Eurasia Journal of Mathematics, Science & Technology Education, 2008, 4(2), 153-168

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On Coordinating Theory with Evidence: The Role of Epistemic Commitments in Scientific Reasoning among College Students

Ava Zeineddin and Fouad Abd-El-Khalick
University of Illinois at Urbana-Champaign, IL, USA

Received 10 June 2007; accepted 19 February 2008

This study examined the impact of two epistemic commitments on the quality of college students' scientific reasoning in the domain of hydrostatics. These were the commitment to the consistency of theory with prior knowledge and commitment to the consistency of theory with evidence. Participants were 12 sophomore science majors enrolled in a large Midwestern university in the United States. They were first administered a 10 short-answer item questionnaire to assess their understandings of buoyancy, and then participated in an individual, think-aloud interview centered on four paper-and-pencil scenarios involving systems of objects immersed in water. During the interview, participants also were asked to justify their responses and explain certain reported "observations" in each scenario. The interviews aimed to explore the impact of participants' epistemic commitments on their reasoning. A majority of participants did not demonstrate coherent reasoning schemes when working with buoyancy problems. To be sure, participants' prior conceptions of buoyancy interacted with the target epistemic commitments in impacting their reasoning. Still, there was a discernable impact for the target epistemic commitments on the quality of participants' reasoning.

Keywords: Reasoning, Epistemological Beliefs, Physics, Buoyancy.

INTRODUCTION

Science teaching has often fallen short of promoting meaningful learning and conceptual understanding (American Association for the Advancement of Science [AAAS], 1990, 1998; National Research Council [NRC], 1996). Rather, emphasis inside science classrooms has mostly been on the memorization of facts and algorithmic problem solving to the neglect of helping students attain robust understandings of key science concepts and their interrelationships. Science learning experiences are mostly isolated from everyday life (Reif & Larkin, 1991) and, hence, do not enable students to apply what they learn to their lives outside the school (AAAS, 1998). Such shortcomings are especially important in the case of scientific reasoning skills, which are considered "real-world" skills (Schunn & Anderson, 1999) needed to tackle both scientific and everyday life problems (Galotti, 1989). Such reasoning skills are also crucial to the preparation of scientifically-literate citizens who could effectively participate in public discourse and decision-making regarding science-related social issues (AAAS, 1990; Hogan, 2002).

Scientific reasoning skills are important for understanding the nature of science (AAAS, 1990) and intrinsic to the processes of scientific discovery (Dunbar, 1993, 2000) and experimentation (Tytler & Peterson, 2003). Lawson, Clark, Cramer-Meldrum, Falconer, Sequist, and Kwon (2000) noted that general reasoning skills are essential to the generation and testing of alternative hypotheses and, thus, are important for conducting scientific investigations. These

Correspondence to: Ava Zeineddin
Department of Curriculum and Instruction,
College of Education, University of Illinois at Urbana-Champaign
1310 S Sixth Street, Champaign, IL 61820, USA
E-mail: zeineddi@uiuc.edu

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E-ISSN: 1305-8223

skills are often associated with the peak of adolescent cognitive development (Klaczynski, 2000) and needed for participation in formal and professional areas of science (Kuhn, 1989). In a word, scientific reasoning skills are key determinants of success at school and in life (Champagne, Klopfer, & Anderson, 1980; Hawkins & Pea, 1987; Williams, Papierno, Makel, & Ceci, 2004). Helping students develop scientific reasoning skills is indeed a major goal for science educators and researchers (AAAS, 1990, 1998; NRC, 1996).

Yet, considerable research in the fields of cognitive and developmental psychology, as well as in science education indicates that students fall short in their reasoning both in academic and everyday life settings (Hogan & Maglienti, 2001; Klaczynski, 2000; Kuhn, 1989; Reif & Larkin, 1991; Stanovich & West, 1997; Varelas, 1996). While this state of affairs could be partially attributed to science instruction, research indicates that a complex interplay of cognitive, motivational, and contextual factors influence students' ability to reason scientifically. Of particular interest to the present study are epistemological commitments, which refer to students' understandings of, and beliefs about, the nature of knowledge and its acquisition; "These commitments include both domain-specific and domain-general norms for deciding what assertions to believe, accept, reject, or modify" (Hogan & Maglienti, 2001, p. 665). Epistemological commitments, it is often argued, may shed light on the divergences that exist between everyday and scientific thinking (Hogan & Maglienti, 2001; Klaczynski, 2000; Reif & Larkin, 1991). Yet, relatively little empirical research has focused on examining the relationship between epistemological commitments and the quality of scientific reasoning. Such is the focus of the present study.

THEORETICAL BACKGROUND

Frameworks for Studying Scientific Reasoning

Research on scientific reasoning skills originated in the fields of developmental and cognitive psychology (Kuhn, Amsel, & O'Loughlin, 1988; Tytler & Peterson, 2003). Initially, science educators interested in this topic used Piagetian formal operations theory as a basic framework for examining thinking skills (Kuhn et al., 1988). Such early research efforts focused on the development of "epistemological reasoning" in children (Tytler & Peterson, 2003). Piagetian theory came under criticism due to the lack of generalizability of developmental thinking skills across domains. This criticism was accompanied by the emergence of a new focus in cognitive psychology and science education on examining children's conceptual understandings: Student naïve, intuitive, alternative, or existing conceptions became the most important element affecting learning (Bransford, Brown, & Cocking, 2000; Kuhn et al., 1988). Thus, this latter line of investigation focused on scientific reasoning processes involved in acquiring new knowledge starting with prior knowledge as a point of departure. Investigating the development of scientific reasoning or thinking under this umbrella has been referred to as a "domain-specific" (Penner & Klahr, 1996; Zimmerman 2000), "knowledge-based" (Samarapungavan, 1992) or "conceptual change" (Schauble, 1996) approach. A second major approach to the study of scientific reasoning deals with processes involved in hypothesis testing and experimental design (e.g., Kuhn et al., 1988; Lawson et al., 2000; Schunn & Anderson, 1999) and has been referred to as a "domain-general" approach (Penner & Klahr, 1996) or "experimentation strategy" (Schauble, 1996).

The above mentioned lines of research suggest the existence of two different characterizations of scientific reasoning: conceptual and procedural (Zimmerman, 2000) and reflect a lack of agreement concerning what scientific reasoning entails. Some researchers (e.g., Penner & Klahr, 1996; Schunn & Anderson, 1999) view these connotations of scientific reasoning as reflecting two types of knowledge, declarative and procedural. Declarative knowledge is descriptive or substantive knowledge (i.e., knowing that), whereas procedural knowledge is performative knowledge that is enacted in the form of skills (i.e., knowing how) (Schunn & Anderson, 1999).

The current dominant frameworks guiding research on scientific reasoning integrate the two aforementioned domain-specific and domain-general research approaches. Klahr and Dunbar (1988) were among the first to present an integrated model of scientific reasoning. Their construct of Scientific Discovery as Dual Search (SDDS) approaches reasoning as a dual search between a space of experiments and a space of hypothesis. The hypothesis-space search is driven initially by prior knowledge and subsequently by experimental results while the experiment-space search is guided by the existing hypothesis and could lead to the generation of new hypotheses. Thus, reasoning or discovery is a search process or *coordination of hypothesis and experimental results* that leads to forming new concepts or knowledge. Klahr and Dunbar argued that the interaction between the two search or reasoning components (i.e., experimental design and hypothesis formation) determines the success of a scientific activity and therefore both components should be taken into account in order to reveal the 'true' nature of scientific reasoning.

Another major integrative reasoning framework is Deanna Kuhn's *coordination of theory with evidence*. Kuhn's (2004) notion of theory-evidence coordination is aligned with Klahr and Dunbar's notion of hypothesis-experiment coordination or search. According to Kuhn, scientific thinking entails more than the strategy of controlling variables and should not only be restricted to the domain of science, but rather is "a human activity engaged in by most people" (p. 371). Scientific thinking or scientific reasoning (Kuhn uses both terms interchangeably) is connected to inference, problem-solving, and argumentation. It is a knowledge-seeking process that is social in nature. More specifically, it is "any instance of purposeful thinking that has the objective of enhancing the seeker's knowledge" (p. 372). It is therefore a process that people engage in or "something people *do* not something they *have* [italics in original]" (p. 372). This process, for Kuhn, involves coordination of theory and evidence and may lead to conceptual change and more accurate understandings.

Indeed, for Kuhn (1989), "The heart of scientific thinking is the coordination of theories and evidence" (p. 674). Skilled scientific thinking entails such coordination, which occurs when both theory and evidence are encoded and represented as separate entities and then "implications of the evidence for the theory are identified" (Kuhn, 2004, p. 374). So, according to Kuhn, theory-evidence coordination does not exclusively mean revising the theory in light of the evidence but considering both independently, distinguishing them, and then finding connections or building relations between them. Successful coordination also entails recognizing the possibilities of alternative explanations and inconsistent evidence (Kuhn, 1989). This recognition, however, requires the acquisition and implementation of metacognitive processes that are not usually apparent in children and lay adults. Thus, for Kuhn, the child-as-scientist metaphor is misleading. Kuhn agreed that children can be viewed as "intuitive scientists" who gain understandings by constructing and revising theories about the natural world. However, she cautioned that the *cognitive processes* the child uses to build mental models are not the same as those employed by scientists. Those processes, nevertheless, do evolve with time as one gains "control over the interaction of theory and evidence in one's own thinking" (Kuhn, 1989, p. 688). **T**he process of theory-evidence coordination is, therefore, developmental in nature.

Kuhn's emphasis on theory-evidence coordination was picked up by other researchers. For instance, Tytler and Peterson (2003) examined young children's reasoning as they generated explanations and developed connections to evidence when differentiating between competing ideas. They identified three dimensions to characterize children's reasoning: (a) the nature of exploration or the way evidence and theory were coordinated, (b) responses to challenging ideas, and (c) identifying and handling relevant variables. Tytler and Peterson also used a "general framework" of reasoning based on the work of Driver, Leach, Millar, and Scott (1996) to elucidate reasoning involved during the exploration and experimentation processes. This framework classifies reasoning into three categories: (a) phenomenon-based reasoning, (b) relation-based reasoning, and (c) concept-based reasoning. The first type of reasoning involves description of phenomena or what one sees. The second type involves finding relations between what is observed without making effort to seek causes; explanations thus tend to be superficial or "uncritical." The third type involves deeper explanations and is marked by relating causes and effects, coordinating hypotheses and experiments, dealing with disconfirming evidence, and seeking alternative explanations. Reasoning categories were related to the identified dimensions to analyze the ways in which children engage in exploration. Tytler and Peterson (2003) found that young children were able to incorporate evidence when building new ideas. The present study adopted Kuhn's (2004) integrative framework of reasoning as coordination of theory with evidence.

Quality of Scientific Reasoning

Scientific reasoning involves a diverse set of skills and, thus, is complex in nature (Schunn & Anderson, 1999). A number of interrelated cognitive, motivational, and contextual factors influence students' ability to reason scientifically. A large body of research in the fields of cognitive and developmental psychology and in science education indicates that the quality of students' scientific reasoning is inadequate (Hogan & Maglienti, 2001; Klaczynski, 2000; Kuhn, 1989; Reif & Larkin, 1991; Stanovich & West, 1997). Students' reasoning is often described as "theory-motivated" (Klaczynski, 2000), and "selective" or "self-serving" (Klaczynski & Narasimham, 1998). Moreover, it is marked by shortcomings or biases (Hogan & Maglienti, 2001; Klaczynski, Gordon, & Fauth, 1997; Klahr and Dunbar, 1988; Kuhn, 1989) and is influenced by prior knowledge and epistemological beliefs (Dunbar, 1993; Greenhoot, Semb, Colombo, & Schreiber, 2004; Hogan & Maglienti, 2001; Klaczynski, 2000; Samarapungavan, 1992; Stanovich & West, 1997).

Excepting a few research findings (e.g., Sodian et al., 1991, Tytler & Peterson, 2003) that revealed some strength in young children's reasoning, the quality of student reasoning has been characterized, in general, as inadequate. Several reasons underlie this characterization. Reif and Larkin (1991) reported that students confuse scientific "goals and cognitive means" with everyday life ones. Students employ goals and ways of thinking that are useful in their lives but are "inadequate in science" and thus "devise ways of thinking ill suited to science" (p. 733). Students acquire everyday life understandings spontaneously or intuitively through informal learning and experience. According to

Reif and Larkin (1991), familiarity with a certain domain or context is an everyday life criterion for generating knowledge. In contrast, contexts or problems in science are usually abstract and unfamiliar to students, and the scientific criterion for knowledge development is making inferences or building conclusions based on evidence. This mismatch between the scientific and everyday life criteria for gaining understandings is rarely addressed in science teaching and thus underlies much of students' learning difficulties in science.

Another major contributor to inadequate reasoning among students is a set of weaknesses in coordinating theory with evidence. Kuhn (1989) and her colleagues found that scientific thinking processes are "significantly different in the child, the lay adult, and the scientist" (p. 676). The child and the scientist coordinate theory and evidence in different ways. Children and nonscientist-adults do not differentiate between theory and evidence as independent entities and they often coordinate them by adjusting or distorting one to fit the other. In contrast, scientists differentiate and coordinate between theory and evidence and have metacognitive awareness of this coordination. Kuhn explained that when the theory and the evidence are compatible, students merge the two together, and regard the evidence as an "instance" or part of the theory. When the theory and the evidence are incompatible, students adjust either one to fit the other, or they ignore the evidence altogether. Kuhn (2004) considered the incident of ignoring or distorting evidence to fit existing theoretical frames as "faulty scientific thinking" because, in that case, existing theories are not challenged and there is no intention to seek new knowledge (p. 373). Kuhn attributed these shortcomings or inadequacies of reasoning to the notion that students usually regard their beliefs as "truths" rather than as testable hypotheses. Hence, they think *with* their theories rather than *about* them, which prevents students from considering alternative theories. Dunbar (1993) also found that many students fail to consider alternative hypothesis or explanations, especially if their goal was to search for evidence that is aligned with existing beliefs.

Student prior knowledge or beliefs are a main source of biased reasoning. The ability to evaluate evidence independently of prior beliefs is a basic component of "effective critical thinking" (Klaczynski et al., 1997). Stanovich and West (1997) regarded the ability to detach one's prior beliefs from the reasoning process as indicative of "good" thinking and used tasks that instructed participants to "ignore" their prior knowledge altogether. Klaczynski and Narasimham (1998) contended that reasoning is "self-serving" in that people attend to evidence that supplements or favors their prior beliefs and help them protect their self-image and self-esteem. Chinn and Brewer (1993) also reported that students tend to protect their prior beliefs by ignoring or distorting contradictory evidence.

Moreover, when scientists and nonscientists seek evidence that will confirm rather than disconfirm their prior beliefs or existing hypotheses, they exhibit what is called a "pervasive confirmation bias" (Klahr & Dunbar, 1988). In other words, reasoners usually refrain from falsifying their beliefs and instead approach tasks with the inclination of finding verification rather than disconfirmation. Indeed, reasoners hold tenaciously to their beliefs even after encountering contradictory evidence. According to Klahr and Dunbar (1988), reasoners tolerate negative evidence by attributing it to an error in either the execution or the results of a task, or they simply reject the evidence altogether.

Additionally, some researchers have attributed the negative influence of prior beliefs on reasoning to contextual and motivational factors. When the context is personal, such as religion, individuals feel threatened and tend to 'blindly' hold to their beliefs. Klaczynski and Narasimham (1998) examined age differences in reasoning abilities and the impact of personal religious beliefs and ego-protective motivations on reasoning biases among 5th, 8th, and 11th graders. The researchers detected improvements in reasoning skills with age and a strong influence for "ego-protective" factors on reasoning biases. They concluded that "like actual scientists adolescents are both cognitively and emotionally attached to their theories" (p. 185).

Role for Epistemic Beliefs in Reasoning

What makes some individuals more prone to bias due to prior-beliefs? What is it that controls or determines the extent to which prior beliefs can bias reasoning? According to Klaczynski et al. (1997), reasoning biases arising from commitments to prior beliefs are more associated with information processing style (e.g., open-mined thinking, rational *versus* intuitive thinking, and the belief that knowledge is certain) than with general cognitive ability. Stanovich and West (1997) asserted that thinking dispositions (e.g., the disposition to weigh new evidence against a prior belief) are influenced by epistemic values. Klaczynski (2000) noted that epistemic beliefs relating to the nature and acquisition of knowledge may in some cases outweigh prior beliefs in the process of reasoning.

Epistemic criteria are, therefore, another major factor influencing the quality of scientific reasoning. Epistemic criteria, also referred to as epistemological commitments, are the standards against which knowledge claims are evaluated or judged (Hogan & Maglienti, 2001; Samarapungavan, 1992). Epistemological commitments (a) elucidate the differences between scientific and everyday reasoning (Hogan & Maglienti, 2001), (b) trigger intentions and dispositions to engage in purposeful thinking (Kuhn, 2004), and (c) guide task-oriented goals (Dunbar, 1993). Moreover, epistemological commitments are gained mainly through participation in the sociocultural activities of a scientific community (Hogan & Maglienti, 2001) and can be facilitated by formal instruction and school-science culture (Samarapungavan, 1992).

The role of epistemological commitments and their relationship with prior knowledge or beliefs are gaining more attention in research on scientific reasoning. For instance, Hogan and Maglienti (2001) investigated the role of epistemological standards in scientific reasoning by comparing the reasoning of scientists and nonscientists. Participants were given a set of observations and 10 conclusions in the domain of ecology and were asked to judge each conclusion as valid or invalid and justify their judgments. Results showed that the reasoning performance of scientists was the highest, followed by technicians, nonscientist adults, and students. In addition, differences in prior knowledge did not affect the reasoning performance of students. The researchers concluded that scientists consistently rely on empirical evidence to judge knowledge claims whereas students rely more on their personal views. These results confirm that epistemic criteria might explain differences between students' and scientists' reasoning.

Greenhoot et al. (2004) investigated the conditions under which prior beliefs can bias reasoning processes. They hypothesized that individual differences, such as appreciation of methodological concepts, might predict how students reason in the presence of contradictory evidence. More specifically, the researchers examined the interaction between prior beliefs, methodological concepts, and scientific reasoning in different contexts. Participants were 211 liberal arts and sciences university undergraduates enrolled in a social science course on child development. Participants worked on two tasks: a physics task about a ball rolling down a ramp and a social science task about language development. Participants' prior knowledge, understanding of four methodological concepts, and reasoning were separately assessed in three sections for each task. The four methodological concepts examined were: function of evidence (or appreciation of empirical data as a basis for knowledge claims), reliability (or appreciation of the quality of measurement), experimental control (or appreciation of the importance of controls), and objectivity (or consideration of possible conflicts in knowledge or interests). Results showed that participants reasoned more accurately in the abstract context than in the personal context. The researchers concluded that prior beliefs negatively affect reasoning especially when understandings of methodological concepts are weak. In addition, reasoning is context-dependent; biases are more likely to occur in personal contexts than in abstract ones. Therefore, the ways in which methodological concepts (or epistemic criteria) and prior knowledge impact scientific reasoning depend on the associated context.

To sum, scientific reasoning is complex in nature. Researchers have tried to capture its nature by focusing on the relevant knowledge *or* the processes employed by learners. Many researchers, however, stressed the importance of both knowledge *and* strategies to scientific reasoning (e.g., Klahr & Dunbar, 1988; Schauble, 1996; Schunn & Anderson, 1999). Developmental differences in reasoning have been detected (e.g., Klaczynski & Narasimham, 1998), but the reasoning of scientists has been found to be superior to that of nonscientist adults (Dunbar, 2000; Hogan & Maglienti, 2001). Therefore, age does not account for all major differences in reasoning skills. Kuhn (2004) attributed differences in reasoning to weaknesses in metacognitive abilities, which lead to shortcomings in coordinating theory with evidence. Kuhn maintained that children cannot differentiate between theory and evidence. Other researchers (e.g., Samarapungavan, 1992; Sodian et al., 1991) reported opposite results. A consistent finding, however, is the persistence of reasoning biases, the most important of which is confirming prior beliefs and ignoring contradictory evidence. Prior knowledge seems to be a powerful source of bias in reasoning especially if the context is personal or emotional (Greenhoot el al., 2004; Klaczynski & Narasimham, 1998). The extent to which prior knowledge can bias reasoning is moderated by the kind of epistemic commitments one holds (Stanovich & West, 1997). Epistemic commitments or criteria are another salient factor underlying scientific reasoning. Greenhoot et al. (2004) implied that prior knowledge can bias reasoning most when epistemic criteria are weak or nonexistent. From a different angle, Samarapungavan (1992) found that the role of epistemic criteria becomes more important when prior knowledge is not contradicted. These findings suggest that the interplay between prior knowledge and epistemic criteria is very influential in determining reasoning performance and hence it merits further examination.

PURPOSE

This exploratory study aimed to assess the impact of two epistemic commitments on the quality of scientific reasoning among undergraduate college students. Scientific reasoning was approached from a coordination of theory and evidence perspective (cf. Kuhn, 2004). The target epistemological commitments were "commitment to consistency of the target theory with prior knowledge or beliefs" (CCTK) and "commitment to consistency of the theory with evidence" (CCTE). The study was contextualized in the specific domain of hydrostatics. The guiding research questions were: (a) To what extent does commitment to consistency of theory with prior knowledge and commitment to consistency of theory with evidence impact the quality of participants' reasoning? (b) To what extent, and in which ways, do these two epistemic commitments interact in their influence, if any, on participants' reasoning?

METHOD

The study was qualitative and exploratory in nature. Think-aloud, individual interviews served as the major instrument for data collection.

Participants

Participants were 12 sophomore science majors (11 females) enrolled in a large Midwestern university in the United States. They were randomly selected from an educational psychology research pool. Thus, participants are not necessarily representative of the larger population of sophomores at this university. Participants had a mean age of 18.6 years (*SD* = 0.4 years) and already have had, at least, 3 credit hours of college level physics. They were mostly white with GPAs ranging from 2.90 to 4.0 on a 4-point scale.

Procedures and Instruments

Answering the research questions entailed accessing participants' epistemic commitments and assessing the quality of their reasoning in a specific context; hydrostatics in the present case. Additionally, given the impact of learners' prior knowledge on their reasoning within a certain domain, it was crucial to elucidate the nature of participants' prior conceptions relevant to hydrostatics.

Students partook in two separate data collection sessions. First, they were administered a short questionnaire to assess their understandings of buoyancy. Next, about a week later, students participated in a think-aloud interview centered on a set of four paper-and-pencil scenarios depicting various systems of objects immersed in water. They were asked to think aloud as they attempted to answer specific questions outlined in the scenarios and justify and explain their responses. Engagement with the four scenarios created a context that allowed examining participants' reasoning in some depth. Such examination was achieved through further probing during the interviews using a set of questions that immediately followed participants' completion of work with the scenarios.

Tapping into students' epistemic commitments, which are mostly tacit and underlie their thinking, is a challenging task. While these commitments are believed to impact their reasoning, students are not necessarily aware of these commitments or able to articulate them (Hogan & Maglienti, 2001). Attempting to access such commitments through various forms of convergent-type instruments entails concerns about validity (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002). A possibly more valid alternative would be to infer these commitments from student actions or responses to more open-ended and carefully designed scenarios (Hogan & Maglienti, 2001) like the ones used in this study.

Conceptions of buoyancy questionnaire. A 10 short-answer item questionnaire was used to assess participants' conceptions of buoyancy. The questionnaire, which was piloted with a group of three freshmen science majors, appears in Appendix A. Items were adapted from Libarkin, Crockett, and Sadler (2003), She (2002), and Hewitt (1998). Participants were administered the questionnaire under the researchers' supervision, and it took them an average of 20 minutes to respond to all items. About a week's time separated participants' responding to the buoyancy questionnaire and sitting down to work with the four scenarios in the context of individual interviews. In the meantime, the researchers analyzed responses to the buoyancy questionnaire and constructed a profile of each participant's conceptions of floating and sinking. Thus, researchers were aware of participants' prior ideas of the target phenomenon before engaging them with the scenarios. Such knowledge was important in framing the interview follow-up and probing questions.

The four scenarios. The scenarios were related to objects partially or fully immersed in water (see Appendix B). Two scenarios were adapted from Hewitt (1998) and two were adopted from Loverude, Kautz, and Heron (2003). A brief text and associated illustrations were used to present each scenario. A statement of Archimedes Principle (i.e., the target "theory") appeared before introducing the scenarios. Each scenario differed in terms of what was asked of participants and the sort of "observations" made available to them through illustrations. The scenarios were constructed in such a way that comparisons of the same student's responses to the scenarios coupled with knowledge of his/her prior conceptions allowed making inferences about this student's two target epistemic commitments (see the data analysis section below). Participants responded to the scenarios in a private room under researcher supervision. On average, participants spent about 10 minutes to complete each scenario and record their justifications.

Think-aloud individual interviews. The primary researcher conducted the interviews. First, she asked interviewees to read the statement about Archimedes Principle before starting to respond to the scenarios.

She then instructed the interviewees to read a scenario and think about it for a while. Next, the researcher asked participants to talk her through as they went about thinking about and answering questions in a scenario and explaining their responses. The interviewer's role was passive during this part of the interview and limited to encouraging participants to go on with, or articulate, their explanations. Once finished with addressing a scenario, interviewees were asked whether they were satisfied with their responses and whether they would like to revisit and/or revise their approach and response to the problem at hand. The interview then proceeded to the next scenario until all four were addressed.

Immediately following their completion of the four scenarios, participants' reasoning was explored in some depth. They were instructed to read a scenario again, as well as their responses and justifications and inform the researcher that they were ready to talk about it. The researcher followed with a set of probing questions. Examples of these questions include: Can you think of another example from everyday life that is similar to what is presented in this scenario? Can you explain why this example is similar to this scenario? Do you agree with the "observations" in this scenario? If we were to conduct this experiment with actual objects, do you think we might observe something differently than what is depicted in this scenario? Can you justify your answer? What do you mean when you say . . . [excerpt from a participant's response]? Can you clarify this idea for me or provide another example? What does buoyancy mean to you? Explain to me how you used your ideas about sinking and floating to answer the questions in this scenario? Do you see any connections between these scenarios? Please explain. Digressions from these questions were numerous as the interviewer probed a certain concept more deeply or followed up on certain ideas derived from analyzing a participant's prior responses to the short item questionnaire. Toward the end of the interview and in case an interviewee did not refer to Archimedes Principle at all, the researcher asked the participant to read and explain Archimedes Principle. She then gave participants the option to make changes to their previous responses if they deemed this necessary. Each interview lasted about 60 minutes altogether. They were audiotaped and transcribed verbatim for analysis.

Data Analysis

Both researchers analyzed the data. Analyses were conducted in three stages. The first stage focused on participants' prior conceptions and understandings of the target phenomenon and associated concepts. Participant responses to the 10 short-answer item questionnaire were first analyzed to assess their prior knowledge of key concepts related to hydrostatics, such as mass, volume, density, weight, pressure, buoyant force, and buoyancy. Second, participants' responses to the scenarios were independently analyzed from the lens of conceptual understanding of hydrostatics, again, to draw conclusions about their knowledge of relevant concepts. Next, inferences about participants' prior knowledge generated from the independent analyses of their responses to the short-answer questionnaire and scenarios were compared and contrasted to generate more valid representations of their prior knowledge.

The second stage of analysis focused on characterizing participants' reasoning. Judgments about the "quality" of reasoning focused on a number of dimensions, which were derived from dimensions explicitly or implicitly emphasized by Greenhoot et al. (2004), Hogan and Maglienti (2001), and Tytler and Peterson (2003). These dimensions were: (a) accurate conceptualization of the task (e.g., identification of what is given—such as "observations" illustrated in a given scenario—and what is required), (b) consideration of all relevant variables, (c) accurate interpretation and/or application of relevant theoretical ideas (Archimedes Principle in this case), (d) consideration of alternative or competing explanations, (e) reaching accurate or supported inferences or conclusions, and (f) depth of conceptual "processing" (e.g., sequencing an argument; connecting evidence with a conclusion; synthesizing evidence, inference, and theory).

Judgments about participants' reasoning were derived from examining interview transcripts. To start with, responses that shed light on some or all of the above mentioned aspects were identified. Next, judgments about the "quality" of students' reasoning with respect to any of the above aspects were made holistically on a somewhat coarse three-level scale of "poor," "intermediate," or "high." Finally, a global judgment on the "quality" of a participant's reasoning was made based on examining these individual judgments as well as interactions among them. It should be emphasized that such global judgments were not algorithmic or quantitative in any sense. To start with, certain interview transcripts did not shed light on some of the aforementioned target dimensions. What is more, students often had mixed "performance" on some of the identified dimensions (e.g., a participant made an explicit attempt to consider two possible explanations but failed to support any one of them by reference to Archimedes Principle). As a result, participants' reasoning was categorized as "poor," "intermediate," or "high," while recognizing that there was a range of performance within each category.

The third stage of data analysis focused on identifying participants' stances on the two target epistemic commitments (i.e., CCTK and CCTE). 'Theory' in the present context refers to Archimedes

Principle. It should be noted that ascertaining participants' epistemic commitments was purposefully conducted during the last stage in the analysis so as not to bias judgments about the quality of participants' reasoning. In other words, given that the study was concerned with exploring the relationship between participants' reasoning and epistemic commitments, it was preferable not to conduct analyses of participants' reasoning while being aware of their epistemic commitments.

CCTK was judged to be apparent when participants, while considering the relationship between their prior knowledge (e.g., alternative views, conceptions, or beliefs) and a scenario before them, attempted to check the match or mismatch between such prior knowledge and Archimedes Principle (i.e., the "theory" provided as an explanatory framework for the scenarios at hand). The reader is reminded that an explicit statement about the fact that all four scenarios dealt with Archimedes principle was prominently shown on the scenarios sheet (see Appendix B). What is more, each interviewee was asked to read the statement about Archimedes Principle before starting to respond to the scenarios. Participants' CCTE was judged as apparent if they referred to relevant and/or accurate "observations" illustrated in the scenarios or other observations derived from their prior experiences when considering Archimedes Principle or other alternative ideas to account for the scenarios at hand. Finally, relationships were sought between the "quality" of participants' reasoning and their CCTK and CCTE.

RESULTS

In general, a majority of participants failed to demonstrate coherent reasoning schemes when approaching the phenomenon of buoyancy. Participants were confused about the relationship between pressure and buoyant force. Also, participants failed on one or more of the following dimensions of reasoning about the four scenarios: (a) clearly distinguishing the concepts of mass, weight, volume, and density, (b) relating the magnitude of the buoyant force to the weight of the displaced liquid, and/or (c) identifying the forces exerted on an object partially or fully submerged in a fluid. Findings were similar to those reported by Heron, Loverude, Shaffer, and McDermott (2003) and Loverude et al. (2003), which is not surprising given that the researchers adopted two of their scenarios.

Conceptions of Hydrostatics

Many student responses to the short-answer questionnaire and scenarios seemed to reflect confusion and inadequate understanding of the target concepts. Analyses of participants' responses to the scenarios are summarized in Table 1 (pseudonyms are used to refer to individual participants). Many participants attributed floating and sinking to the weight of the immersed object. They believed that heavy objects (of any size) would sink and light objects would float. Moreover, many did not differentiate between mass and weight and used them interchangeably. Very few participants explained floating and sinking by referring to the forces acting on the submerged object and their overall effect. Some cited causes (e.g., pressure, surface tension) without giving further justification. Others just repeated one or more observations given in a scenario, such as attributing easier floatation in sea water to the presence of salt, or attributing equal magnitudes of the buoyant force to the fact that all objects are in the same solution or tank.

In addition, some participants demonstrated a partial or inadequate knowledge of the relations and connections among the target concepts. For example, some related the density of an object only to its mass or weight without considering its volume. Some thought that the mass, weight, and/or density of an object (not the volume of the submerged part) determine the amount of water it displaces. Thus, they failed to correctly link the buoyant force to the weight of the displaced water. Linking the buoyant force to the weight of the object rather than the weight of the displaced liquid was also reported by other researchers (e.g., Burbules & Linn, 1988). More than that, some participants were inconsistent in their justifications. For example, they attributed the strength of the buoyant force to the factor of depth in the case of one object and mass in the case of another object. This finding could be also attributed to an inability to simultaneously handle more than one variable or simply to confusion. The following sections explore participants' responses to the four scenarios in some detail.

Scenario I: Floating block of wood. This scenario (adapted from Hewitt, 1998) shows a block of wood floating on the surface of still water (see Appendix B, Figure 1). Students were asked whether there are any forces acting on the block, and if so, to name and compare them. To answer correctly, students should mention the existence of a downward force of gravity balanced by an upward buoyant force. There were four (out of 12) accurate responses (see Table 2). Answers which referred to the buoyant force as an upward force caused by the water were considered correct. Incomplete or partially accurate answers mentioned the existence of one force. Inaccurate and partially accurate responses ranged from stating that there are no forces acting on the block because it is floating or not moving, to mentioning only the force of gravity, to mentioning other variables such as mass, surface tension, and pressure as being forces.

Table 1.Characterization of Participants' Responses to the Four Scenarios

Participant	Scenario			
	Floating block	Iron ball	Five blocks	Suspended cubes
Keely	PA	I	I	I
Leslie	I	PA	I	I
Mandi	PA	I	I	I
Amy	PA	I	I	A
Erin	PA	PA	I	I
Laura	A	PA	I	I
Rosa	PA	PA	I	PA
Morris	A	A	I	I
Tess	A	A	I	I
Liza	PA	A	PA	I
Susan	PA	A	PA	A
Kate	A	A	PA	A

A = Accurate; PA = partially accurate; I = inaccurate
Participants in order of increasing performance from top to bottom

Table 2. Number of Accurate, Partially Accurate, and Inaccurate Responses for Each Scenario

Task	Accurate	Partially accurate	Inaccurate	Total
Floating block	4	7	1	12
Iron ball	5	4	3	12
Five blocks	0	3	9	12
Suspended cubes	3	1	8	12

Scenario II: Iron ball. In this problem (adapted from Hewitt, 1998) an iron ball suspended by a spring balance is submerged in water. The scale shows a decrease in the ball's weight (see Appendix B, Figure 2). [continue paragraph]

Students were asked to explain the "loss" in weight. An accurate answer requires the student to indicate that the spring balance measures the apparent weight acting on the ball, and while this force was only the force of gravity when the ball was suspended in air, it is now the force of gravity countered or diminished by the upward buoyant force.

There were five correct responses to this scenario (see Table 2). Partially correct responses referred to an upward force exerted by water on the ball but included one or more inaccurate statements such as, "There is a buoyant force acting up on the ball and therefore its mass will be less." Inaccurate responses included, "The weight decreased because there was a pressure exerted by the water," or "there is less gravity within water than in air." Few answers included a mere repetition of the observation: "The weight at the end of the balance is now resting in a liquid, as opposed to being free to hang in the air." One participant even rejected the observation: "I don't agree with the picture because I think it will weigh more in water."

Scenario III: Five blocks. This problem (adopted from Loverude et al., 2003) shows five blocks of the same size and shape but different masses, with block 1 having the least mass and block 5 having the largest mass (see Appendix B, Figure 3). All blocks are held halfway in a tank of water and then released. The final positions of blocks 2 and 5 are shown: Block 2 barely floats and block 5 sinks. Students were asked to determine and draw the final positions of the other three blocks. According to Loverude et al. (2003), an accurate answer to this problem requires an inference that since block 2 barely floats, it should have a density very close to that of water, and since $m_1<m_2$, m_1 must have a smaller density and thus will float higher than block 2. Block 3 will sink because it has a larger mass than block 2 and hence its density will be greater than that of water. Block 4 will also sink. However, the problem does not specify the exact differences between the masses of the blocks. Therefore, another possible result for this problem is that Block 3 could have the same density of water and it could stay "suspended" half-way where it was released.

There were no completely accurate responses for this problem (see Table 2). Three responses referred to the relative masses and densities of the blocks in comparison to the density of water but did not arrive at any of the two expected results. These responses were considered partially correct. The most common inaccurate response showed blocks 3 and 4 descending linearly in water, indicating that the majority of participants attributed the final positions of the blocks to their increasing masses or weights. This finding is in accordance with Loverude et al.'s (2003) "descending line" response.

Scenario IV: Three suspended cubes. This problem (adopted from Loverude et al., 2003) describes three blocks of equal volume suspended underwater by strings. There are two blocks of the same mass at different depths (A and B) and two blocks of different mass at the same depth (A and C). Students are asked to rank the buoyant forces and tensions in the strings (see Appendix B, Figure 4). According to Loverude et al. (2003), to answer correctly, students need to recognize that the submerged blocks displace the same weight and volume of water because they all have the same volume and are fully immersed in the water. Therefore, the buoyant forces acting on them are all equal, and hence the tensions must be equal because the cubes are in equilibrium. If one of the blocks had been floating, then it would have displaced a smaller volume and the buoyant force acting on it would have been less. One student (Kate) was able to make this last observation and link it to the floating block scenario.

Three students accurately ranked the buoyant forces and tensions acting on the three cubical blocks. Two of the three struggled in comparing the buoyant forces and could only arrive at an accurate conclusion after carefully considering Archimedes Principle. For example, one said, "After checking with the theory, all three have the same buoyant force because they displace the same amount of water and I think the string is the primary cause of the different depths." One response was considered partially accurate because it ranked the buoyant forces as equal but lacked a reasonable justification: "The buoyant force is equal because they're all in the same solution or tank." Inaccurate responses ranked buoyant forces according to mass and/or depth of the object. For example, one participant said, "A and C should have the same buoyant force and B should have greater buoyant force because it is lower."

Quality of Reasoning

Judgments about the "quality" of participants' reasoning appear in Table 3 and, as noted above, were based on the absence or presence and accuracy, of the following dimensions: (a) accurate conceptualization of the task, (b) consideration of all relevant variables, (c) accurate interpretation and/or application of relevant theoretical ideas, (d) consideration of alternative or competing explanations, (e) reaching accurate or supported inferences or conclusions, and (f) depth of conceptual "processing."

For example, "poor" and "poor to intermediate" reasoning have been attributed to participants who considered irrelevant variables (such as pressure or surface tension for the floating block scenario), did not differentiate between different variables (such as using mass and weight interchangeably), misinterpreted Archimedes Principle (by considering that the buoyant force depends on the weight of the object), and/or relied on rote knowledge to seek answers (such as trying to remember a formula or an equation).

In general, a comparison of Table 1 and the first column in Table 3 indicates that participants' reasoning was related to their performance on the four scenarios. Poor reasoners failed to give an accurate response to all of the four tasks. Poor to intermediate reasoners succeeded in giving only one accurate response or two partially accurate responses. Intermediate reasoners, who despite searching for alternative explanations and considering relevant variables, were not able to draw accurate conclusions to, at least, two scenarios. High reasoners displayed deeper information processing, more accurate understanding of the underlying concepts, and a consistency in referring to Archimedes Principle and drawing inferences based on it. They gave partially accurate or accurate responses to all four scenarios. It should be noted that decisions regarding the quality of reasoning were very hard to make in the case of some participants and, hence, we found that a range of reasoning qualities (e.g., from poor to intermediate, or intermediate to high) would provide a more accurate representation of the findings. Details about participants' reasoning are provided in the three illustrative case studies that appear below.

Epistemic Commitments

As detailed in the data analysis section, participants' commitments to the consistency of theory with prior knowledge (CCTK) and consistency of theory with evidence (CCTE) were inferred from their interview transcripts and were categorized as "apparent" or "not apparent" (see Table 3, columns 2 and 3). For example, Leslie held the prior belief that buoyant force depends on the weight of the object (not the weight of the displaced water) and she based her conclusions on this belief. She did not attempt to consider or reconcile this belief with the statement of Archimedes Principle. Indeed, when asked to consider the principle, she distorted it to fit her prior conceptions: "It says about the weight of the liquid displaced by the object, and they [i.e., Archimedes] say if something has less mass it's going to displace less water, so that's where the buoyant force would be less for C." Her CCTK was thus judged to be absent. In comparison, Susan consistently referred to Archimedes principle and compared the ideas she invoked to this principle as she reasoned about the scenarios (and, eventually, reached accurate conclusions) and, thus, was judged to have a CCTK:

> What I'm trying to say is that the more mass, the more buoyant force is put on it (long pause). No, *the theory says*, they're the same size, so the liquid displaced by the object, they displace the same amount of liquid, and

Table 3.Categorization of Participants' Reasoning Performance and Epistemic Commitments

Participant	Level of Reasoning	CCTK[1]	CCTE[2]
Keely	Poor	Not apparent	Not apparent
Leslie	Poor	Not apparent	Not apparent
Mandi	Poor	Not apparent	Not apparent
Amy	Poor to intermediate	Apparent[3]	Apparent
Erin	Poor to intermediate	Not apparent	Not apparent
Laura	Poor to intermediate	Apparent[4]	Apparent
Morris	Intermediate	Not apparent	Not apparent
Rosa	Intermediate	Apparent[4]	Not apparent
Tess	Intermediate	Apparent	Apparent
Liza	Intermediate to high	Apparent	Not apparent
Susan	High	Apparent	Apparent
Kate	High	Apparent	Apparent

[1] CCTK = Commitment to the consistency of theory with prior knowledge
[2] CCTE = Commitment to the consistency of theory with evidence
[3] Student was partially consistent with applying this commitment across scenarios
[4] Student only referred to theory after being prompted by the researcher

> because this liquid that's displaced has the same weight, so it'll all be equal because the buoyant force is equal to the weight of the liquid that they displace [italics added].

On the other hand, some participants did not refer to any of the observations provided in the scenarios or experiences from their everyday lives to *check* or *test* the accuracy of their responses. Rather, these participants simply restated or applied their prior knowledge to reach a conclusion about a scenario while disregarding the fact that their ideas do not agree with, or lead to, the observations illustrated in that scenario. These participants were judged to lack a CCTE. In comparison, as evident in the cases below, those participants who compared the consequences of their ideas with observations (provided in the scenarios or derived from their everyday life experiences—such as swimming) were judged to have a CCTE.

Illustrative Case Studies of Selected Participants

This section presents the cases of three participants who demonstrated poor, intermediate, and high reasoning performance. These case studies help to illustrate how judgments about participants' reasoning and epistemic commitments were arrived at.

Case I: Keely (poor quality reasoning). Keely held the prior belief that light objects float while heavy objects sink. Upon remembering the case of a submarine and that it can float, which conflicted with her prior belief, she dismissed this counterexample and retreated to her prior conception (lack of CCTE):

> (Floating block scenario)
> Keely: It is light enough to float on water and there's nothing pushing down on it.
> Researcher (R): What would your answer be if this block was made of iron? What would you predict would happen then?
> Keely: Well, if it was solid iron, I think it would sink, but one of the previous questions was steel or something and it floats, like a submarine floats [pause] so I don't know.
> R: Think about this, give it a try.
> Keely: Well, I still think that there would be a weight then, I guess. The force of its weight [pause] it just depends on how solid the material is, I guess. I don't really know; because when I think of a wooden block, I think of it just being lighter than a steel block, so it would float.

Keely did not even try to resolve the inconsistency that a submarine is heavy and yet can float. She did not check Archimedes Principle at all or attempted to see how her recall of this "observation" could impact her thinking. Indeed, she even dismissed "observations" in the scenario as "not possible" when these conflicted with her ideas:

> (Iron ball scenario)
> Keely: I don't agree with the picture; I think it will weigh more in water.
> R: So you don't agree with the observation?
> Keely: Well, I would think it'd weigh more. Adding more weight to it with the water. So that's why I'm kind of lost in explaining how there was a loss in weight.
> R: So you don't agree with the figure to start with?
> Keely: No.
> R: Okay. What do you feel when you swim?
> Keely: Lighter.
> R: Okay, and have you ever tried to hold something in water?
> Keely: Yes.
> R: How does it feel?
> Keely: Easier.
> R: So why do you think this is the case? Have you ever thought of that?

Keely: As far as like salt water, the salt makes you float. But I don't know, I don't ever pay attention to it. Just the weight of the water since it's different than what we're made of. I don't know.

Again, Keely dismissed the contradictory examples and provided superficial explanations.

(Three cubes scenario)

Keely: I think that first would be B then A and C.

R: Would be what?

Keely: It (buoyant force) would be like the largest. And then A and C, just because B has a longer string, and it's the heaviest. And then, A is equal (in mass) to B and then, C is the lightest.

R: Why do you think so?

Keely: Well, since A and B are equal in mass, and then it's . . . well, as I just said the string length because it was deeper in water.

R: Why did you say that C is least and it has the same depth as A?

Keely: Because it's the lightest and there's not much force pushing it into the water.

This shows that Keely retained her belief that position in water depends on how light or heavy something is. She also believed that buoyant force depends on depth; the deeper the object, the higher the force acting on it. She linked the depth to the weight by thinking that since B is heaviest, the buoyant force is strongest and the string is longest (as if B pulls down on the string). But it can clearly be seen from her answer regarding block C that she resorted to her prior belief that it all depends on how light or heavy something is and this indicates her strong commitment to her prior beliefs. Her reasoning was considered to be poor because she failed to consider all relevant variables, failed to give alternative explanations, did not check with Archimedes Principle, and made inaccurate inferences.

Case II: Tess (intermediate quality reasoning). Tess strongly believed that the theory must be right and used it to come up with the answer to the floating block task (and, thus, was judged to have a CCTK):

Tess: Well, I wasn't sure, but I just know because there's no liquid displaced. And so, the principle says the force acting on it should be equal to the weight of the liquid displaced by the object, and I didn't see any liquid being displaced.

R: Okay, so if I told you that the liquid displaced maybe is not shown in the figure, would that affect your answer?

Tess: Yes, it would . . . Because my first instinct was to say that there must be some sort of force acting from underneath the block to hold it up . . . but I guess my understanding of the principle maybe would change my answer.

R: Tell me more.

Tess: So yes if you told me that there was liquid displaced that I couldn't see from the picture, it would change my answer.

R: How would this change your answer?

Tess: Yeah, I would say that there would be forces acting on the block. The kind of force?! I guess I would call it a buoyant force, and it would be equal to the weight of the liquid that was being displaced.

R: Any other thoughts?

Tess: Well, I guess gravity is also acting on it. So there's gravity on it and there's the buoyant force and they would be equal cause it's not sinking.

Tess is an interesting case because her prior knowledge about the topic was minimal and inaccurate. Yet, she managed to analyze the presented principle and use it to arrive at accurate conclusions for two scenarios. She tried to think of many variables and referred to everyday experiences in making inferences (clearly displaying a CCTE). Tess's case serves to show that a simple one-to-one relationship between naïve ideas and poor reasoning would not suffice to account for findings in the present study. Epistemic commitments might, on occasion, outweigh bias in reasoning caused by naïve beliefs. This is not to say that prior beliefs do not impact reasoning. Indeed, in the case of Tess, a misconception did confound her reasoning and she failed to correctly analyze two other scenarios (her reasoning was thus judged to be intermediate):

(Three cubes scenario)

R: Does it bother you that A and C are at the same depth in water?

Tess: I still think that A would have a higher buoyancy force than C just because it's heavier. So that doesn't trouble me cause I think it's heavier, so I think it would still displace more water.

Case III: Kate (high quality reasoning). Kate demonstrated deeper understanding of hydrostatics concepts. Her explanations and justifications were rich, deeply processed, systematic, and consistent with the presented theory and "observations." She sought alternative explanations and compared them to Archimedes Principle to draw final conclusions. She was judged to have both CCTK and CCTE and her reasoning was judged to be of high quality:

Kate: Second thoughts, after the revelation, the only way that C would have a greater buoyancy force would be if it was, if it had a small enough density that it didn't stay completely submerged in the water, but rather, floated to the top. Because then it would, then the amount of water that it would displace would only be equal to that to the amount of the block that was still in the water. So this is, the shaded area (she makes a drawing) is the volume of water displaced. Cause what it says here is that this is where they're lowered to, but it doesn't say that, it doesn't mean that they don't

> float up all, they don't float up. So therefore, C, you can't really tell if it has the same buoyancy force as A and B, or if it actually has a less buoyant force in the fact that it floats to the top, and part of the block becomes exposed and is no longer fully under water. If all three remain under water, they'll all have the same; they all take up the same amount of volume in the water. So therefore, the amount of volume of water that they displace is the same, therefore, making their buoyancy forces the same. Does that make any sense?

DISCUSSION AND CONCLUSIONS

Not surprisingly, the results of the present study indicate that participants' quality of reasoning was impacted by the accuracy of their prior knowledge and beliefs about hydrostatics. All high reasoners had relatively more accurate conceptions than poor reasoners, who ascribed to a number of naïve ideas about sinking and floating. This is consistent with prior studies, such as those of Hogan (2002), Reif and Larkin (1991), Schauble (1996), and Schunn and Anderson (1999). However, the story is a bit more complicated. In some cases, participants who held naïve conceptions reasoned at an intermediate level and those who held some accurate conceptions reasoned poorly. In other cases, participants were inconsistent in their reasoning about the different scenarios. In this rather grey area (i.e., participants who showed intermediate reasoning abilities and/or partially accurate prior conceptions), the two target epistemic commitments seem to come into play (see Table 3).

Again, high reasoners demonstrated both a CCTK and CCTE, while poor reasoners lacked these commitments. In the somewhat grey area of partially accurate understandings, the presence or lack of CCTK and/or CCTE seemed to have impacted the quality of reasoning. While the design of the present study does not allow making causal inferences, the tentative results point to an interesting and possible role for the two target epistemic commitments in impacting the quality of reasoning (or, at least, serving as mediating factors in impacting reasoning). These results are consistent with those of Hogan and Maglienti (2001) even though their conclusions were about more global commitments related to the culture of science. Instead, the present study points to a possible influence on the quality of reasoning of two specific epistemic commitments that are, in principle, teachable in pre-college science classroom settings (see Schauble, 1996). These specific commitments are different from the rather global commitments targeted by Hogan and Maglienti (2001), which could be effectively acquired through immersion in the practice and culture of science; a sort of immersion that is often untenable in the case of the larger majority of pre-college science students.

The ability to make stronger inferences about a possible causal relationship between learners' epistemic commitments and the quality of their reasoning require a study of a different design that would address the limitations of the present study. To start with, a possibly narrower but more refined definition of "reasoning" and a typology or categorization of the "quality of reasoning," and an associated analytical framework are needed. While such definition and framework might limit the generality of the results, they would entail more accuracy in making judgments about participants' reasoning. Second, an experimental study would be needed to eliminate the effect of some variables while controlling for others in order to make more solid and possibly causal inferences about the relationship between reasoning and epistemic commitments. For example, it is evident that participants' prior conceptions interact with the quality of their reasoning. In an experimental study, pre-testing can be used to ascertain participants' prior conceptions and select sub-samples (e.g., tose with only naïve *versus* those with only accurate conceptions) to respond to carefully designed scenarios that would elicit one or the other of a set of target epistemic commitments.

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Appendix A: Conceptions of Buoyancy Questionnaire

1) What enables you to float in a swimming pool, pond, or lake?

2) How can a steel ship weighing about 500 Tons float in water?

3) A block of aluminum with a volume of 10 mL is placed in a beaker of water filled to the brim. Water overflows. The same is done in another identical beaker with a 10 mL block of lead. Does the lead displace more, less, or the same amount of water? Why?

4) Some people say that it is easier to float in sea water than in fresh water (as in a river for example). Do you agree with this statement? Why or why not?

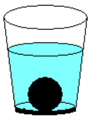
5) A block of aluminum with a mass of 1 Kilogram is placed in a beaker of water filled to the brim. Water overflows. The same is done in another identical beaker with a 1-Kilogram block of lead. Does the lead displace more, less, or the same amount of water? Why?

6) What would happen to an *empty soda can* if we put it into 2% salt water and 22% salt water? Explain your answer.

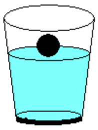
7) How can a submarine sink down in the ocean and then float on the surface again? In other words, how can it dive deep in water and then go back up to the surface?

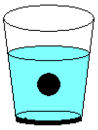
8) A block of aluminum with a weight of 10 Newton is placed in a beaker of water filled to the brim. Water overflows. The same is done in another identical beaker with a 10-Newton block of lead. Does the lead displace more, less, or the same amount of water? Why?

9) Mary and Tony are in science class. They are using two balls, one large and one smaller, made of the same material. Mary puts the larger ball in the water and watches it sink.



After removing Mary's ball, Tony puts the small ball into the water. What do you think will happen when Tony puts the small ball into the water? Circle the figure that you think best represents what will happen to the small ball. Explain why you circled this figure.


A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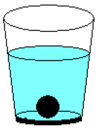
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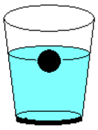
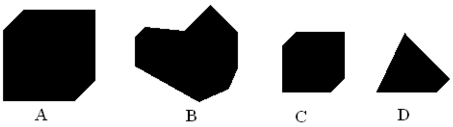
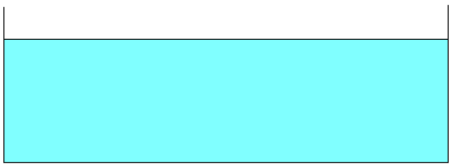

D

10) The teacher walks by and hands Mary and Tony four objects made of the same material as the large and small balls in item (9):



Mary reminds Tony that the large ball sank earlier when they put into the water. DRAW each of the four objects in the water filled container below based on whether you think they will sink or float. Explain why you have drawn the objects this way.



Appendix B: The Four Scenarios

The following problems deal with **Archimedes Principle**. This principle states that the buoyant force acting on an object partially or fully submerged in a liquid is equal to the weight of the liquid displaced by the object.

Use this principle to answer the following questions:

(1) A block of wood is floating on the surface of still water as shown in Figure 1 below. Is there any force or forces acting on the wooden block? If yes, specify the kind of force and compare their magnitudes (strengths).

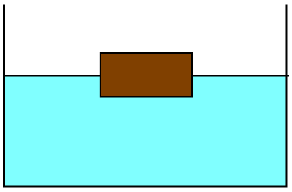


Figure 1

(2) The weight of a solid iron ball is 30 Newton in air as indicated by the spring balance. When the ball is submerged in water the weight becomes 25 Newton. How do you explain the loss in weight?

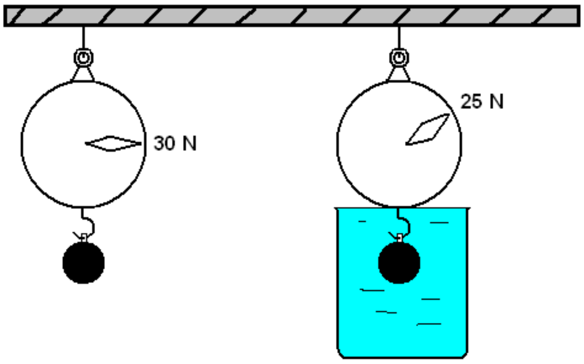
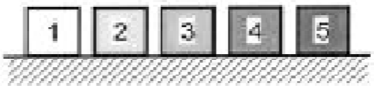


Figure 2

(3) Five blocks of the same size and shape but different masses are shown in the figure below. The blocks are numbered in order of increasing mass (i.e. $m_1 < m_2 < m_3 < m_4 < m_5$). All the blocks are held approximately halfway down in an aquarium filled with water and then released. The final positions of blocks 2 and 5 are shown in Figure 3 below. On the diagram, sketch the final positions of blocks 1, 3, and 4. Explain your reasoning.

$m_1 \quad < m_2 \quad < m_3 \quad < m_4 \quad < m_5$



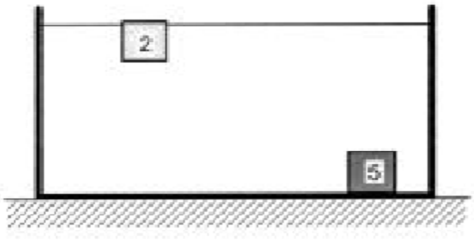


Figure 3

(4) Three cubical blocks of equal volume are suspended from strings. Blocks A and B have the same mass and Block C has less mass. Each block is lowered into a fish tank to the depth shown in the figure below.

a) Rank the buoyant force acting on each block from largest to smallest. If any buoyant forces are equal indicate that explicitly. Explain your reasoning.

b) Rank the tension in each string from largest to smallest. Explain.

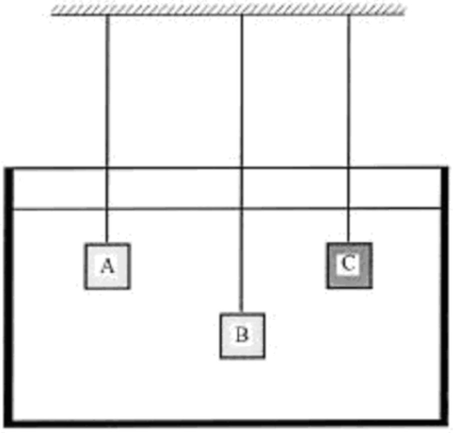


Figure 4