes. This reading document involved three most commonly discussed topics regarding climate change: Earth's temperature change, rising sea level, and extreme weather events. The three topics were presented on separate pages with arguments from both sides. The interview questions were designed to assess three aspects: 1) prior knowledge about climate change, 2) evaluation of evidence and arguments, and 3) perspectives toward climate science. As they read the documents, participants were asked to read aloud and think aloud to help us probe into their thinking processes. They then evaluated the evidence used in the reading, critiqued on the arguments, and discussed their viewpoints about climate science.

Data analysis

The interviews were audio-recorded and later transcribed verbatim. Transcripts were entered into NVivo 10 for further analysis. Constant comparative analysis (Glaser & Strauss, 1967) was employed for data analysis and it involved three stages of coding (*open coding*, *selective coding* and *axial coding*) to allow theoretical categories to emerge. Data analysis was conducted in two layers. The first layer featured identification of the four influential factors during reasoning. The second layer analyzed participants' reasoning processes based on the complexity of their cognitive processes when thinking aloud and responding to the interview questions. The combination of the two layers thus generated fine-grained analysis of the dynamics among the proposed four factors.

To establish the trustworthiness of data analysis, techniques such as memoing and diagramming were employed throughout the coding processes. In addition, during data analysis, categories that were similar in their definitions were further compared and contrasted to decide their final categorization. These efforts all helped to achieve the goal of establishing credibility, transferability, dependability and confirmability in the data analysis (Lincoln & Guba, 1985).

Results

Table 1 lists the outline of our coding system for this data set. We also identified sub-factors under reading capacity, epistemic beliefs, and personal attributes. In particular, reading capacity was analyzed based on participants' ability to use reading strategies such as monitoring their reading progress, epistemic beliefs captured participants' views about the nature of knowledge and expertise in climate science, whereas personal attributes involved their attitudes, as well as related belief systems, toward climate issues. Broadly, three patterns were identified to categorize reasoning processes-*withdrawal from reasoning, limited reasoning*, and *complex reasoning*-where the relationships of the proposed four factors were further investigated. Given the limited space, here we present three brief examples to demonstrate key findings at each reasoning pattern. Quotes from participants are specified with their assigned participant number (such as P1, P2, and so on).

Table 1: Outline of the core coding system

Factors	Sub-Factors	Definitions
Prior Knowledge		Existing understandings participants hold about climate change
Reading Capacity	Monitoring Comprehension	Timely reflection of reading progress and problems encountered
	Making Associations	Relating texts to existing beliefs or knowledge
	Making Inferences	Generating explanations or comments based on texts
	Others	Responses such as "I don't like the wording here"
Epistemic Beliefs	Nature of Science	Perception of the nature of scientific knowledge in general, such as whether knowledge is fixed or fluid
	Relativity	Relative correctness of multiple perspectives
	Perception about Credibility	The trustworthiness of the source of evidence, the reliability of the source, the scientific foundations of measurement, etc.
	Scientist's Expertise	Scientists' certainty about the causes and consequences of climate change, consensus in the science community on the anthropogenic nature of climate change, etc.
	Flexibility of Beliefs	Reflection on one's own and others' stance and likelihood to change such stance
	Complexity and Uncertainty of Climate Science	Perception of the nature of climate science
Personal Attributes	Personal Beliefs	The role of political and religious beliefs
	Attitudinal Orientation	Preferences for and support of certain stance and arguments
	Personal Interests	Personal relevance of the topic of interest, curiosity toward the topic, etc.
	Motivation	Reasons to/not to actively seek relevant information on the topic of interest

Withdrawal from reasoning

This pattern consisted of responses from participants that were mainly repeating the information presented. Sometimes they may request specification or clarification after reading information that they were not familiar with or uncertain about. While they might recognize and briefly identify the consistency or conflict of information in the reading with what they already knew, they would not resort to their epistemic beliefs when evaluating evidence and making conclusions. For example, after reading about the composition of the atmosphere and the percentage of CO_2 in it, P14 responded "OK, I guess I didn't know that CO_2 only constitutes less than 1% of the trace gases." While she acknowledged that "scientists might realize ten years later that they're missing some information", P14 often simply conformed to or refuted a given argument without further reasoning about the evidence provided.

Limited reasoning

Reasoning processes identified into this pattern involved more cognitive efforts and included more details about how participants processed any given information. However, this reasoning pattern was limited as participants mostly emphasized the surface features of evidence as well as the arguments it supported. Their overwhelming focus on writing features, such as tone of writing, sometimes may override their attitudes and beliefs about the topic when they attempted to evaluate evidence and make conclusions. For instance, after reading the sentence "Changes in the frequency and intensity of extreme weather events are due to human-caused Earth's temperature increase", P22 commented that "even though I believe this, this sentence came off a little biased. Even though I do believe that it is human caused, it came off a little strong, so I don't know (whether I agree with it)."

Complex reasoning

This reasoning pattern represented participants' advanced skills in drawing upon their cognitive and affective resources. P25, for example, demonstrated her abilities to reason about statistical meanings of numerical values. When presented with numbers such as the percentage of CO_2 in the Earth's atmosphere, P25 raised concerns that these numerical values alone might not be telling the whole story and requested clarification for the scientific meanings of these numbers. P25 explained her concerns about the need for more information regarding the statistical significance of evidence as follows:

> Like if the increase of CO_2 went from like 0.5 to 1%, I mean I don't know how significant that would be. Um, they're also showing that the increase in the Earth's average surface temperature, but it looks like a very small amount too. I don't know how big an impact that would have.

Furthermore, P25 also actively related information to her religious beliefs and reflected on how her beliefs may have affected her thinking process. When evaluating the evidence that was used to support "Rising sea level is not human-caused", P25 stated that "I would have tried to find sources that were like based on the Creation (God's creation of the world) rather than the Theory of Evolution". Similarly, after reading "In particular, the number of hurricanes and tropical storms during 1995 and 2004 doubled that during 1970 and 1994 in North Atlantic", P25 reported the following as she was thinking aloud:

> The Bible warns in the book of revelation when Christ returns his coming, that there will be more like catastrophic events like that, like as his return years. So, like, as a Christian, as a follower of Jesus, it's kind of exciting, because you will wait for him to come back a second time, so I mean because God's words warn about that, that makes me think of (this argument) just from that perspective.

The PREP Framework: A step further

The two-layered analysis in this study provided rich information on the complex dynamics among the four factors proposed. Based on the current findings, the nature of the relationships among these factors makes it difficult to come to a conclusive model. Nonetheless, some main themes emerged in this work presented opportunities to further develop the PREP Framework and inform future efforts in capturing scientific reasoning.

First, the potential role each factor may play is relatively consistent and predictable. Figure 1 presents a simplified process model based on the current findings to help illustrate the functional characteristics of these factors during reasoning. In particular, when individuals are exposed to multiple arguments in writing, information encoding takes place and their capacity in reading comprehension acts as the first filter for what they may choose to focus on as they continue to further interpret the information. During their reasoning processes, intentionally not unintentionally, individuals relate to prior knowledge to construct mental models of the information. As they align such models with their epistemic beliefs about climate change, individuals choose to engage in reasoning or withdraw from it. Individuals' personal attributes play a critical role in how they reason. Those who show lack of interests in issues related to climate change are more likely to avoid reasoning about the different arguments. At the same time, when individuals integrate their personal values such as religious beliefs into their perspectives about climate change, they approach reasoning much more differently. It should be noted that the relationship between personal beliefs and the chosen paths of reasoning can be reciprocal: while the former affects how individuals evaluate different aspects of the arguments, their focus on arguments that support their own perspectives can further strengthen their beliefs and even biases. This process model can serve as a preliminary application of the PREP Framework to help us understand the proposed factors and their interactions.

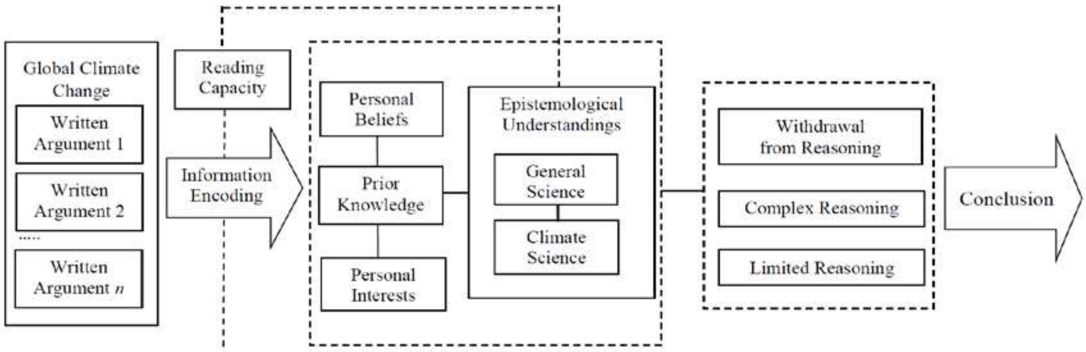

Figure 1. A process model of scientific reasoning on global climate change.

Second, interactions among the four factors fluctuate not only between individuals but also within individuals. For instance, based on the present results, whether more prior knowledge and advanced epistemic beliefs may result in more complex reasoning depends on the level of reading comprehension one achieves at the moment. Therefore, rather than pushing for a uniformed characterization of scientific reasoning, PREP leaves sufficient flexibility for future research to probe into the dynamics among these factors across contexts.

It should be noted that while findings from this qualitative work can serve as a foundation for further development of the proposed PREP Framework, cautions should be taken when employing this framework. First, this study adopted a qualitative research approach to investigate scientific reasoning processes. While integrating the grounded theory approach has yielded in-depth discussions on how undergraduate students reason about climate issues, like all qualitative studies, concerns may arise regarding the trustworthiness and credibility of this work. While great efforts were made throughout data collection and analysis to avoid biases and minimize preconceptions for grounded theory, given the nature of qualitative studies, it is open for further investigation whether the PREP framework can be generalized across subject domains for different populations. Moreover, the topic of interest here was global climate change, whereas scientific reasoning processes may differ as the topic varies. Follow-up studies will continue to explore how this theoretical framework may apply to reasoning with other socioscientific issues, such as genetic engineering and water pollution. To obtain a more comprehensive understanding about the contributing factors of scientific reasoning, later researchers may find it helpful to expand the scope of investigation and consider aspects that have not been discussed very much in scientific reasoning research such as social and religious factors.

Research on scientific reasoning has been of great interests to the learning sciences community. The PREP Framework proposed in this paper aimed to pursue a more integrated view of scientific reasoning and investigate its influential factors. Through capturing the dynamic interactions among four factors, including prior knowledge, reading capacity, epistemic beliefs, and personal attributes, this framework demonstrates a holistic view toward scientific reasoning and reveals the complexity of its underpinning mechanisms. PREP adds to the current efforts in facilitating the theoretical construct development for scientific reasoning. The uniqueness of the grounded theory methodology makes the exploration of individuals' reasoning processes more naturalistic and brought a new lens to research on scientific reasoning.

Educational implications

This work has important implications for classroom science teaching and learning. Despite the numerous studies in the field of scientific reasoning, no consensus is reached on what instructional support should be provided to facilitate student reasoning (Osborne, 2010). A central goal of science education is to enhance students' skills in effective communication of scientific issues. National science education standards in the U.S. have emphasized that students should be able to reason scientifically in order to engage in scientific argumentation and thus communicate about issues that impact their daily lives (NGSS Lead States, 2013). Osborne (2010) suggested that there are several aspects of scientific reasoning skills that science education might seek to develop such as identifying patterns in data and resolve uncertainty of scientific inquiry. However, there have not been many empirical studies that provide empirical support for this proposal. Rooted in empirical data, the PREP Framework is consistent with the proposal Osborne made, but extended its scope in the context of a socioscientific issue. By revealing participants' perspectives and thinking processes about climate issues, this study provided critical information for teachers to consider as they develop their curricula.

Furthermore, findings from this work add to the ongoing debates in climate change education about how to enhance climate literacy. One of the most critical educational objectives is for students to learn about how socioscientific issues are handled and evaluated within society so that they are able to act as responsible citizens in the future (e.g., Höttecke, Henke, & Riess, 2012). Educational and policy documents have suggested that students should develop reasoning skills that can help them evaluate the causes and effects of global climate change (NRC, 2001, 2012). Students should be more actively engaged in evidence-based reasoning about human impacts on the Earth's climate system to propose, test and modify possible solutions to current climate issues. Incorporating scientific reasoning into climate change education will help fulfill this goal. It is essential that the general public come to appreciate the relevance of scientific reasoning and its impact on climate literacy. However, although the importance of scientific reasoning in climate change education has been established, there have not been many detailed discussions on effective approaches to promote scientific reasoning and climate literacy. As this grounded theory study looked into the complex relationship between scientific reasoning and prior knowledge as well as identifying multiple factors that may have affected students reasoning about climate issues, it may serve to initiate conversations between scientists and educators for potential collaborations in their efforts of enhancing the public's climate literacy.

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Acknowledgments
The author thanks Dr. Frances Lawrenz for her helpful suggestions on earlier manuscripts of this work.