USING A CROSS-CUTTING THEORETICAL FRAMEWORK TO EXPLORE DIFFICULTIES LEARNING HUMAN ANATOMY AND PHYSIOLOGY

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Tara Nicole Slominski

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

SUPERVISORY COMMITTEE:

Jenni Momsen
Chair

Lisa Montplaisir

Jeffrey Boyer

Tim Greives

Warren Christensen

Kimberly Vonnahme

Approved:

April 27, 2020
Date

Kendra Greenlee
Department Chair

ABSTRACT

Across the United States, Human Anatomy and Physiology (HA&P) courses typically have some of the highest withdrawal and failure rates on college campuses. These high enrollment course typically serve as gate-keepers for those individuals with aspirations of entering the medical field. In light of the growing national shortage of healthcare professionals, there is a pressing need to improve the state of HA&P education at a national scale. The goal of this dissertation is to understand why undergraduate students struggle to succeed in HA&P courses. I leveraged multiple frameworks from biology education research, physics education research, and cognitive psychology to understand the source of student difficulty in HA&P. I used a mixed-methods approach to unpack how students reason about the complex phenomena covered in HA&P classes. The data presented here suggest student difficulties in HA&P are not the product of a culmination of individual conceptual difficulties. Rather, this work suggests students have difficulty reasoning with the many complex systems that are at the heart of HA&P curriculum. Students appear to frame these complex systems in a manner that activates reasoning strategies that are often in conflict with course goals. The findings from this work advocate for a dynamic view of student cognition that recognizes the implications of context features on student reasoning of complex systems.

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DEDICATION

This dissertation is dedicated to my parents who worked so hard to make sure our futures were full of open doors.

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CHAPTER 1. INTRODUCTION

The U.S. Bureau of Labor Statistics recently reported that the healthcare industry is the fastest growing occupational group (2019). Projections indicate that over the next 10 years, we will need to drastically increase the number of graduating healthcare workers to meet these expected demands. When we look to the training and educational curriculum that is required of the various healthcare programs (i.e. nursing, dietetics, physical therapy, medical school, etc.), the introductory human anatomy and physiology (HA&P) course series typically serves as an early gatekeeper, regulating who can move on to their intended program and, ultimately, their intended career. Unfortunately for those undergraduate students with aspirations of pursing healthcare professions, the HA&P course series is notoriously a difficult gate to breach.

HA&P is Hard

Across the U.S., the HA&P course series is typically considered especially challenging by both students and faculty (Sturges & Maurer, 2013; Michael, 2007). These perceptions align with more traditional measures of difficulty, as these courses are often plagued with high drop, withdrawal, and failure rates (DFW) (Sturges et al., 2016; Harris et al., 2004). High DFW rates are especially troubling when one considers the high enrollments typically associated with the HA&P course series.

Despite the nationally recognized need to improve HA&P education, little progress has been made to understand why students struggle to succeed in HA&P. Much of the existing HA&P education research takes a pedagogical focus and attempts to rectify student difficulties one concept at time, one instructional intervention at a time. This approach to discipline-based education research often works towards developing a suite of empirically tested instructional tools and techniques for each of the various topics covered in the HA&P series. Instead of treating each conceptual struggle as an isolated phenomenon, I adopt a more holistic approach and searches for a common underlying cause (not tied to any singular concept) that can begin to explain why students struggle to learn in HA&P classrooms.

In the sections that follow, I leverage findings and frameworks from biology education research, physics education research, and cognitive psychology to propose four potential sources for the difficulty students experience in HA&P: teleological reasoning, context effects, framing and resources, and complex systems.

Teleological Reasoning

Due to the nature of the content, it is reasonable to assume students enter the HA&P classroom with a wide array of preexisting ideas, beliefs, and experiences of how the human body functions. These preexisting notions likely arise from the numerous observations students have made about their own body (and those around them) as they've gone about their daily lives. Additionally, I argue students are likely to associate their preexisting ideas and observations with the goal of health or survival. For example, observations and insights gained from personal experiences like exercising, dietary behaviors, aging family members, and the recent COVID-19 outbreak could all be associated with attempts to improve or maintain their own personal well-being or the well-being of others.

Because students likely have many informal knowledge structures developed through personal experiences, it is possible students refer back to these ideas (either consciously or subconsciously) when asked to reason about a physiological event in the HA&P classroom. Further, a substantial body of biology education research is in support of this argument: we do see strong evidence of students using goal-based reasoning when reasoning about physiological phenomena (Slominski, 2017; Badenhorst et al., 2016; Cliff, 2006; Michael et al., 2002; 1999; Modell, 2000; Michael, 1998; Richardson, 1990). Recognized widely by the discipline-based education research communities and the cognitive psychology literature, goal-based reasoning is referred to as teleological reasoning. Teleological reasoning is a way of reasoning in which one assumes that objects and events exist and function in a manor intended to support a specific purpose (Southerland et al., 2001; Keleman, 1999a; 1999b; Tamir & Zohar, 1991). A teleological approach relies on the outcome(s) to explain *why* the events occurred as opposed to focusing on the underlying mechanisms to explain *how* the event was produced.

Teleological reasoning is in conflict with causal or mechanistic reasoning, in which phenomena are seen as not goal-driven and having emerged unintentionally. In a causal or mechanistic reasoning approach, emphasis is placed on how interactions between the individual components of a system gives rise to a particular function or event (Russ et al., 2008). Often unbeknownst to the student, teleological thinking is problematic as it is strongly correlated with an inaccurate understanding of biological phenomena (Richard et al., 2017; Coley & Tanner, 2015; 2012; Bishop & Anderson, 1990). Teleological reasoning prohibits a student from incorporating important biological principles like variation and randomness into their mental models (Alters & Nelson, 2002). Because a student's success in HA&P depends on them being able to reason mechanistically across and within body systems, a teleological approach will likely hinder a student's ability to generate an accurate mental model of physiological phenomena.

A large body of evidence suggests students are inclined to approach biological phenomena with a teleological lens. From the cognitive psychology literature, there is strong evidence to suggest both adults and children have a tendency to explain phenomena in terms of its purpose (Lombrozo & Carey, 2006; Kelemen, 1999a; 1999b; Keil, 1995). Kelemen argues the human mind is designed in such a way that we have an innate tendency to view objects as having been intentionally designed for a specific purpose (Kelemen, 1999a; 1999b). Kelemen and others term this innate tendency as a teleological cognitive construal (Coley and Tanner, 2015; Kelemen, 1999a; 1999b). Extending this view to student difficulties in HA&P, proponents of teleological cognitive construals would argue that students likely consistently apply teleological reasoning to the various topics covered in HA&P (Figure 1). Ultimately, this broad application of teleology could lead students to developing a faulty or incomplete understanding of the numerous phenomena covered in HA&P.

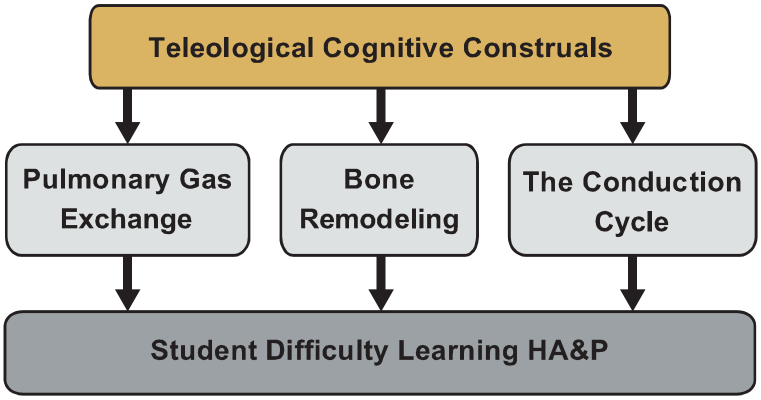

Figure 1. Explanatory Model Depicting How Teleological Cognitive Construals May Impact Student Difficulty in HA&P.

From the K-12 education literature, we know regardless of grade level, students are more likely to provide teleological explanations than mechanistic explanations when reasoning about biological phenomena. An interview study from Tamir and Zohar (1991) found that high school students are inclined towards teleological reasoning and often use teleological reasoning to describe structure and function and complementarity. Similarly, Southerland and colleagues (2001) published a multi-site interview study that asked a total of 96 second, fifth, eighth, and twelfth grade students (8 students from 4 grade levels at 3 sites) to explain a variety of different biological phenomena. In this study, researchers asked students to provide explanations for four different biological scenarios and then categorized the explanations they provided. Across the twelve student cohorts, teleological reasoning was the most prevalent explanation in all but one student cohort (twelfth graders in New Hampshire). More recently, Trommler and colleagues found that when given the choice, high school students were drawn to selecting teleological explanations over mechanistic explanations (Trommler et al., 2018).

This trend continues at the undergraduate level, as there are numerous empirical reports of students using teleological explanations when faced with biological questions. In the evolution education literature, many have evidenced the high pervasiveness of teleological reasoning by asking undergraduate students to reason about natural selection (Barnes et al., 2017; Coley & Tanner, 2015; 2012; Nehm & Reilly, 2007; Bishop & Anderson, 1990). Looking more specifically to HA&P education research, Michael and colleagues have conducted multiple studies probing student predictions and their resulting explanations of physiological phenomena in the context of the cardiovascular and respiratory systems (Michael et al., 2002; 1999; Michael, 1998). These studies all demonstrate students have a strong tendency to use teleological sense-making when reasoning about human physiology. The findings from Michael and colleagues contribute to a larger body of literature in which teleological tendencies have been found to exist at high frequencies at various stages in the HA&P curriculum and persist even after completing undergraduate physiology courses (Slominski, 2017; Badenhorst et al., 2016; Cliff, 2006; Modell, 2000; Richardson, 1990).

Context Effects

As described above, students likely have already acquired numerous ideas about the human body prior to entering the HA&P classroom. While this informal acquisition of prior knowledge is not exclusive to HA&P content, one could argue students have had more frequent and immersive experiences with the human body compared to many other biological content areas. Take, for example, the nitrogen cycle, a concept covered in the introductory biology course series. It is reasonable to assume an undergraduate student has acquired fewer informal ideas about the nitrogen cycle as compared to an

HA&P topic like respiration. It is also reasonable to assume a student is less likely to develop strongly held notions regarding the goal or purpose of the nitrogen cycle, especially when compared to respiration, wherein a student could identify obtaining oxygen or staying alive as the goal or purpose. Therefore, because students have robust experiences with the human body, they may be inclined to reason differently about biological scenarios if they are presented within the context of the human body.

There is a growing body of work that recognizes the impact context features may have on student reasoning. In a recent paper, Gouvea and Simon (2018) argue the contextual features of a problem, scenario, or activity influence the way a student approaches the task and the kinds of knowledge they employ. In this case, contextual features can refer to a number of different factors, the physical environment in which the activity takes place, the surface context used in the activity itself, or even the experiences a student has leading up to an activity. For the purposes of this dissertation, I focus on the surface context included in a prompt or questions that situates a task in a particular content area.

There is a grown body of literature from the biology education research community that is in support of context effects impacting student thinking. In 2011, Nehm and Ha found evidence to suggest students reason differently about natural selection when presented with a question asking about trait gain versus trait loss. Similarly, Heredia and colleagues (2012) found that when asked to reason about natural selection, students employ different reasoning strategies when presented with a question discussing animals than when it contains plants. Students were more likely to provide correct responses to questions containing animals than questions containing plants. Further, students were more likely to apply an inaccurate “survival of the fittest” reasoning approach when the assessment contained an “unfriendly” animal as opposed to a more “friendly” animal.

Extending the existing work on context effects to student difficulties in HA&P, it is possible the human-centric context of HA&P curriculum impacts student reasoning by increasing the likelihood students will draw on their pre-existing ideas, experiences, and beliefs pertaining to the human body (Figure 2). By activating and applying these pre-existing ideas, experiences, and beliefs to the complex physiology presented in the HA&P classroom, students may be less inclined to reason about HA&P phenomena in a manner that aligns with course objectives and thus, experience increased difficulty.

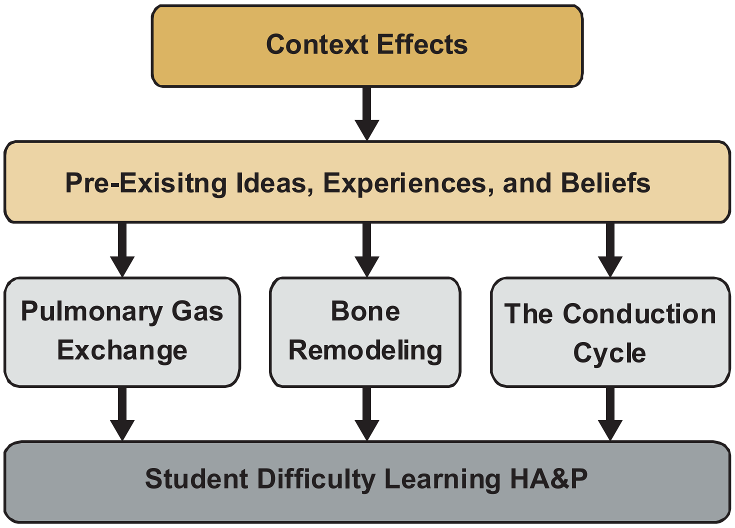

Figure 2. Explanatory Model Depicting How Context Effects May Impact Student Difficulty in HA&P.

Framing and Resources

As mentioned previously, much of the existing body of HA&P education research has sought to 1) identify the specific content areas in which students struggle, and 2) develop instruction to effectively combat those difficulties. Consequently, much of the HA&P education community has been heavily invested in a misconceptions view of student difficulties. Historically, the student difficulties research has used the term ‘misconception’ or ‘alternative conception’ to refer to the wrong answers students offer in response to an assessment or probe - though individual authors rarely articulate their intended meaning for the term (Maskiewicz & Lineback, 2014). These incorrect answers are considered to be the product of strongly held, context-specific, stable, and inherently incorrect knowledge constructs (Maskiewicz & Lineback, 2013; Hammer, 1996; Smith et al., 1994). More recently, some in the education research community have recognized this view of student difficulties to be problematic and have argued for a shift in our perceptions of students’ conceptions to adopt a model that supports the fundamental principles of the constructivist learning theory (Maskiewicz & Lineback, 2014; Smith et al., 1993;). The framing and resources framework has been identified as one such model by those in opposition to the misconceptions view of student difficulties.

The framing and resources theoretical framework originates out of the physics education research community and was developed by David Hammer and Andrew Elby (2003) with contributions from Redish and Scherr (2005) and builds on the knowledge-in-pieces from Andrea diSessa (1993;

1988). Under this framework, student answers are seen as the products of the activation of small knowledge structures that have been compiled to form an answer in real time (Hammer et al., 2005). A significant difference from the misconceptions view is that these small knowledge structures (or conceptual resources) are not inherently correct or incorrect themselves. Instead, it is the way a student activates and assembles these knowledge structures that results in an incorrect response - students' conceptual resources are not considered to be wrong, but instead misapplied in the context at hand. When these conceptual resources are selected or applied incorrectly (e.g., they don't account for assumptions or limitations), a student is likely to identify with or provide an incorrect answer.

The specific resources a student activates and the manner with which they are compiled is dependent on how the individual frames the problem at hand. When an individual frames a problem, the individual focuses (either consciously or unconsciously) on the various context cues associated with the problem. These cues include the contextual surface features used in articulating a scenario or a problem, the format they are asked to respond with, the physical setting in which they receive the problem, or the individual who presented the problem (Gouvea et al., 2019). Each of these cues could impact how an individual frames the problem, and thus, the various conceptual resources the individual activates to solve the problem (Gouvea & Simon, 2018; Hammer et al., 2005; Smith et al., 1994). It is important to note that while individual conceptual resources are often associated with a given frame, they are not directly tied to one particular frame, but instead, have the potential to be activated in conjunction with multiple frames.

The framing and resources framework has had substantial use in the physics education research community, though few in biology have adopted this view of student thinking. Biology is the application of physics in the living world, so it is plausible that framing and resources are a useful way to describe the ways students in biology reason about a phenomenon. Further, the aforementioned observations of context effects on student reasoning of natural selection do align with the framing and resources model of student cognition. For these reasons, the framing and resources cognitive framework has the potential to explain the difficulty students experience in HA&P classrooms (Figure 3). As a result of the human-centric context of HA&P course content, students may be approaching these concepts through the lens of a HA&P frame, and thus, activating resources associated with this frame. The activation of these resources could result in students being less inclined to reason about HA&P phenomena in a manner that aligns with course objectives.

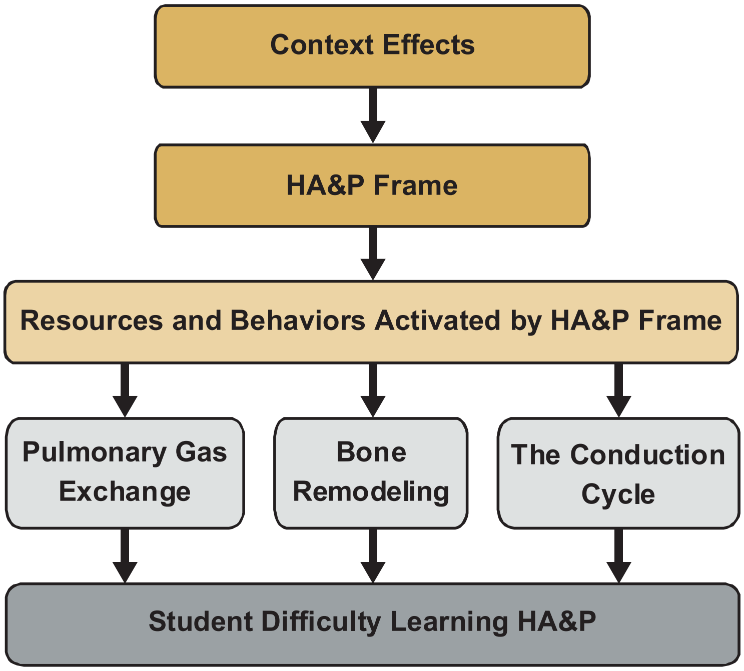

Figure 3. Explanatory Model Depicting How Framing and Resources May Impact Student Difficulty in HA&P.

Complex Systems

As a discipline, physiology seeks to understand and explain the dynamic mechanisms occurring within and across organizational levels that give rise to the functions performed by living things. Students in HA&P courses are routinely expected to reason mechanistically across and within complex systems. As such, it is fitting to recognize the role these complex systems may have in regard to student difficulties in HA&P.

Across the biology education research, there are numerous empirical works that culminate in the finding that students struggle to reason with and about complex systems. A number of distinct challenges have been identified in the systems thinking literature, many of which are directly applicable to the student difficulties observed in HA&P. For example, the existing work on systems thinking maintains novice learners struggle with causality when reasoning about complex systems (Scott et al., 2018; Chi et al., 2012; Sommer & Lücken, 2010; Hmelo-Silver et al., 2007; Jacobson & Wilensky, 2006). Students misinterpret emergent processes as direct, inappropriately assigning linear narratives and agency to complex systems (Chi et al., 2012; Chi, 2005). Some in the systems thinking field argue learners have a "centralized mindset", which causes learners to inherently seek a governing or controlling agent(s) whenever reasoning about a complex system (Wilensky a& Resnick, 1999; Resnick, 1996; 1994).

Those in favor of the centralized mindset theory would argue students in HA&P innately seek a governing agent when presented with a complex physiological system, just as they would if they were presented with other types of complex systems (Figure 4). By indiscriminately seeking agency in complex systems, students in HA&P may be inherently directed towards linear reasoning strategies as opposed to mechanistic reasoning strategies. As a result of this centralized mindset, students would be less likely to develop a mechanistic understanding of physiological phenomona, a core goal of physiology as a discipline.

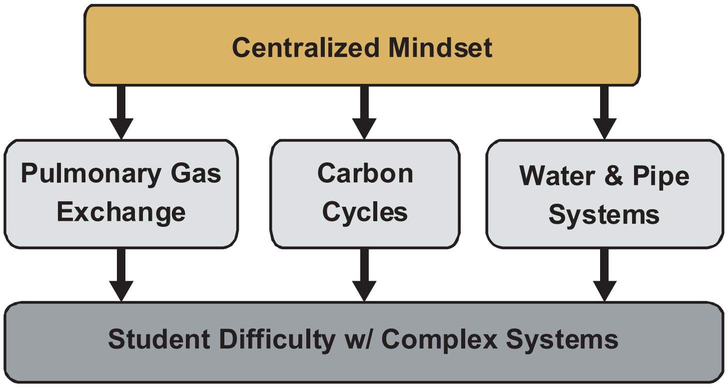

Figure 4. Explanatory Model Depicting How a Centralized Mindset May Impact Student Difficulty with Complex Systems.

Despite few HA&P education researchers leveraging this body of work, the systems thinking literature does align with much of the findings of HA&P education research. In a 2013 study by Sturges and Maurer, students recognized their own tendency to think about physiology phenomena in terms of purpose and acknowledged this tendency did add to the difficulty they experience in HA&P. Students in this study also reported difficulty think causally, and again acknowledged it as a barrier to their own learning.

Students in HA&P are constantly required to reason about complex systems. Therefore, the centralized mindset theory and the claims made by the systems thinking literature do have explanatory potential for student difficulties in HA&P. However, due to the nature of HA&P content, it is quite challenging to differentiate the difficulty students experience when thinking about complex systems from the difficulty students experience from reasoning HA&P context.

Connecting the Student Difficulties Literature

The existing evidence on teleological reasoning, context effects, framing and resources, and complex systems indicate any one of these theories has direct implications for the difficulties students experience in HA&P on their own. However, I argue these theories are inherently connected and by recognizing that interconnectedness, they hold more explanatory power and instructors will be better informed on where student difficulties originate from. For example, students struggle to avoid teleological reasoning, even after realizing it is detrimental to their learning (Sturges & Maurer, 2013; Cliff, 2006). Instead of trying to replace students incorrect, teleological ideas about specific physiological phenomena, this collective body of literature would indicate that focusing instruction on the recognition of context effects or the development of specific systems thinking skills could mitigate teleological reasoning for later content.

Research Questions

The goal of this dissertation is to understand why students struggle to succeed in HA&P. By identifying underlying causes of student difficulty (as opposed to a series identifying individual content-based difficulties), HA&P educators will be able more effectively combat these difficulties early on in their instruction, presumably resulting in improved student learning in HA&P. For this dissertation, I primarily rely on the role of item context, framing, and teleological reasoning to guide this research. This research will address the following questions:

Chapter 2 – What makes HA&P hard? (perceptions from HA&P students and faculty)

- Do student perceptions of physiology difficulty align with those in the Sturges and Maurer (2013) population?
- Do student perceptions of physiology difficulty vary across intuitions?
- Do faculty perceptions of physiology difficulty align with the those in the Michael (2007) population?

Chapter 3 – How do experts reason about a physiological phenomenon and how is that reasoning impacted by surface context?

- How do experts in physics and biology approach questions about fluid dynamics?
- How can experts from physics and biology could reason about fluid dynamics so differently?
- Does surface context features impact expert reasoning of fluid dynamics?

Chapter 4 – How do students reason about a physiological phenomenon and how is that reasoning impacted by surface context?

- Do HA&P students and physics students differ in their reasoning of fluid dynamics, a complex, interdisciplinary phenomena?
- What reasoning strategies do HA&P students employ when thinking about fluid dynamics?
- Do surface context features affect the way introductory students reason about fluid dynamics?

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CHAPTER 2. PHYSIOLOGY IS HARD: A REPLICATION STUDY OF STUDENTS' PERCEIVED LEARNING DIFFICULTIES

Human Anatomy and Physiology (HA&P) has long been recognized as a difficult course. A 2007 (Michael, 2007) study sought to better understand this difficulty by asking faculty for their perceptions of why students struggle to learn in HA&P. Later research built on these findings by investigating why students find physiology difficult (Sturges & Maurer, 2013). However, without replication these claims are limited in their generalizability. There is a need in physiology education research to replicate studies like these across different institutions to support generalizations. We therefore replicated both of these studies by collecting survey responses from 466 students at four different institutions and 17 instructors at 15 different institutions. We found that students in our study identified similar factors as the students surveyed in the original study. Students most strongly agreed with items that attributed the difficulty of HA&P to the nature of the discipline, as opposed to the way physiology is taught or the way students approach learning it. Faculty in our sample , like those in the original study (Michael, 2007), agreed most strongly to items that attributed physiology's difficulty to discipline-specific factors. Our data reinforce the results of Sturges and Maurer (2013) and Michael (2007). We can more confidently claim that HA&P students and faculty believe the difficulty in learning physiology is the result of inherent features of the discipline itself and not factors related to instruction or the students themselves.

Introduction

Human Anatomy and Physiology (HA&P) is widely recognized as a difficult course, often characterized by high drop, withdrawal, and failure (DFW) rates (Sturges et al., 2016; Harris et al., 2004). Unfortunately, the HA&P education community has little research that explicitly investigates *why* undergraduate students struggle to succeed in HA&P. Research suggests students find physiology content more difficult to learn than anatomy (Sturges & Maurer, 2013; Michael, 2007) but few studies have investigated the drivers behind student difficulty when learning physiology.

In an attempt to better understand the struggles students face learning physiology, Michael (2007) conducted a study to gauge why *faculty* think physiology is difficult for students to learn. Michael's survey consisted of a three-part model of the challenges of physiology education that included 1) the nature of the discipline, 2) instruction, and 3) the student. Faculty responses indicated that, as a whole, they believed physiology instruction wasn't the source of student difficulty. Instead, faculty cited the discipline itself as inherently challenging. Faculty also attributed difficulty to student-related factors; for example, students equate memorizing with learning, students think about systems or phenomena in isolation and fail to think across and between systems (Michael, 2007).

While these results are valuable, they do not reflect students' perceptions of the difficulties in learning human physiology. Sturges and Maurer (2013) adapted the Michael (2007) survey for use with students and reported the responses of 279 students (183 from HA&P I, 93 from HA&P II) from a single time point at a university in Georgia. These results revealed how *students* perceived the difficulties associated with learning physiology, as opposed to how faculty *think* students perceive these difficulties. Students in this population did not attribute their learning difficulties to the manner in which physiology was taught; rather, they attributed their learning difficulties to the inherent difficulty of the discipline. These results indicate some student agreement with faculty, as per the Michaels study (2007). Further, students in this study showed high agreement with statements attributing learning difficulties to teleological tendencies, dynamic process, and thinking in terms of cause and effect.

The findings reported by Sturges and Maurer (2013), while providing some insight into student perceptions of the learning difficulties associated with physiology, are limited in their generalizability. In particular, the data were gathered from a single student population at one institution a four-year university in southeast Georgia. These results may not reflect the perceptions of students from across the nation and at other institution types. Much like in psychology, replication studies are critical in education research (Makel & Plucker, 2014). Direct replications use the same methods as the original study, seeking to corroborate the findings of the initial study. Through direct replication studies, we can generalize results to different populations (Schmidt, 2009).

To our knowledge, there has been no formal replication of either Sturges and Maurer (2013) or Michael (2007). There is a need to replicate these studies with new populations in order to verify the generalizability of these results. We therefore used a direct replication approach, administering the same surveys from Sturges and Maurer (2013) and Michael (2007) to new populations at different institutions. Such a replication allows us to make more generalizable claims.

We surveyed faculty and students from several institutions across the US to generate a robust data stream to investigate perceived physiology learning difficulties. Our investigation is guided by the following research questions:

- Do student perceptions of physiology difficulty align with those in the Sturges and Maurer (2013) population?
- Do student perceptions of physiology difficulty vary across the intuitions?
- Do faculty perceptions of physiology difficulty align with the those in the Michael (2007) population?

Methodology

To gather student perceptions of the difficulties of learning human physiology, we used an adaptation of the survey generated by Michael (2007) (Table 1). Michael's survey is organized to reflect a three-factor model for student difficulty: physiology as a discipline, how students learn physiology, and how physiology is taught. The survey consists of 18 items representing these three factors. These 18 items are presented in a Likert-type fashion, asking students to indicate their level of agreement with the given statement (strongly disagree, disagree, etc).

Table 1. Summary of Survey Items.

What is it about the subject matter of physiology that makes it hard *[for students]* to learn? [Discipline]	
[1] Physics and chemistry, [2] Different organizational levels, [3] Cause and effect, [4] Dynamic systems, [5] Encourages thinking in terms of purpose, [6] Quantitative abilities, [7] Language of HA&P	SD D N A SA
What is it about the way physiology is taught that makes it hard *[for students]* to learn? [Teaching]	
[8] Textbooks, [9] Common themes, [10] LOs, [11] Memorization, [12] Jargon, [13] Little student talk	SD D N A SA
What is it about the way students attempt to learn physiology that makes it hard *[for students]*? [Students]	
[14] Memorization, [15] Pigeon-hole, [16] Connections, [17] All positive, [18] Ignore visuals	SD D N A SA

Sturges and Maurer (2013) made minor changes to the Michael (2007) survey to make it more appropriate for use with undergraduate students. For example, the Michael (2007) version used words and phrases like “simultaneously”, “reason causally”, and “teleological thinking”. Sturges and Maurer (2013) changed these items to use phrases like “at the same time”, “in terms of cause and effect”, and “thinking in terms of their purpose” respectively. We also used these modifications in our survey. In the Sturges and Maurer (2013) version of the survey, the term “AP” was used whereas Michael (2007) used the term “physiology”. In our survey, we used the term “physiology”. We also asked a series of demographic questions to better describe and compare survey participants (major, ethnicity, gender, ACT/SAT score, etc.). We used the same version of the survey for the instructor participants (not including student demographic questions).

Study sites for both the student survey and the faculty survey were solicited in Fall 2016 via personalized emails and three professional listservs (American Physiological Society, Human Anatomy and Physiology Society, and Society for the Advancement of Biology Education). These emails asked for faculty participants that would be willing to 1) administer the student survey in their HA&P class and 2) complete the faculty survey.

Twenty-five instructors agreed to participate in our study. Participation included completing the faculty survey and administering the student survey in their HA&P or physiology courses. We sought Institutional Review Board (IRB) approval from each institution to administrate the student survey and we received IRB approval from our home institution to administrate the faculty survey. We received IRB approval to administrate the student survey in 15 of the 25 courses. Of the 15 courses, the instructors of 10 courses successfully administered the student survey in the last two weeks of the Fall 2016 semester. We excluded data from courses that 1) were not considered an introductory HAP course or 2) did not achieve a student survey response rate greater than 40%. Student surveys were administered electronically through Qualtrics survey software (Qualtrics Software, 2018).

Of those 25 instructors who agreed to participate, 17 completed the faculty survey between late October and early December of 2016. Faculty surveys were administered electronically through Qualtrics survey software. All participants in our study (both students and faculty) were 18 years of age or older, in compliance with approved IRB protocol SM17069.

Analysis

Data for this study are comprised of responses to Likert scale items. There is a longstanding debate as to how Likert scale data should be analyzed. Many researchers in numerous disciplines argue that Likert data can be mapped to an interval scale and thus, parametric measures are appropriate (Carifo & Perla, 2008; 2007). Conversely, a substantial body of literature contends that Likert data is inherently ordinal and should be analyzed using non-parametric measures to generate sound conclusions (Bishop & Herron, 2015; Jamieson, 2004; Clason & Dormody, 1994). In addition, previous studies have found that students' interpretations of "agree" vs. "strongly agree" are not consistent; these categories represent different magnitudes of response across and within populations (Semsar et al., 2011; Adams, et al., 2006).

While the debate on Likert scale analysis is likely to continue for the foreseeable future, individuals on both sides of this argument agree on one important facet: individual Likert items should not be considered a "Likert scale" and, in most cases, should not be analyzed individually (Harpe, 2015; Carifo & Perla, 2008; 2007). Both Sturges and Maurer (2013) and Michael (2007) assumed an interval scale and compared means of individual Likert items. We opted not to do this, because of the existing body of literature on Likert scale analysis. Instead, we chose to peruse a non-parametric approach and compare the rank order of the 18 individual items.

To compare responses from Sturges and Maurer (2013) and Michael (2007) with responses from our populations, we compared the rank order of the items. To facilitate this ranking, we collapsed the five-point Likert scale into a three-point scale consisting of "agree", "neutral", and "disagree" in accordance with the approach taken by Adams et al. (2006). For example, the "agree" category in the three-point scale encompasses all student responses that indicated either "strongly agree" or "agree". As a result, all agreements are accounted for but less emphasis is placed on the intensity of that agreement. In terms of our findings, students responding with "agree" can draw on similar experiences, arguments, or emotions as students who respond with "strongly agree", so the implications of our data are not compromised. We then ranked each item in terms of percent agreement, that is, how much of the population agreed to each of the 18 items. Those items with the highest percent agreement were ranked as most important.

We compared the rankings of the 18 items provided in the instrument to the rankings presented by Sturges and Maurer (2013) and Michael (2007). The 18 items were ranked in terms of overall percent agreement (with 1 being the item with the highest percent agreement and 18 being the item with the lowest percent agreement). Kendall's tau correlation coefficient was measured to evaluate the correlation between our rank order and the order reported by Sturges and Maurer (2013).

A Kruskal-Wallis test was used to identify any statistically significant differences across institutions for each of the 18 items. Because we were conducting multiple tests of the same hypothesis, we faced an increase risk of Type I error. To prevent reporting a false positive, we ran a Bonferroni correction. All statistical analyses were conducted using the R statistical environment (R Core Team, 2018).

Results

We collected data from 17 instructors at 15 institutions (Table 2); of those study sites, four instructors administered the student survey to their students, for a total sample size of 466 students.

Table 2. Faculty Respondent Demographics, Respondents Per Institution Type & Geographic Region.

Institution Type		Geographic Region	
Associate's College	1	Midwest	8
Baccalaureate College	3	South	7
Baccalaureate/Associate's College	3	West	2
Doctoral University	7		
Master's Colleges and Universities	3		

Demographics

Student responses were collected from four different institutions that vary in terms of class size, Carnegie Classification (The Carnegie Classification of Institutions of Higher Education) , and geographical location (U.S. Department of Commerce Economics and Statistic Administration)(Table 3). Across all institutions, most students were female and taking HA&P to fulfill a requirement for their desired program. Students at institutions A, B, and C were predominantly white/Caucasian. The population at institution D was more diverse, with 49% of students identifying as white/Caucasian and almost 44% of students identifying as Black or African American.

Students varied in terms of the number of undergraduate semesters completed and their self-reported undergraduate GPA. Most students at institutions A and B had an undergraduate GPA above a 3.5, while the GPAs reported from students at institutions C and D were more evenly distributed between a 2.5 and a 4.0 (Table 3). The class rank (as measured by ‘Undergraduate Semesters Completed’) varied a great deal across the four institutions, with no sub-population exceeding 45%.

Students in our sample reported a wide array of declared majors, with responses spanning from criminal justice and music performance to nursing and pharmacy. Although there was a great deal of variation across and within each institution, a large number of students at each institution reported being either a nursing or pre-nursing student (Figure 5). Similarly, three institutions (B, C, and D) had a substantial number of exercise science majors take the survey.

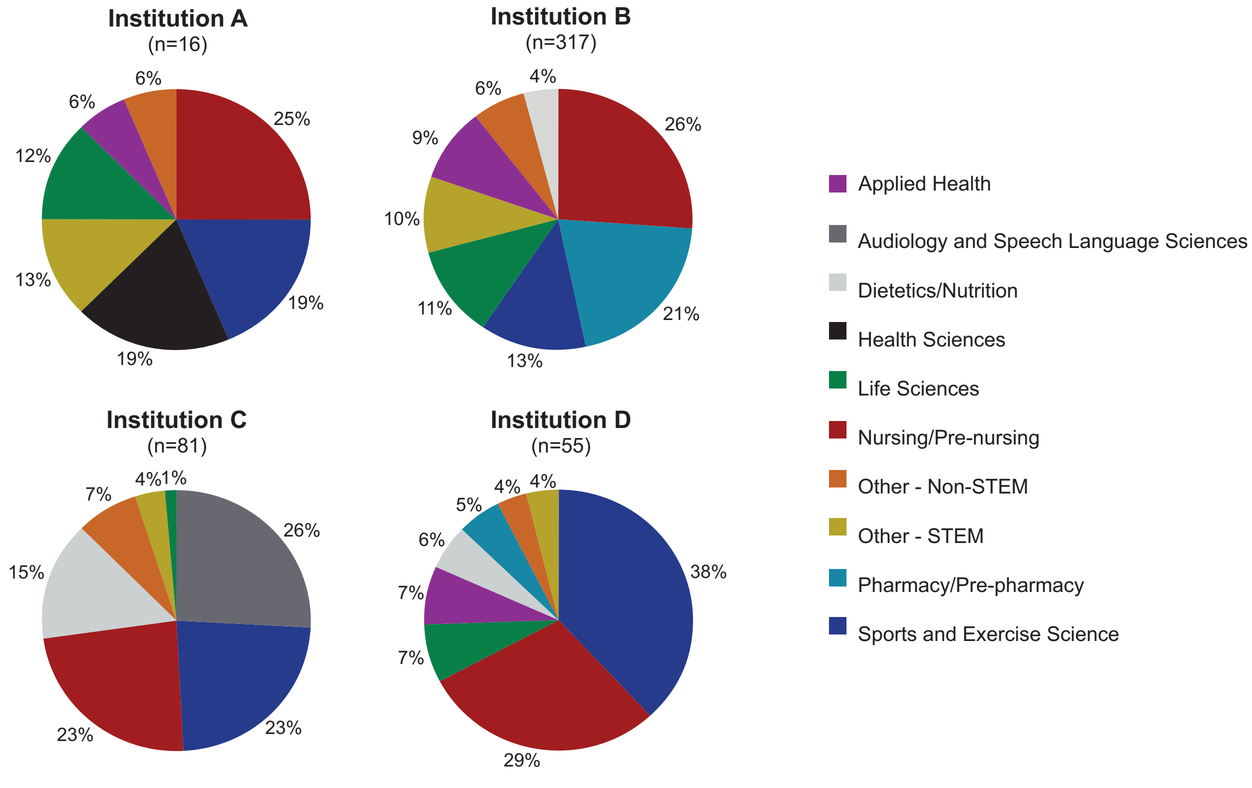

Figure 5. Student Major Demographics by Institution. Majors were clustered to form comparable groups across institutions when possible. Some majors were represented at similar proportions at all institutions (e.g. Nursing/Pre-nursing, Other – Non-STEM), while other majors were represented at varying proportions across the four institutions (e.g. Pharmacy/Pre-pharmacy, Dietetics/Nutrition).

Table 3. Student Respondent Demographics.

Institution	n	RR*	Institution Type	Geographic Region	Gender[†]	Race and Ethnicity[†]	Undergraduate Semesters Completed[†]	Undergraduate GPA[†]	Required Course?[†]
A	15	0.47	Baccalaureate College	Midwest	80.0% Female	80.0% White/Caucasian	40.0% 5 to 6	66.7% 3.5 to 4	73.3% Yes
B	316	0.74	Doctoral University	Midwest	71.2% Female	89.6% White/Caucasian	43.4% 1 to 2	60.8% 3.5 to 4	82.9% Yes
C	80	0.73	Doctoral University	West	85.0% Female	70.0% White/Caucasian	35.0% 3 to 4	30.0% 3.5 to 4 30.0% 2.5 to 2.99	95.0% Yes
D	55	0.55	Doctoral University	South	74.5% Female	49.1% White/Caucasian	32.7% 1 to 2	30.9% 2.5 to 2.99	92.7% Yes

*RR = Response rate

[†] Reporting majority response

Because different institutions offer different programs (e.g. Audiology and Speech Language Sciences is offered at institution C but not at institution B), we were cautious in how we compared students' majors across institutions. For example, we could not compare perceptions of medical laboratory sciences students to the perceptions of nursing students, as there are only 7 medical laboratory sciences in our sample compared to more than 100 nursing or pre-nursing students. Also, medical laboratory sciences students only reside at one of the four institutions, so we could not be confident that any observed differences could be attributed to declared major alone.

Do Student Opinions Align with the Opinions Gathered by Sturges and Maurer?

There was a statistically significant lack of independence between the rankings provided by students in our pooled population and the rankings provided by Sturges and Maurer (2013) (Table 4, tau = 0.725, p < 0.001). Students in both populations exhibited similar levels of agreement to the 18 items of the difficulty survey, and thus, the resulting rankings of the items are similar. This finding was consistent when rankings were compared at the institutional level – rankings from each institution had a statistically significant lack of independence among themselves, and when compared to the pooled population ranking and the Sturges and Maurer (2013) population (Table 5).

Students in our population reported the most agreement to item 5 (Physiology, like other life sciences, seems to encourage thinking about things in terms of their purpose) and item 3 (Understanding physiology requires the ability to think in terms of cause and effect) (Table 4). The Sturges and Maurer population also reported the strongest agreement to these items (Table 4).

Do Student Opinions of Difficulty Vary Across Intuitions?

Students at all four institutions reported similar levels of agreement on all survey items pertaining to the Discipline (Table 4). A Kruskal-Wallis test with a Bonferroni correction ($\alpha_{adjusted} = 0.0028$) showed a statistically significant difference in reported agreement for the following seven items: 10, 11, 12, 13, 15, 16, and 18 (Table 4). However, students collectively reported little agreement to these items with the highest of these items ranked as the 7th most impactful factor contributing to physiology's difficulty. Students at all institutions reported similar levels of agreement for the 11 other items on the survey. Students identified items 3 and 5 as the top two sources of difficulty at institutions A, B, and C. At institution D, students reported the most agreement with items 5, 2, and 3.

Table 4. Student Ranking of Survey Items.

Survey Item	**Factor**	**Pooled Rank**	**Institution A**	**Institution B**	**Institution C**	**Institution D**	**S&M[†] Rank**
5	Discipline	1	2	2	1	1	1
3	Discipline	2	1	1	2	3	2
2	Discipline	3	6	3	2	2	5
4	Discipline	4	3	4	4	4	3
7	Discipline	5	4	5	5	6	6
1	Discipline	6	13	6	11	5	11
16*	Student	7	4^{ab}	7^{a}	6^{b}	7^{a}	8
14	Student	8	7	8	9	8	4
8	Teaching	9	7	10	13	9	12
6	Discipline	10	10	9	17	12	16
15*	Student	11	9^{ab}	11^{a}	10^{b}	11^{ab}	7
18*	Student	12	13^{ab}	12^{a}	12^{b}	9^{ab}	9
11*	Teaching	13	12^{ab}	13^{a}	8^{b}	16^{a}	13
13*	Teaching	14	10^{b}	16^{a}	7^{b}	15^{a}	10
17	Student	15	13	14	16	13	14
12*	Teaching	16	16^{a}	17^{a}	14^{b}	14^{ab}	15
10*	Teaching	17	18^{ab}	15^{b}	15^{c}	18^{a}	18
9	Teaching	18	16	18	18	17	17

[†] Sturges and Maurer (2013) population.
*Results from Kruskal-Wallis rank sum test by four institutions (with Bonferroni correction for 18 groups = 0.0028).

Table 5. Student Ranking Correlations Across Institutions.

	Institution A	**Institution B**	**Institution C**	**Institution D**	**S&M[†]**
Pooled	0.763	0.935	0.669	0.852	0.725
Institution A	-	0.723	0.678	0.691	0.723
Institution B		-	0.603	0.813	0.660
Institution C			-	0.625	0.761
Institution D				-	0.695

[†] Sturges and Maurer (2013) population.
*Kendall Rank Correlation Coefficient. All p-values < 0.001.

Do Faculty Opinions Align with the Opinions Gathered by Michael?

There was a statistically significant lack of independence between the rankings provided by faculty in our population and the rankings provided by faculty in the Michael (2007) study (Table 6, tau = 0.588, $p < 0.01$). Faculty in both populations reported similar levels of agreement to the 18 items of the difficulty survey, and thus, the resulting rankings of the difficulty items are similar.

Table 6. Faculty Perception Ranking Compared to Michael (2007).

Item	**Factor**	**Slominski Percent Agreement**	**Slominski Rank**	**Michael Rank**
3	Discipline	1.000	1	1
4	Discipline	1.000	1	3
14	Students	1.000	1	2
1	Discipline	0.882	4	8
2	Discipline	0.882	4	5
5	Discipline	0.765	6	15
15	Students	0.765	6	7
16	Students	0.765	6	6
6	Discipline	0.647	9	4
13	Teaching	0.588	10	14
7	Discipline	0.529	11	11
18	Students	0.529	11	9
17	Students	0.471	13	18
10	Teaching	0.412	14	16
9	Teaching	0.353	15	11
8	Discipline	0.294	16	10
11	Teaching	0.294	16	13
12	Teaching	0.059	18	17

The faculty in our survey reported the strongest agreement to item 3 (*Understanding physiology requires the ability to think in terms of cause and effect*), item 4 (*Understanding physiology requires at least some limited ability to think about dynamic systems*), and item 14 (*Students believe that "learning" is the same thing as "memorizing").* All 17 faculty participants in our study indicated they either “agreed” or “strongly agreed” with these items, resulting in a mean agreement score of 1.0 for all three items. The faculty in Michael’s population also reported the strongest level of agreement to these three items (Table 6).

Discussion

We conducted a direct replication study to establish the generalizability of the findings of Sturges and Maurer (2013) and Michael (2007). Our results, coupled with their findings, document a general trend in physiology education, namely that it is the nature of the discipline itself, and not instruction or student learning approaches that make physiology so challenging to learn. Our replication, using the original surveys, gathered responses from students and instructors from across the nation, asking them what makes physiology difficult to learn. Students and faculty agreed that the discipline itself is challenging, and this may be due to the complexity of causal reasoning and the approachability of teleological reasoning. We also find evidence to support the claim from Michael (2007) that faculty also attribute students' difficulty to learning physiology to their tendency to equate learning with memorizing.

Replicating Earlier Studies

The studies conducted by Sturges and Maurer (2013) and Michael (2007) provide valuable insight into student difficulties in HA&P, but are limited to a single population. Direct replication studies like the present study help to establish generalizations across the broader HA&P community and are essential in education research. For example, the demographics of HA&P populations can vary greatly across the United States (as demonstrated by Figure 5). These demographic differences could result in different skills, motivations, and approaches to learning, and thus, result in different sources of difficulty in HA&P classrooms. Further, no study has sampled students and instructors simultaneously, such that instructors and students responded to the survey with the same courses in mind. Thus, our study goals included replicating both the Sturges and Maurer (2013) and Michael (2007) across institutions in the U.S to support the generalizability of their findings.

Our sampling efforts used listservs and direct solicitation of faculty, resulting in the recruitment of four HA&P populations that had a number of distinct differences from the original population surveyed by Sturges and Maurer (2013). First, freshmen only made up 1% of Sturges and Maurer's population but often comprised more than a third of our HA&P population (Table 3). This is an important consideration because freshman and sophomore-level students often have a more novice-like approach to learning new material, relying on extensive memorization and using less effective and/or alternative reasoning pathways in response to contextual surface features (diSessa, 1988; Chi et al., 1981). These novice-like learning tendencies, in conjunction with limited experience learning in undergraduate science classrooms, could lead a student to attribute physiology's difficulty to teaching practices or studying approaches, as opposed to the discipline itself.

Second, the four institutions sampled in our study also showed variation in the majors represented and the proportions of those majors at each institution (Figure 5). For example, Exercise Science students were present at all institutions, but made up 13% of the population at Institution B and

38% of the population at Institution D. Institution B also contained a significant number of ‘Pharmacy/Pre-pharmacy’ students (e.g. 21%), whereas other institutions (i.e. A and C) contained no ‘Pharmacy/Pre-pharmacy’ students. Declared major could impact student prior knowledge, motivations, and performance goals and, by extension, their learning approaches in a HA&P course. Students with different majors could experience different challenges in the HA&P learning environment.

Despite such demographic variability, we found significant agreement about the difficulties of physiology across our study populations and institutions. Students identify the discipline as the primary driver of difficulty when learning physiology, and our findings thus reinforce the results of Sturges and Maurer (2013). From this collective body of work, we can now state with some confidence that HA&P students struggle with the discipline, particularly using causal reasoning effectively, often resorting to a less productive, teleological approach. These challenges persists across student populations, instructional designs, and institutional settings. Human anatomy and physiology educators and education researchers should consider the unique features of the discipline and the ways students think about the discipline in addition to more traditional educational variables (e.g. instructional strategies or student engagement) when striving to reduce student difficulties learning physiology.

Teleological Reasoning

Students in our populations most strongly agreed with the two survey items that attributed course difficulty to reasoning approaches, specifically avoiding teleological reasoning (item 5) and employing causal reasoning (item 3). These results echo research documenting the pervasive use of teleological reasoning by students across various populations of HA&P and life sciences (Michael, 1998; Tamir and Zohar, 1991; Richardson, 1990). Through forced-choice and open response assessments, students convey a tendency to use teleological reasoning by providing (or selecting) explanations like *“breathing deepens because the body needs more oxygen”* and *“the strength of the heartbeat will increase because the tissues need blood”* (Michael, 1998).

A teleological learning approach uses the ‘ends’ or outcomes of a physiological phenomenon to explain the functional events leading up to that outcome. This way of reasoning about physiology relies on the outcome to explain *why* the events occurred as opposed to focusing on *how* the actual mechanisms drive the physiological events (Tamir & Zohar, 1991). In contrast, causal reasoning requires students to reason more dynamically about the structures, behaviors (or mechanisms), and functions of a complex system. This type of reasoning requires thinking across different biological levels or scales within the organism. Students need to be able to understand how the dynamic interactions that occur within these levels give rise to functions at higher levels (Hmelo-Silver et al., 2007). The results of this research demonstrate that students are aware of both of these reasoning approaches, but they struggle to move beyond teleological reasoning strategies when faced with physiological phenomena.

Faculty Perceptions

The faculty responses in our study mirrored the responses gathered by Michael in 2007 and again contribute to the generalizability of our findings. Every faculty member surveyed agreed that students struggle to learn physiology because of 1) students' causal reasoning abilities (item 3), 2) students' systems thinking abilities (item 4), and 3) students' belief that memorizing is the same as learning (item 14). While faculty and students surveyed in this research agreed on the role of causal reasoning and, to some extent systems thinking skills in learning HA&P, faculty also identified a learning strategy (memorization) as a source of difficulty in HA&P classrooms.

A student in an HA&P course has 12 or more years of learning experience. Memorization is a common learning strategy used in middle and high school and it is likely they learned to rely on memorization as a means to study. From physics education research, we know that students' tendency to memorize often persists into their undergraduate career: struggling undergraduate students report trying to approach learning physics by compartmentalizing and memorizing individual pieces of information (Adams et al., 2006). Extending these findings to the HA&P classroom and our study, we hypothesize that struggling HA&P students may fail to recognize that learning isn't the same as memorizing. Students may conflate the ability to recall a number of basic facts and functions of a given organ or tissue with confidence that they have learned and understand the material. However, the student has not practiced reasoning causally; thus, they may underperform their expectations on physiology-related questions and may resort to teleological reasoning strategies. Students may not report their learning strategies (e.g. memorization) as a contributor to learning HA&P because they have limited experience with other study or learning strategies.

Implications for Instruction

Starting in elementary school, students' develop an inclination to answer "why" instead of "how". A study by Southerland et al. (2001) found primary and secondary students offered "why" responses despite being asked "how" questions. Even when explicitly asked for a mechanistic understanding of biological phenomenon, students responded with a teleological rational for the occurrence of the phenomenon.

We found that students at multiple institutions agree that physiology encourages teleological reasoning. Because students have identified this inclination as a challenge to their own learning, we would urge instructors to take note of how students use teleological reasoning in their own classroom and explicitly and repeatedly address this issue with their students. We encourage instructors to provide examples to students that demonstrate how a teleological reasoning approach could result in a faulty or incomplete understanding of a physiological event. By training students to recognize how and when they use teleological reasoning in HA&P classrooms, students may become careful and deliberate in the language they use when explaining the mechanisms that drive physiological phenomena. Further, if instruction explicitly targets mechanisms spanning multiple organizational levels and/or multiple body systems, students may be more equipped to move beyond teleological explanations and reason about physiology with a more causal, mechanistic approach.

It is interesting to note that students reported that most teaching factors were not a major source of difficulty. For example, students did not report high agreement to the items pertaining to high memorization demands (item 11) and the high degree of jargon (item 12). However, there was disagreement across institutions on 4 of the 6 teaching factors: item 10 - *Teachers do a poor job of defining and communicating our learning objectives,* item 11 - *Teachers expect too many memorized facts and too little understanding at the same time,* item 12 - *Teachers and authors use language imprecisely, use too much jargon, and use too many acronyms, all to the detriment of learning*, and item 13 - *Teachers talk too much and students talk too little*. This variation across institution responses likely results from variation in instructional practices. Perhaps some instructors make good use of clear and measurable learning objectives, and thus, students in those courses would disagree with this item while students at other institutions (where learning objectives are not utilized to the same degree) respond with more agreement. While there was variation across these items (and items 15, 16, and 18), students did not find these factors as impactful as the inherent features of the discipline (items 1-5 and 7), of which there were no observed differences across institutions.

Implications for Research

In our study, faculty and students agreed on the most influential sources of difficulty when learning physiology - *Understanding physiology requires the ability to think in terms of cause and effect* and *Physiology, like other life sciences, seems to encourage thinking about things in terms of their purpose*. We advocate for more qualitative investigations into this tendency to use teleological reasoning in physiology (as opposed to causal reasoning). Developing a better understanding of when and how students employ teleologic reasoning will better support instruction that mitigates this detrimental tendency.

The findings of our replication study, while not new or flashy, establish the generalizability of these claims about student difficulties when learning physiology and provide valuable insight into the difficulties students experience. Students most strongly agreed with items that attributed the difficulty to the nature of the discipline, and not the way HA&P is taught or how students approach learning. Faculty in our sample also confirmed the original study by Michael, agreeing most strongly to items that attribute difficulty to the nature of HA&P as a discipline. Faculty also highly attributed student difficulty to memorization strategies, whereas students did not report this to be a considerable source of their own difficulty.

However, it is important to note that our data reflect student and faculty perceptions of difficulty and not the difficulties realized during instruction. It is possible that students are not consciously aware of (or able to put into words) all of the sources of difficulties they experience when learning in the HA&P classroom. Future research should focus on unpacking student difficulties in real time through more qualitative means.

Conclusion

Our replication research establishes the generalizability of the claims made by Michael (2007) and Sturges and Maurer (2013) by surveying students and instructors from different institutions across the United States. Our study population represents students enrolled in both large and small courses, with a wide range of career goals. The results of this research reinforce Michael (2007) and Sturges and Maurer (2013) in identifying the discipline of physiology as inherently difficult for students. Students and instructors both identify challenges associated with casual and teleological reasoning in physiology. This body of research underscores a need for qualitative and quantitative research that explores how students reason in HA&P.

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CHAPTER 3. USING FRAMING AS A LENS TO UNDERSTAND CONTEXT EFFECTS ON EXPERT REASONING

National calls to transform undergraduate classrooms highlight the increasingly interdisciplinary nature of STEM. As biologists, we use principles from chemistry and physics to make sense of the natural world. One might assume that scientists, regardless of discipline, use similar principles, resources, and reasoning to explain cross-cutting phenomena. However, the context of complex natural systems can profoundly impact the knowledge activated. In this study, we used the theoretical lens of framing to explore how experts from different disciplines reasoned about a cross-cutting phenomenon. Using interviews conducted with faculty (n=10) in biology, physics, and engineering, we used isomorphic tasks to explore the impact of item context features (i.e., blood or water) on how faculty framed and reasoned about fluid dynamics, a cross-cutting concept. While faculty were internally consistent in their reasoning across prompts, biology experts framed fluid dynamic problems differently than experts in physics and engineering and as a result, used different principles and resources to reach different conclusions. These results have several implications for undergraduate learners who encounter these cross-disciplinary topics in all of their STEM courses. If each curriculum expects students to develop different reasoning strategies, students may struggle to build a coherent, transferable understanding of cross-cutting phenomena.

Introduction

Undergraduate students pursuing a STEM degree typically spend a great deal of their first two years navigating a busy schedule full of introductory science courses, including physics, chemistry, math, and biology. In these courses, students are introduced to the principles, concepts, and skills that comprise the fundamentals of these disciplines, many of which are interdisciplinary or cross-cutting concepts that transcend a single domain or introductory science course (National Research Council, 2012). Unfortunately, the inherent disciplinary segregation of the higher education system means very little instructional collaboration across disciplines. As a result, STEM faculty typically know very little about how these cross-cutting concepts are taught in other STEM courses. Without understanding how our students learn these cross-cutting concepts in physics, chemistry and math courses, how do we know our students are prepared to use and apply these concepts to our standards when they reach our biology courses? This concern was recently made evident to us after realizing we ourselves were giving students somewhat contradictory instruction on the topic of fluid dynamics (a cross-cutting concept) in our introductory physics and HA&P courses. Through interdisciplinary conversations, we discovered that we broach this concept in fundamentally different ways and have very different expectations for our students regarding this concept.

When we looked to popular introductory textbooks from our respective fields, we found even more disparate takes on the topic. Based on our interdisciplinary conversations and the introductory textbooks, it appeared that our courses were training students to use different reasoning approaches for fluid problems. We found this observation to be quite troubling, especially with the knowledge that many students either simultaneously enroll in these courses or will be expected to complete both courses to satisfy major requirements. In response to this observation, we developed a research project to determine *1) how experts in physics and biology approach questions about fluid dynamics*, *2) better understand how experts from physics and biology could reason about fluid dynamics so differently*, and *3) determine if item surface context impacted expert reasoning of fluid dynamics*.

Cross-Cutting Concepts

A tacit component of undergraduate education is that students will develop the ability to work fluently across domains of science and to understand and use crosscutting concepts when problem solving (McDonald, 2015; National Research Council, 2012). However, students struggle to transfer their understanding within a discipline, let alone across disciplinary boundaries (Bransford et al., 2000). Students often compartmentalize their courses and by extension, science disciplines: energy in physics is not the same as energy in chemistry or biology and different rules or ways of reasoning may apply.

Experts, however, appear to have little trouble identifying and using these crosscutting scientific concepts to solve complex problems in science. Indeed, research documents that novices and experts have different approaches to problem solving (Bodner & Herron, 2002; Simmons & Lunetta, 1993; Camacho & Good, 1989; Smith & Good, 1984). Chi and colleague’s (1981) foundational study found, through a simple sorting task, that novices tended to sort physics problems according to surface features of the problem while experts sorted problems based on underlying physics principles. Recent work in biology has documented a similar phenomenon: novice learners in biology tend to sort tasks by superficial features while experts used core biological concepts (Smith et al., 2013).

Little research has explored the similarities and differences in how cross-cutting concepts are taught across disciplines, which may impact students' ability to transfer their understanding and subsequently build connections. Experts have deep content knowledge, which includes these cross-cutting concepts. However, discipline norms and ways of thinking may cause experts to teach about cross-cutting concepts in narrow ways that inhibit students' transfer abilities. We argue that to understand how students are taught to reason with and about cross-cutting concepts, it is critical to understand how the experts teaching these courses think about cross-cutting concepts. To explore experts' reasoning across disciplines, we introduce a theoretical frame from cognitive science, framing and resources.

Theoretical Framework: Framing and Resources

Under the traditional view of student difficulties research, "alternative conceptions" or "misconceptions" are incorrect answers result from strongly held, context-specific, stable, and incorrect knowledge constructs (Maskiewicz & Lineback, 2013; Hammer, 1996; Smith et al., 1994). An alternative view is that wrong answers can be the result of activating and integrating smaller ideas that are not necessarily inherently wrong but are used in ways not appropriately suited for the case at hand (Hammer et al., 2005; diSessa, 1993). Using this alternative framework, student thinking isn't stable, but dynamic and context dependent (Gouvea & Simon, 2018).

The theoretical framework of framing and resources specifically attempts to model a perspective of cognition as emergent and dynamic by identifying specific cognitive or procedural resources, which are fine-grain ideas that may be unconsciously or consciously activated by an individual (Hammer et al., 2005; Hammer & Elby, 2003). Developed by Hammer and Elby (2003), with contributions by Redish and Scherr (2005), this framework builds from diSessa's knowledge-in-pieces framework (1993, 1988). The framing and resources theoretical framework has been used extensively in Physics Education Research (PER). In BER, a theoretical framework of framing and resources has also had recent use (Gouvea & Simon, 2018; Slominski et al., 2017; Southerland et al., 2001).

Within this theoretical framework, the specific resources that an individual activates depends on how the individual frames, often unconsciously, a particular situation. An individual's framing could depend on features within the problem itself, such as the phrasing of the question, the syntax, or the notation used, or it could depend on the context or setting in which the problem was given, or who was asking the particular question (Gouvea et al., 2019). Perhaps the most important consideration of framing within a resources framework is that the resources activated by an individual are influenced by how they've framed the particular problem. It *is* possible that an individual has additional resources that might be activated by a different problem or task, and that an alternative framing, or a shift to a different frame, might activate some of these additional resources. While resources are often associated with a particular frame (or frames), it is important to recognize resources are not exclusive to a particular frame. Therefore, analysis of responses can never conclude that an individual does not *have* a particular resource, rather analysis must conclude that an individual did not *activate* a resource. It is quite possible that an individual could have activated a particular resource if the individual had framed the problem differently.

Context and Reasoning

A hallmark of this dynamic view of student cognition is that framing and resource activation happen in the early moments of a student encountering a problem or scenario. Because framing is a situated event, the conditions surrounding the problem or scenario greatly impact the resulting frame students employ (Gouvea & Simon, 2018; Hammer et al., 2005; Smith et al., 1994). Assessment features, like item context, are just one of the many factors that can impact framing and resource activation (Nehm & Ha, 2011; Sabella & Redish, 2007; Hammer et al., 2005; diSessa et al., 2004; Chi et al., 1981). As an individual begins the process of problem solving, the context of the problem may cause the learner to subconsciously (or at times consciously) frame the problem (e.g., this is a math problem or this is a biology problem) and therefore impact the suite of concepts and problem-solving resources the learner activates. For example, biology education researchers have found that student reasoning about evolution is profoundly impacted by item context. Nehm and Ha (2011) suggested students approach and reason differently about evolution involving trait gain versus trait loss. Similarly, Heredia and colleagues (2012) found that students were more likely to reason correctly about natural selection when discussing animals than plants. In addition, students were more likely to apply inaccurate "survival of the fittest" reasoning when the assessment contained an "unfriendly" animal. Collectively, these studies demonstrate that seemingly insignificant context features of an assessment cause students to retrieve different knowledge and to subsequently reason differently.

Experts have a well-developed set of discipline-specific resources and associated frames that may impact their reasoning about cross-cutting science concepts. For this research, we are particularly interested in the role of an expert's disciplinary expertise on how they frame a problem about a cross-cutting science concept and how context intersects with that framing. Ultimately, we believe expertise may impact framing and subsequent reasoning, which likely has consequences for instruction. In particular, expertise may impede cross-cutting instruction that would enable students to build connections across disciplines about cross-cutting concepts.

In the present research, we explored the role of disciplinary expertise on expert reasoning through the theoretical lens of framing and resources. We also investigated how contextual surface features intersected with framing to impact experts' reasoning approaches. Thus, the focus of this research is on how framing of a cross-cutting concept differs across experts.

Methodology

Study Participants

This research took place at North Dakota State University, a midwestern, land-grant university with high research activity (The Carnegie Classification of Institutions of Higher Education). To obtain experts with diverse disciplinary backgrounds, we solicited faculty participants from biology, physics, and engineering departments. Potential interview participants were identified through review of their respective research biographies posted on the university website. We sought out faculty with either research or teaching experience in 1) animal physiology, 2) agricultural irrigation, or 3) general fluid dynamics. Twelve candidates were identified and contacted via email. Of those, ten faculty agreed to participate in our study, four from biology (Blake, Bernie, Bailey, Blair), three from physics (Pacey, Peyton, Pat), and three from engineering (Emerson, Emery, Ellis). Throughout the manuscript, we assume these pseudonyms are non-gendered and adopt the personal pronouns they, them, and their.

All interviews were conducted by the same interviewer (TS, graduate student) in May of 2017. This interview structure created a potential power imbalance: a graduate student interviewed a faculty member. This power imbalance may have impacted the dynamics of the conversations that took place during the interviews. For example, faculty may have adopted the role of a teacher when talking to a graduate student rather than engaging in collegial discussions.

The interviewer was known to the biology participants and one physics participant (Pat), but unknown to the remaining interview subjects. All participants had a range of experience teaching the underlying concept of fluid flow in the undergraduate setting and all were actively engaged in research.

Interview Prompt

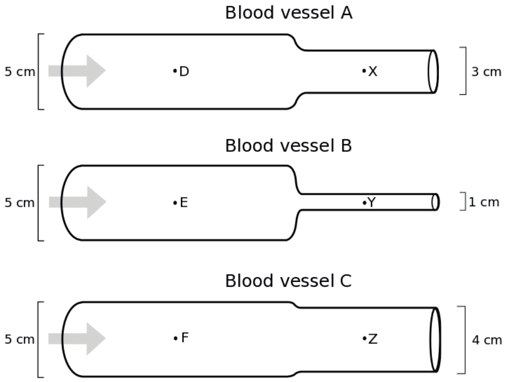
To determine how different contextual features could affect the way experts reasoned about a problem, we designed two isomorphic prompts pertaining to fluid dynamics (Figure 6). The biology version of the prompt was situated in the context of blood and blood vessels (we will refer to this as the BV prompt) and the non-biology version was situated in the context of water and pipes (we will refer to this as the WP prompt). The prompts contained identical figures and text, with the exception that “blood” and “blood vessel(s)” were used in the BV prompt where “water” and “pipe(s)” were used in the WP prompt.

The prompts were designed to probe participants’ reasoning about aspects of fluid dynamics that are important in undergraduate physics, engineering, and physiology contexts. A biologist (TS) and a physicist (JB) designed the initial version of the prompt which then went through several rounds of revision, both by soliciting feedback from other biologists, physicists, and engineers, and by piloting the prompt with a different group of biologists, physicists, and engineers.

The prompt asks participants to rank the fluid speed, fluid flow rate, pressure, and resistance at three locations (X, Y, and Z) in three different systems (Figure 6). The order of items was deliberate. We asked about fluid speed first because it seemed likely that participants would be most familiar with this concept. We next asked about fluid flow rate as this concept is central to reasoning about cardiovascular physiology. Third, we asked about pressure, another core concept in cardiovascular physiology which makes use of the Bernoulli equation, a primary concept in physics and engineering. We asked about resistance last because, during prompt development, we discovered that this concept was most likely to provide disparate responses from the disciplines.

Biology Version (BV Prompt)

The figure below shows three different blood vessels (A, B, and C) with blood flowing through them (designated by the gray arrow on the left). The volume of blood entering the left end of the blood vessel every second is the same in Systems A, B, and C. The pressure in the blood is the same at points D, E, and F. The blood viscosity is very low. The diameter on the left end of each blood vessel is the same (5 cm).



“Order the speed of the blood coming out of the right end of the blood vessels A, B, and C. If two or more blood vessels have equal speeds at the exit, say they are equal. Please try to think aloud.”

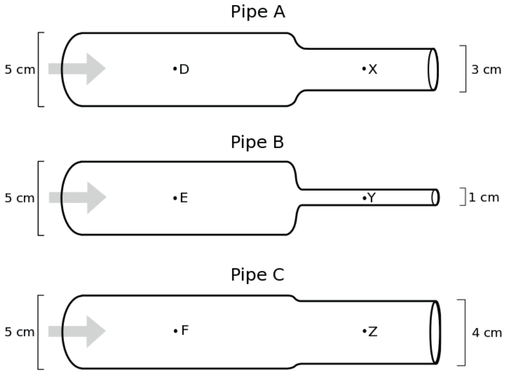
“Order the fluid flow rate coming out of the right end of blood vessels A, B, and C. If two or more blood vessels have equal fluid flow rates, say they are equal. Again, try to articulate your thinking as you answer this question.”

“Order the pressure of the blood in the blood vessels at points X, Y, and Z. If two points have equal pressures, say they are equal. Please try to think aloud.”

“Order the resistance in the blood at points X, Y, and Z. If two points have equal resistances, say they are equal. Please try to think aloud.”

Non-Biology Version (WP Prompt)

The figure below shows three different pipes (A, B, and C) with water flowing through them (designated by the gray arrow on the left). The volume of water entering the left end of the pipe every second is the same in Systems A, B, and C. The pressure in the pipe is the same at points D, E, and F. The water viscosity is very low. The diameter on the left end of each pipe is the same (5 cm).



“Order the speed of the water coming out of the right end of the pipes A, B, and C. If two pipes have equal speeds at the exit, say they are equal. Please try to think aloud.”

“Order the fluid flow rate (volume of water flowing per unit of time) coming out of the right end of pipes A, B, and C. If two pipes have equal fluid flow rates, say they are equal. Again, try to articulate your thinking as you answer this question.”

“Order the pressure of the water in the pipes at points X, Y, and Z. If two points have equal pressures, say they are equal. Please try to think aloud.”

“Order the resistance in the water at points X, Y, and Z. If two points have equal resistances, say they are equal. Please try to think aloud.”

Figure 6. The Biology Version (BV) and Non-Biology Version (WP) of Our Isomorphic Prompt.

After participants provided their ranking and reasoning for a particular concept, we then asked them to provide a definition of the concept (e.g., fluid flow rate) they were working with, and if their answer was consistent with their definition. If participants provided an equation, they were asked to recall where they learned that equation. If participants provided an analogy, they were asked to describe what caused them to think of that analogy.

In the fourth and final question, which dealt with resistance, the protocol differed slightly. After participants gave their ranking and explanations, they were asked to provide a definition of resistance. If they could not provide a definition of resistance, they were asked for their best guess at the question when hearing the word “resistance” in this context. After an initial guess, if the interviewer was asked for a definition, participants were told that “some biologists would say resistance is ‘a force that opposes movement,’” and asked to answer the question using that definition.

We used a semi-structured interview protocol, recording audio and video for all interviews. All interviews were transcribed using Express Scribe. Participants responded first to the prompt considered outside their discipline: biology faculty first reasoned about the WP prompt, while physics and engineering faculty first reasoned about the BV prompt. Using this approach, we intentionally did not cue participants to their disciplinary knowledge. Participants then completed a distractor task, meant to redirect the participant to think about a concept unrelated to fluid dynamics, before responding to the prompt within their discipline. This ordering of prompts supported our efforts to determine if context cues impacted reasoning or if participants would adopt a frame that differed from the context presented in the prompt.

Data Analysis

We used thematic analysis (Braun & Clarke, 2006) to identify broad themes in expert reasoning about fluid dynamics, a cross-cutting concept. This inductive approach involved three analysis phases, briefly described below.

Analysis Phase 1: Initial Reading

Phase 1 of our analysis was completed by TS and AF. We began by independently reading the responses to the speed question from all 10 participants and making notes of early thoughts on faculty responses. During this initial reading, we independently identified key words or phrases that seemed to exemplify a participant’s reasoning. We came together and compared notes, identifying potential or early themes in responses to the speed question. We repeated this process for the fluid flow rate question. After individually reading all 10 responses and taking notes, we compared the early themes from the speed question to those of the fluid flow rate question and noticed there were both similarities and differences in the initial themes. We repeated this process with the pressure question and the resistance question, each time reflecting back to initial themes identified in the previous responses.

Analysis Phase 2: Generalizing Themes

Phase 2 of our analysis was completed by TS and AF, followed by discussion with JM. We compared themes gathered from reading all four questions embedded in our interview prompt and combined themes that reflected similar ideas. When themes were disproportionately represented across a single question or discipline, we questioned the utility of that theme and dropped them when appropriate. We generated a list of themes based on the early themes that emerged from initial readings. We formalized descriptions of these themes and generated an early coding rubric.

We independently re-read all 10 responses to the speed question, identifying the presence of early themes and documenting specific examples of dialog that aligned with theme descriptions. We compared themes and the accompanying dialog. Any disagreements were discussed until a consensus was reached. We then updated our rubric. We repeated this process with the 3 remaining questions. Each iteration resulted in minor theme modifications and refinement.

Analysis Phase 3: Finalizing Themes

Phase 3 of our analysis was completed by TS and AF, with discussion with JM. We came together and discussed patterns in our data and lingering questions. After consulting with JM, theme descriptions were refined further and one theme was removed, leaving us with our final rubric consisting of four themes: *Switching Context*, *Disciplinary Knowledge*, *Everyday Knowledge*, and *Relationships and Equations*. We again independently read all 10 transcripts and coded the dialog according to the final rubric. We met a final time to discuss any disagreements, reaching resolution in all instances.

It is important to note the four themes we identified in our data (Switching Context, Disciplinary Knowledge, Everyday Knowledge, and Relationships and Equations) are not intended to serve as frames or as conceptual resources. Instead, these themes are intended to convey the patterns we observed looking across experts' reasoning at a grain-size that is appropriate. We feel the data collected is insufficient to name specific conceptual resources within these frames with a high level of certainty. It is possible some or all of these themes share similarities with the conceptual resources experts are activating in response to our prompt, however, the identification of these themes as resources under our current study design would be inappropriate.

Results and Discussion

Comparing Rank Order Predictions

For every direct quote, we represent the prompt version and sub question in brackets (e.g., [BV, pressure] or [WP, resistance]). We believe it is crucial to make clear the context to which the participant is responding as our argument centers on the context of the prompt and how the participant responds to that context.

In most cases, all faculty generated similar rank-order predictions about both scenarios (Table 1), although there were a few notable exceptions. Among the biologists, Blake differed in their response to the speed question and there was some disagreement on the fluid flow rate question. Two biologists gave a ranking of CAB, while Blair said BAC, and Bernie stated that they would have the same fluid flow rates.

Table 7. Rankings Provided by Experts in Response to the BV and WP prompts.

	Out of Discipline Context				Discipline Context			
	Speed	**FFR**	**Pressure**	**Resistance**	**Speed**	**FFR**	**Pressure**	**Resistance**
Biologists	**WP**				**BV**			
Blake	CAB	CAB	BAC	BAC	CAB	CAB	BAC	BAC
Bernie	BAC	=	BAC	BAC	BAC	=	BAC	BAC
Bailey	BAC	CAB	BAC†	BAC	BAC	CAB	=†	BAC
Blair	BAC	BAC	BAC	BAC	BAC	BAC	BAC	BAC
Physicists	**BV**				**WP**			
Pacey	BAC	=	*†	BAC	BAC	=	BAC†	BAC
Peyton	BAC	=	=	BAC	BAC	=	=	BAC
Pat	BAC	=	BAC	BAC	BAC	=	BAC	BAC
Engineers	**BV**				**WP**			
Emerson	BAC	=	BAC	BAC	BAC	=	BAC	BAC
Emery	BAC	=	CAB	BAC	BAC	=	CAB	BAC
Ellis	=	CAB	=	CAB†	=	CAB	=	BAC†

†Indicates a participant switched their answer after receiving the other version of our prompt.

*Pacey stated they were unable to provide an answer based on the information provided.

Physicists and engineers varied in their response to pressure. Ellis provided rankings that were quite different from the other engineers and physicists included our sample (Table 1). In light of these differences, it is interesting to note that Ellis has arguably the most extensive research experience in fluid dynamics of all our study participants. Characterization and measurement of fluid flow is one of Ellis's self-identified research areas and they have experience working in biological systems. Using the theoretical lens of framing, it is possible that Ellis has framed this problem differently than the other engineering and physics faculty. Considering Ellis has a great deal of experience working with fluids in a biological setting, it is possible that Ellis's knowledge and experience of biological systems has impacted the way they consider this problem and thus, the conceptual resources they activate when solving it.

We observed three instances where faculty changed their answers when given the second, within discipline prompt. Bailey initially provided the ranking of BAC when reasoning about pressure in response to the WP prompt, but switched to Equal when responding to the BV prompt. When asked to explain their reasoning about pressure on the BV prompt, Bailey said:

> *"This is just like me guessing, purely based on intuition. But the idea is like if you have blood pressure, you know you're measuring that, usually you can measure it at one point in the body, and it's assumed that it's the same everywhere else. I know that that's not a great assumption, but that's like how medicine passes forward, right?" [BV, pressure]*

Based on this response, Bailey may have been drawing on ideas of mean arterial pressure and peripheral resistance, originating from their knowledge of cardiovascular dynamics. Bailey is a good example of biologists consistently framing these questions in a biological way.

We also observed what may be a context effect in Pacey's response to the pressure questions. When presented with the BV version of the prompt, Pacey struggled to generate a response based on the constraints of our prompt:

> *"So... You know, I'm struggling with this. I don't know what you... You have to tell me what you mean by pressure exactly, then I can try to answer the question. Right now I'm really puzzled, right? I don't know how to rank it at the moment." [BV, pressure]*

Pacey goes on to explain why this question is problematic for them. They eventually provide a rank order, but immediately reiterate their concerns, and, ultimately, state they are unable to provide an answer.

> *"... When you squeeze this, um, fluid through these, um, different tubes here, this small capillary and then this big one here, it has to speed up as I argued, right? So if the speed is connected to the pressure, then that would suggest that the pressure is larger here than it is here {pointing to*

> *handout} and, um, in the smallest tube you would have the largest pressure. But again, without defining a pressure properly, I cannot answer the question. So I feel unable to answer it."*

Later in the interview, when Pacey is asked about pressure on the WP prompt, they restate their concern regarding the definition of pressure in this problem but are more willing to provide a response to the question. In this case, we see that Pacey may be more comfortable making assumptions about the system when presented with their own disciplinary context.

The third instance of within-subject variation comes from Ellis in response to the resistance question. When presented with the BV version of our prompt, Ellis provided a ranking of CAB. However, on the WP version, they changed their answer to BAC. When asked to explain their reasoning, Ellis said:

> *"... Yeah, I was looking at the walls so, so I may have said it wrong before. Now that I think of it this way it would define it... Define it how much force distance is here, so you have to do, uh... Basically, this will see less actually, and I think I said it the other way last time, so." [WP, resistance]*

In the quote above, we see Ellis articulate how their approach differed between the two versions of the prompts. In the BV prompt, Ellis was focusing on resistance as a property of the walls of the vessels. When presented with the WP version, they identified resistance as a property of the fluid. As stated earlier, Ellis has experience working with and measuring fluid dynamics in biological systems. It is possible Ellis's robust experience working with a system similar to the one portrayed in the BV prompt may have impacted their approach to solving the BV prompt, and may explain why their responses were different across the two versions of the prompt.

> Ellis: *"Yeah, I see they're both flowing, they both have the same properties. Viscosity is very low. Um, the volume of fluid is the same. See, there is one other thing you do when you try to replicate the blood stream. You're not gonna use real blood in general, it's difficult. You use something similar and something similar has similar, uh, properties. So in this case, you know, you could tell me the blood viscosity is very low, water viscosity is very low, and we use, actually, water to model blood sometimes."*

When looking across disciplines, we see much more variation in the way experts answered the individual questions embedded in our interview prompts. The biologists in our study often assigned different rank orders than experts from physics and engineering (Table 1). Engineers typically provided rank orders more similar to those offered by physicists, though there were still multiple instances of disagreement across the two disciplines.

This surface-level analysis suggests experts from biology, physicists, and engineering differ in their conceptualization of and approach to reasoning about fluid dynamics. When we look beyond the rank orders and examine the reasoning approaches used by faculty participants, we find distinct differences in the kinds of knowledge and experiences experts from different disciplines were using to generate their prediction

Comparing Reasoning

We present sample excerpts from our interviews in Table 8. Our goal was to share as much of the qualitative data as possible in order to illuminate our thematic analysis. The quotes chosen are indicative of the broader pattern of responses we observed across all interviews. We present our data using the four themes generated during our thematic analysis. These themes are not intended to be considered to be conceptual resources but instead, a way to organize and present the patterns we observed in expert responses. Along with these results, this section includes our interpretation of the data using the framing and resources theoretical frame.

Table 8. Examples of Expert Responses to the BV and WP Prompts.

Theme	Biology Faculty	Physics Faculty	Engineering Faculty
Switching Contexts	**Blake:** “Or that how fast blood flows. So when you said speed, the first thing that came to my mind was actually just blood flow. I didn't think about it in any other way besides blood flow.” [WP, speed]	**Pacey:** “Flow rate... I don't know how you define it. It could be... It could mean it's the velocity per, um, particle that is moving with the flow. But it could also mean it's the total amount of fluid that is passing at a given point per unit time.” [BV, fluid flow rate]	**Emerson:** “Well, you've got the same volume or flow rate, so many gallons per minute or whatever, right? And you've got same pressure, pressure hasn't changed. So you've got a smaller area, right? So, flow in pipes is related to.... if you've got the same flow coming in to all of these and you got the same flow going through here {pointing to handout}, the only way you can make up for it is increase the velocity.” [BV, speed]
Disciplinary Knowledge	**Blair:** “Right, because the pressure would be, shoot it out further. There's more pressure. So this one... one of the things that's making me think about... cause I haven't had physics, but I have had physiology... is how do we do this... like if you consider pipe B, where you have venous flow or arterial flow and you go down to small capillaries, right? And one of the things you have to have is multiple outlets for that otherwise you'd have to blast open your capillaries.” [WP, pressure]	**Peyton:** “A shear gradient. Viscosity is a material property that has to do with the shear gradient. It's not, it's not a f-- Hmm... Sorry, let me rephrase that. Loss has to do with the shear gradient times a constant that we call viscosity. Viscosity is a material property so it's the same for the material, but the, the loss or the hardness of pushing the fluid has to do with how far the walls are apart.” [BV, resistance]	**Emery:** “... we're not going to have a perfect system. We're going to, uh, have to pay, pay for the thermal dynamic laws.” [WP, resistance]

Table 8. Examples of Expert Responses to the BV and WP Prompts (Continued).

Theme	Biology Faculty	Physics Faculty	Engineering Faculty
Everyday Knowledge	**Bernie:** “... I'm going to say pipe B because when you have a garden hose and you put your thumb over the end of the hose to make it smaller, it shoots out faster, and sprays.” [WP, speed]	**Pat:** “Resistance, is it kind-of harder or easier to move? So if I make an analogy, it's kind-of easier to move through large openings than it is through narrow openings. It's just the common sense. Like if, if you see it's a bottleneck, right? Like a traffic, um... It's a bottleneck. So the resistance is higher the narrower the opening is. Um, but that's just intuition speaking.” [BV, resistance]	**Emerson:** “And so it depends on what kind of material. So like for instance, if you pump the same amount of water through cast iron, which has a rough internal wall, and you pump it through PVC, which is smooth, you'll have less friction loss. And therefore, less pressure loss.” [BV, resistance]
Relationships and Equations	**Bailey:** “Um... well, cause if you were taking a let's say fixed volume of fluid and trying to shove it through a much let's say uh higher surface area to volume tube, then it's just going to exert a lot more pressure on that tube.” [WP, pressure]	**Pacey:** “So blood is fairly incompressible, I believe. So since you have the same current left and right... That means material conversion per unit length along the flowing direction, meaning that the speed has to grow when the diameter of the vessel becomes smaller.” [BV, speed]	**Emerson:** “Yeah, the same, if the same volume per time is entering the left-hand side it's got to come out the other side. Uh, that's Bernoulli's principle, by the way.” [BV, fluid flow rate]

Switching Contexts

At some point during each of their individual interviews, all four biology faculty explicitly articulated thinking and reasoning about the cardiovascular system when responding to the WP prompt. Biology faculty used language and concepts that indicated they were thinking about cardiovascular systems, despite responding to questions about water and pipes. From our theoretical perspective, these observations are consistent with an individual framing the WP prompt as a biology question, and, as our framework predicts, activating terminology and concepts that are connected within that frame.

At times, biology participants would even call our attention to this framing by explicitly describing how they were relying on their knowledge of cardiovascular physiology. For example:

> Blake: *"Or that how fast blood flows. So when you said speed, the first thing that came to my mind was actually just blood flow. I didn't think about it in any other way besides blood flow." [WP, speed]*

Despite being asked about water and pipes, Blake framed this as a biology question. Blake's framing may be in response to the underlying conceptual component of our prompt (fluid dynamics). Alternatively, this framing could be in response to a number of other factors that are both known and unknown to the interviewer and the participant. As Gouvea and colleagues note, framing can be "influenced by both an individual's prior knowledge and experiences and by the physical and social cues presented by a setting" (2019). No matter the cause of the framing, we would expect Blake to activate biology-related conceptual resources, which in this case would be resources related to cardiovascular flow dynamics. When we look to Blake's earlier explanation to the speed question, we see them focusing on the radius of the pipe and later what we believe to be an equation meant to resemble what would be found in an introductory anatomy and physiology textbook:

> *"But what was most influential, um, was the radius at the end of the pipe on the right-hand side." (clarifying question from TS) "So, the relationship, um, between radius and speed is...direct, meaning that although I don't have the equation memorized, flow equals I believe it's the change in pressure times pi times radius to the fourth over I believe it's viscosity times length."*

Blake's equation uses language and terms more aligned with those used in cardiovascular physiology than in physics, suggesting this is a resource activated in response to a biology frame.

We also observed instances when biology faculty were less explicit about switching contexts:

> Bailey: *"Um... I don't really remember capillary physics all that well but I think that pipe B would have the highest speed of water coming out of it, pipe A would have the medium and pipe C would have the least." [WP, speed]*

Bailey stated they don't remember capillary physics, a unit unfamiliar to us in either physics or biology courses. This statement suggests to us that Bailey considers the principles of capillary physics, which we believe refers to the biological phenomena that occur in capillaries, a useful frame for answering this question. Thus, Bailey is framing this problem as biological, not physical. By framing this as a biology problem, we would predict Bailey would be inclined to employ conceptual resources associated with biology, thus explaining their mention of capillary physics. However, in this instance, Bailey couldn't articulate any resources from this frame and seemed to drop it. Instead, Bailey framed the problem in the real-world example of forcing liquids out of a syringe:

> Bailey: *"I couldn't remember how the equations were so I tried to think about what would happen if you just had these from previous experience, so if you try to force a large volume at the same basic pressure through a smaller tube, then like the water would squirt out much farther. Um, so I assume that translated to speed, I'm not super sure. Um... yeah, so that was like pretty much what it was based on." [WP, speed]*

Compared to the biologists, physicists and engineers were less inclined to explicitly identify when they used their discipline-specific context. Similar to biologists, there were instances where physics and engineering faculty framed the context to be consistent with their own discipline, when they used words like "pipe" or "water" in their response to a BV prompt:

> Emerson: *"Well, you've got the same volume or flow rate, so many gallons per minute or whatever, right? And you've got [the] same pressure, pressure hasn't changed. So you've got a smaller area, right? So, flow in pipes is related to.... if you've got the same flow coming into all of these and you got the same flow going through here {pointing to handout}, the only way you can make up for it is to increase the velocity." [BV, resistance]*

While this framing is not as explicit as the framing observed in biology faculty responses, they represent a shift away from a biological context. Contexts of water flowing through pipes are canonical in physics and engineering textbooks, and using these words is evidence for activating a physics or engineering frame. In doing so, faculty within this frame are expected to call on resources that exist within their physics/engineering frame. This is seen in Emery's response calling on the continuity equation:

> *"I'm assuming that the blood is basically incompressible as a fluid, or liquid, actually. And so Q is equal to VA, velocity times cross-sectional area. V is then, uh, Q divided by A. And the smallest A produces the, um, biggest velocity, for Q being a constant." [BV, speed]*

Again, these cases were neither as explicit or as frequent as those observed with biology faculty, but they are framed distinctly from how the prompt is presented.

Physicists and engineers often removed the biological context for the BV version of our prompt, as demonstrated by Peyton:

> *"The fluid's moving, so it's not a simple hydraulic kind-of problem where I have a weight on one side and it pushes down on a cross-sectional area and that pushes up on a different cross-sectional area and then I make a ratio and get my forces that way." [BV, pressure]*

Here, Peyton refers to the blood as "fluid" and references it as "not a simple hydraulic" problem. Instead of adding additional context, like we saw in the biologists' responses, we see Peyton removing context. Although it's a different strategy when compared with the previous example of framing the BV prompt to be about water in pipes, abstracting the problem to a generic fluid is also a common practice, especially in physics. We would expect to see activation of resources from a physics frame, like the relationship of pressure, force and area:

> Peyton: *"Pressure is force divided by area." [BV, pressure]*

Disciplinary Knowledge

As described in the previous section, biologists often adopted a biology frame when asked about the WP prompt. Biologists tended to use biological terms like blood vessel and cardiovascular, clearly using disciplinary content expertise to reason through the problem. In addition, biologists expanded the boundaries of the system, bringing in ideas from cardiovascular physiology to explain their responses to the WP prompt (Table 8, Disciplinary Knowledge, Blair). For example, Blake used ideas of cardiac output and peripheral vessel resistance to provide a definition of “pressure”:

> *“...It's almost like I keep wanting to go back to, well pressure is cardiac output times resistance. Like I just have that... I don't know. That feeling of needing to, like, rely on that equation.” [WP, pressure]*

To the biologists, it seems that this additional, discipline-specific knowledge was helpful for explaining the WP fluids problem, despite it containing no explicit reference to a biological system. These experts are activating knowledge structures that originate from their time learning and working in biology and are applying that knowledge to a seemingly non-biological system.

We also observed all three physicists using knowledge we considered to be originating from time spent in their discipline. The explicit usage of this physics knowledge was apparent through participants' reasoning about the BV prompt, and again when discussing the WP prompt. Throughout the physics responses, we identified instances of explicit use of disciplinary knowledge like electrical currents, conservation of mass, and shear gradients. Below is an example to show how Peyton used their disciplinary knowledge to reason about resistance in response to the BV prompt:

> *“... viscosity has to do with shear.” (clarifying question from TS) “A shear gradient. Viscosity is a material property that has to do with the shear gradient.” [BV, resistance]*

One physicist clearly used their disciplinary knowledge to connect the BV prompt to current (although they were not specific about what type of current), and then later commented on how this related to current in a circuit which we take to be an electric circuit.

> Pacey: *“...so then the flow rate is the same for all three examples because again, the current generally is the same.“* and later *“So the concept again has to do with compressibility--incompressibility of the fluid. Because it's incompressible and because the current is the same. Uh, at every point along a circuit in a way, you must have the same amount of fluid pass at every, at any given point along this horizontal axis where fluid flow takes place.” [BV, fluid flow rate]*

Engineers, like physicists, used disciplinary knowledge that sharply contrasts with biologists. We identified multiple instances of engineers introducing concepts or ideas that seemed to originate from their experiences working in their discipline. Notions about mathematical concepts linked to speed and velocity were observed:

> Emerson: *“When you ask engineers or physicists, they, speed is, uh, is-- Velocity is a vector, speed is a, is just kind-of a, a scalar product.” [BV, speed]*

Elements of abstraction were also evident, in thinking about the fluid as air flow:

> Emerson: *”Yep. It's just that... Yeah, to a, to an engineer or other people, fluid…air is a fluid. So it's, it's just a different density, different, it's got different characteristics but it, in many… The difference between air and water is that air is compressible and that adds some differences in the equations and calculations.” [WP, fluid flow rate]*

And connecting that with other mechanical phenomena like airplanes flying:

> Emerson: *“Well, a lot of times for calculating, uh, the, your... Bernoulli's principle governs the... It, it's pretty much the same principle governing why airplanes fly.” [WP, fluid flow rate]*

We observed participants across all three disciplines making explicit calls to knowledge within their own discipline. The context of the problem, whether blood in vessels or water in pipes, did not seem to impact participants framing of the problem. Participants framed both problems within their own discipline and utilized resources from that discipline.

Everyday Knowledge

We also observed our participants using knowledge that did not appear to originate from experiences in their respective disciplines. In several instances, participants reasoned using ideas from their everyday experiences. For example, three biologists, Blake, Bernie, and Blair each made reference to garden hoses or domestic plumbing in response to the WP prompt (Table 8, Everyday Knowledge, Bernie). In the example below, we see how Blair draws on their everyday experience with garden hoses to generate their predictions:

> *“Because the constriction, I'm thinking of a water hose and like how much it's gonna shoot out when it comes out. And if you restrict a water hose, this will just.... the big one {points at Pipe C} will trickle down, this one {points at Pipe B} will shoot out, and this one {points at Pipe A} will be in between those two.” [WP, speed]*

Blair is using their previous experiences with garden hoses to explain how the speed will differ across the three systems and Blair explicitly states that they are thinking about water moving through hoses. This quote, and others like it, are in response to the WP version of the prompt. Considering the lack of disciplinary knowledge provided in this response and applying our theoretical lens, we would hypothesize that Blair has framed this scenario in such a way that aligns with and activates their experiential knowledge of real-world phenomena.

Physicists and engineers were less likely to incorporate what we would consider to be everyday knowledge in their responses. We have provided two examples in Table 2 (Everyday Knowledge, Pat and Emerson), though these were not nearly as representative of the rest of the explanations generated by physicists and engineers. Similar to what we saw in the biologists' responses, Pat and Emerson provided this kind of real-world knowledge in response to the out-of-context prompt.

Relationships and Equations

Biologists used fewer equations when generating their predictions. Instead, biologists would more typically identify a proportional relationship between two variables, in particular how a change in one variable or property would affect another component of the system. For example, Bernie said:

> *"... So the pressure increases as you decrease the diameter because you're trying to push the same amount of water into a smaller space, and so that's going to increase pressure, that's going to increase the force of it pressing against the outsides of the pipe." [WP, pressure]*

By contrast, physicists and engineers frequently used equations and generalizable relationships when generating their predictions. The formal equations were different from the two variable relationships we observed among biologists, in that they involve numerous quantities and are often named principles or equations. Specifically, both physicists and engineers used variations of the Bernoulli equation,

> Emerson*: "Yeah, the same, if the same volume per time is entering the left-hand side it's got to come out the other side. Uh, that's Bernoulli's principle, by the way." [BV, fluid flow rate]*
>
> Pat: *"Okay. If I'm, if I tried to make sense of what... um... So I'm just interested in Bernoulli's principle, it's more like that's how it is." [BV, pressure]*

as well as the continuity equation and its expression in terms of fluid speed,

> Emery: *"Oh, okay. The equation, uh... The original, the basic form is Q is equal to VA." [BV, speed]*

Engineers and physicists often articulated a specific principle and then followed with an application of that principle to the scenario provided in the prompt. For many of the engineers and physicists, highlighting the fact that the fluids were incompressible and that all matter is contained within the system were important to how they thought about the problem.

> Pacey: *"So blood is fairly incompressible, I believe. So since you have the same current left and right... That means material conversation per unit length along the flowing direction, meaning that the speed has to grow when the diameter of the vessel becomes smaller." [BV, speed]*
>
> Emery: *"My reason for that. Okay, we have a constant volume. I'm assuming that the blood is basically incompressible as a fluid, or liquid, actually." [BV, speed]*

A Note on Resistance

Resistance was a productive idea for biologists but less so for physicists. Some biology faculty used the concept of resistance when reasoning about questions that did not ask about it. Blake was especially reliant on the concept of resistance and we see them explicitly make use of this idea early on during the interview:

> *"Okay. So the pressure does depend on volume, but it also depends on resistance, um, and resistance does depend on the radius of these pipes. And I know that the, um, the bigger the radius, the less resistance there will be. And the less resistance there is, the less, um, pressure there is on the wall of the pipe." [WP, pressure]*

Other biology faculty were less inclined to use the term resistance but provided reasoning that suggested they were using the principle of resistance without explicitly making mention of the term. Bernie, for example, focused their reasoning on the diameter of the tube to generate a prediction based on their experience with vasoconstriction and, ultimately, resistance:

> *"Alright. So it's flowing in at the same rate in each pipe, and is at the same pressure until it reaches the bottleneck, and then we have different diameters. I know that... I think all that matters... I know with like blood vessels, when you vasoconstrict that can raise blood pressure,*

for sure. I'm going to say pipe B because when you have a garden hose and you put your thumb over the end of the hose to make it smaller, it shoots out faster, and sprays." [WP, speed]

This reliance on resistance isn't surprising. Resistance is an important concept for biologists (Redish & Cooke, 2013), and Anatomy and Physiology textbooks typically do not consider fluid flow in the absence of resistance due to its importance on the cardiovascular system.

In contrast to biologists, physics faculty did not incorporate resistive effects, and did not use the term resistance when answering the first three items. When asked about resistance in the fourth question, all physics faculty were completely unfamiliar with the term in the context of fluid flow and asked for clarification about the definition of resistance. In addition, physics faculty struggled to offer a definition of resistance in this context:

Peyton: *"I would guess you're getting somehow at some kind of weird conceptual idea of what viscosity might be like in it? Either that or how hard it would be for the fluid to go through the tube. Both seem kind-of ill-designed." [BV, resistance]*

The physics faculty were still not comfortable answering questions about resistance after being provided with a working definition from biology. Physics faculty found the biological definition of resistance to be problematic, and at times, voiced concern with how biologists use the term resistance in the context of fluid dynamics:

TS: "*Did you think that [resistance] was a useful question?"*

Peyton: *"Nope, I think it's a bad idea."*

Peyton's comments were one of the more pointed examples of a common perspective - physicists were dissatisfied with the way resistance is represented in the introductory physiology curriculum. This difference in opinion leads us to presume physicists would not teach resistance in a way that resembles how a biologist might teach resistance and fluid dynamics.

This contrasting opinion aligns with the work of Redish and Cooke (2013) and exemplifies the epistemological differences found between physics and biology. The underlying concepts that give rise to a biologist's view of resistance are discussed in introductory physics courses (i.e., length, diameter, viscosity), though never in association with the term resistance:

Peyton: *"...Viscosity is a material property so it's the same for the material, but the, the loss or the hardness of pushing the fluid has to do with how far the walls are apart." [BV, resistance]*

It is interesting to note that physicists regularly use the term resistance in the context of electric circuits. We observed all three participants incorporating ideas from circuits when explaining their reasoning on the resistance questions:

TS: *"Is that [resistance] a familiar concept at all to you?"*

Pat: *"No, but I can make an analogy with, um, resistance in electric circuits."*

Finally, engineers appeared to have more varied perspectives on the concept of resistance compared to physicists. Similar to physicists, Emerson was somewhat uncomfortable with describing resistance as a force. Conversely, when asked to define resistance, Emery offered a description similar to what we might expect from a biologist:

Emery: *"Opposition to the flow. And that which I would--is partially defined as the change in pressure between the two reference points." [BV, resistance]*

General Discussion

To our knowledge, there are few instances of the framing and resources framework being used to explain expert reasoning across disciplines. We believe this theoretical framework is well-suited for describing expert reasoning as it accommodates both the formal disciplinary knowledge that an expert acquires through their training, as well as the more informal, intuitive knowledge that an expert would acquire experiencing the natural world (diSessa, 1988). The resources framework respects disciplinary norms and accommodates epistemological differences across distinct domains. The resources framework also emphasizes and elucidates the impact context has on reasoning. Without this theoretical frame, we may recognize a difference in expert responses, but we would be unable to understand or explain why that difference existed.

Differences Across Disciplines

We asked faculty from biology, physics, engineering to reason about the cross-cutting concept of fluid dynamics in two contextual settings, blood/vessels and water/pipes. Faculty came to similar ranking conclusions compared to their disciplinary counterparts, though there were stark differences when comparing rankings across disciplines.

One might assert that one disciplinary group of experts is ‘wrong’ and another is ‘right’. We would argue such a perspective fails to recognize the inherent and important epistemological differences of the disciplines. Biology and physics are different disciplines, with distinct ways of knowing the natural world (Redish & Cooke, 2013). Physicists find value in simplified or abstracted systems models and are often more interested in how outside forces impact the system of interest. In contrast, biologists embrace complexity, working to understand the mechanisms underpinning complex living systems. These epistemological differences were present throughout our observations, and perhaps highlighted when participants switched contexts (see above). Biologists added biology content into the WP prompt, while physicists abstracted the biology content out of the BV prompt:

Pacey: *“So yeah, it's all analogous to what we already did for the blood, right?” [WP, resistance]*

Biologists, on the other hand, expanded the focus of our prompt to more authentically discuss cardiovascular physiology, even when reasoning about a WP question. Consistent with Redish and Cooke (2013), we found that biologists prioritize the function of system (and the system more broadly) when reasoning about a cross-cutting concept like fluid flow, whereas physicists focus more deeply on the constraints of the system provided. We found engineers to have epistemological behaviors somewhat similar to both biologists and physicists. Much like physicists, engineers emphasized the importance of the constraints on the system (i.e. conservation of matter); however, they were more conservative in the ways they likened water to blood when reasoning across our prompts:

Emerson: *“...the only thing with blood is that it's, it's primarily a fluid, little different viscosity. Um, you do have the cells in there...“ [WP, pressure]*

Outside of the three instances described earlier, we did not see evidence of faculty rankings being affected by the different prompt contexts (Table 1). Most faculty used similar reasoning strategies and came to the same conclusions in both interview contexts. This observation is consistent with previous research looking at how experts categorize physics problems (Smith et al., 2013; Chi et al., 1981). These authors found that experts categorize problems based on the physics principles required to solve the problem, whereas novices were more impacted by the superficial context of the problem.

Extending these findings to our research, it is possible that the differences in rank orders across disciplines arise from experts not focusing on the superficial context of the prompt and instead, framing the problem in a manner that aligns with the way phenomena are conceptualized in their discipline. These experts have gone through numerous years of training to think like an expert in their field, and that training has reinforced framing behaviors that are productive in their respective fields.

Implications for Instruction

The differences in ranking responses we observed across disciplines might make us question the expertise of our study participants on the topic of fluid dynamics. However, it is important to remember that the faculty in our study have extensive disciplinary experience which has shaped them into expert thinkers. Taking into account the differing epistemological cultures as well as the potentially disparate conceptual frames and resources routinely activated by our experts, it is appropriate that faculty from different disciplines would reach different conclusions when reasoning about a cross-cutting concept like fluid flow. When biologist reason about a cross-cutting problem using a biological frame and the resulting conceptual resources, they make sense of the system and generate predictions in a way that is productive in the field of biology. It is possible their reasoning and resulting predictions may be seen as incomplete in the eyes of a physicist, but what is productive in one discipline will not necessarily be seen as productive or sufficient in another due to the epistemological differences between disciplines.

While it may be appropriate that experts frame problems on cross-cutting concepts differently, this disciplinary framing might flow into instruction, which could impede students' transfer of cross-cutting ideas. Knowledge can be tightly bound to context, particularly when learners are taught in a single context (Bjork & Richardson-Klavehn, 1989). This is often the case in undergraduate STEM classrooms - students are taught about a concept like fluid flow in the context of physics or biology and so learn to associate specific ideas with those classes and associated norms. Students then struggle to see the connection between these classes and may not be able to recognize the epistemological differences between the disciplines, and thus, are unable to reconcile seemingly competing instruction. Instruction that helps learners abstract concepts and principles, however, supports transfer and may help students bridge the gaps between their introductory STEM courses (Gick & Holyoak, 1983). For this to occur, instructors need both a working understanding of how these cross-cutting concepts are used and taught in different disciplines and an ability to use cases and examples that bridge disciplines.

In the case of fluid dynamics, many students enrolled in anatomy and physiology at our institution are required to complete the introductory algebra-based physics series and many students enroll in these courses simultaneously. Based on the findings from our study, it is likely that these students will receive distinct physics and biology instruction and will struggle to see fluid flow in physics as the same concept in anatomy and physiology. Instructional practices currently do not support that transfer of understanding.

We encourage instructors, especially those teaching introductory courses, to connect with faculty across STEM departments to discuss cross-cutting concepts. Faculty from across STEM disciplines need to engage in meaningful conversations that explore disciplinary expectations around cross-cutting science topics. Engaging in this dialogue will help faculty to create instruction that bridges disciplines, and helps students transfer knowledge across domains. Transfer between courses is hard enough (Bransford et al., 2000). Students need support to connect and organize the bits and pieces of cross-cutting concepts they collect during their academic career.

Conclusion

The framing and resources framework was a productive approach to supporting our exploration of expert reasoning about a cross-cutting concept. We found that experts, despite being asked to reason about a context outside of their own discipline, framed the problems in ways that aligned with their disciplinary background and thus activated conceptual resources connected to that frame. Through this framing, we found that experts differed in their epistemological problem-solving behaviors, and in the importance ascribed to resistance, a productive concept in physiology. By extension, it is plausible that experts then teach in ways that align with their disciplinary framing and subsequently reinforce disciplinary boundaries already perceived by STEM students.

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CHAPTER 4. THE ROLE OF CONTEXT AND FRAMING ON STUDENT REASONING OF FLUID DYNAMICS

Introduction

Healthcare is the fastest growing industry in the U.S. (U.S. Bureau of Labor Statistics, 2019). Many undergraduate students enter college with a goal of being a healthcare professional and most of those students will be required to complete the introductory human anatomy and physiology (HA&P) series. Unfortunately, the current state of HA&P education struggles to meet the needs of this large, increasingly diverse student population. Further, physiology is an essential component of a biology curriculum and national documents like Vision and Change (2011) and the Next Generation Science Standards (2012) include core concepts pertinent to physiology. Despite this important role, physiology education (and HA&P more broadly), is an area that lacks substantive research on teaching and learning.

Human Physiology is Difficult

Human anatomy and physiology courses are often associated with high drop, withdrawal, and failure rates (Sturges et al., 2016; Harris et al., 2004), and are often considered to be exceptionally challenging by both the students and faculty across the United States (Slominski et al., 2019; Sturges and Maurer, 2013; Michael, 2007). Our recent, multi-site replication (Chapter 2 and Slominski et al., 2019) of Sturges and Maurer's study (2013) found evidence of this perceived difficulty at multiple institutions, suggesting students' perceptions of course difficulty are independent of unique variables like institution type, class size, and the pre-requisite courses required.

We find it troubling that the introductory HA&P series, an important course for both biology majors and aspiring health professionals, is consistently so problematic for students. Unfortunately, little progress has been made to understand and explain why students struggle to succeed in the introductory HA&P series – most efforts to improve HA&P education focused on aspects of pedagogical techniques and curriculum design and not student reasoning or broader learning challenges.

A 2007 study by Michael took a more holistic approach to understand the student difficulties present in HA&P. Michael developed a survey that asked faculty what made physiology difficult for students. Results from 56 instructors across the United States indicated that faculty attributed student difficulty to inherent characteristics of the discipline, as opposed to factors pertaining to the way physiology is taught or the way students attempt to learn physiology. This study was repeated with student populations at different institutions across the United States and the results are consistent – students attribute their difficulty learning physiology to the inherent characteristics of the discipline, as opposed to the way physiology is taught or the way students approach learning it (Chapter 2 and Slominski et al., 2019; Sturges & Maurer, 2013). More specifically, students believe physiology itself encourages them to think about physiological phenomena and structures in terms of their purpose or goal. Students also report difficulty thinking about physiology phenomena in terms of cause and effect.

Identifying physiology's disciplinary characteristics as a source of difficulty is a valuable finding on its own, but more research is needed to better understand how and why human physiology content gives rise to student difficulties in HA&P. Isolating the impact of human physiology context on student thinking is an essential step in understanding the difficulties students experience in HA&P.

Context Matters

It is reasonable to believe that every student enters the HA&P classroom with pre-existing notions of how their body functions (e.g. noticing how their body responds after exercise) and has some experience with managing dysfunction or homeostatic imbalance (e.g. drinking water when they are dehydrated). It is likely these personal experiences have been recognized by the student (both subconsciously and consciously) and have contributed to a belief that staying alive is the goal of all body systems. In most HA&P classrooms, we also operate under this belief and teach HA&P content with the underlying intent or goal of survival – we discuss how the body functions under normal conditions, or, in the event of a dysfunction, we discuss how either the body or external resources can intervene to mitigate the dysfunction.

This is different than the content covered in an introductory biology course, in which students learn about concepts like carbon movement through an ecosystem and natural selection. In the case of the carbon movement for example, students are less likely to have an assumed goal of cycling in mind prior to instruction, nor is it likely they will have as much personal experience with predators and prey, or photosynthesis and herbivory. For these reasons, we argue the human physiology context of HA&P likely brings about ideas and ways of thinking that may not be as applicable to other introductory biology courses. To our knowledge, there has been little research investigating the impact human context has on student reasoning about physiology. However, when we situate context effects more broadly in the biology education literature, there is evidence that context can profoundly impact student reasoning.

Contextual features of a system or problem influence whether or not a student draws on or employs an incorrect knowledge structure, frame, ontological kind, or way of thinking (Gouvea & Simon, 2018). These contextual surface features can be especially impactful on novice students (Chi et al., 1981). Novice students, like those enrolled in HA&P, are more likely to focus on the superficial aspects of a problem, whereas more expert-like students look for underlying conceptual features when determining how to approach a problem or scenario.

One of the most recognized studies on context effects in biology comes from Nehm and Ha in 2011. This study used 12 variations of an open-ended prompt designed to elucidate the effect of context on student reasoning about natural selection. Analysis of student responses revealed the accuracy of students' explanations of natural selection was impacted by the context included it the prompt, suggesting students reason differently about prompts involving trait gain versus trait loss. Another study from Heredia and colleagues (2012) found that students are more likely to reason correctly about natural selection when discussing animals than plants. Findings from this study also indicate that students are more likely to apply inaccurate 'survival of the fittest' reasoning strategies when assessments contain an 'unfriendly' or 'aggressive' animal.

Extending these findings to our work, it is possible that students rely on their everyday knowledge and experiences when reasoning about complex phenomena in HA&P and, further, experience difficulty when their everyday knowledge and experiences may encourage them to think about the phenomena in terms of a goal (survival).

Framing and Resources

The aforementioned evidence of context affecting student reasoning leads one to question how the surface features of a prompt can have such a profound impact on student thinking. The framing and resources framework (Hammer et al., 2005; Hammer & Elby, 2003) offers a theoretical viewpoint that very much aligns with such a question. Under this framework, the surface features used in articulating a scenario or a problem can dictate how a student situates or frames the problem internally (Gouvea & Simon, 2018). When a student situates a problem using a particular frame, either unconsciously or consciously, it results in the activation and integration of particular conceptual resources. These conceptual resources are small ideas that the student then relies on when working through the problem (Hammer et al., 2005; diSessa, 1993; 1988). Students accumulate these cognitive resources as they make sense of the world around them (both in the classroom and outside of the classroom) and thus, these cognitive resources have an explanatory power for a student. Due to the dynamic nature of how cognitive resources are acquired and activated, one cannot consider these resources to be neither correct or incorrect. Instead, one can only consider the appropriateness of a particular resource (or resources) being activated in conjunction with a particular problem or scenario.

The framing and resources framework models cognition as an emergent, dynamic, and situation-dependent process. This model is distinctly different than the widely recognized view of “alternative conceptions” or “misconceptions”. Misconceptions are considered incorrect answers that result from pre-existing, strongly-held knowledge constructs that are context-specific, stable, and inherently inaccurate (Maskiewicz & Lineback, 2013; Hammer, 1996; Smith et al., 1994). Using the framing and resources framework model of cognition, wrong answers are the result of contextual features that activate students’ small knowledge constructs (or conceptual resources) and compiles them to form an idea in real time (Hammer et al., 2005). When these conceptual resources are incorrectly selected or applied incorrectly (e.g., they don’t account for assumptions or limitations), a student is likely to identify with or provide an incorrect answer. In comparison to misconceptions, it is not students’ conceptual resources that are considered wrong, but instead, they are misapplied in the context at hand. The same conceptual resource may be useful reasoning in a different context.

The framing and resources framework has been widely adopted in the physics education research community and is considered to be a valuable tool for understanding and explaining student reasoning. Biology is an application of physics, so it is plausible that the framing and resources model of cognition is a useful way to describe how students in biology reason about a phenomenon.

Research Questions

To better understand why students find human physiology so difficult, we sought to isolate the affect human physiology context has on student thinking in HA&P. Our work seeks to discern whether students struggle in HA&P because of the nature of the context or because they are grappling with a complex systems (as is the nature of the discipline).

To begin investigating these broad questions, Study 1 isolates the effect HA&P context has on student reasoning of fluid dynamics, a complex system routinely covered in HA&P classrooms. We use fluid dynamics as an interdisciplinary canvas because as a complex system, it can naturally accommodate human physiology context (blood and vessels) and an unrelated context (water and pipes). In order to determine how adding HA&P context to an assessment impacts student reasoning, our data comes from both HA&P students and physics students. Our interdisciplinary study design enables us to address the following questions:

1. Do HA&P students and physics students differ in their reasoning of fluid dynamics, a complex, interdisciplinary phenomena?
2. Do surface context features affect the way introductory students reason about fluid dynamics?

Study 1

Methods

To isolate the affect of surface context on student reasoning, we used a previously developed isomorphic prompt that asked students a series of questions regarding fluid dynamics (Chapter 3 and Slominski et al., *in revision*). Students were asked to complete four ranking tasks (i.e. fluid flow rate, speed, pressure, and resistance) that required them to make comparisons across three different versions of a system. Students were then asked to explain their reasoning following each task. There were two versions of this assessment (Figure 6) in which the only difference was the surface context used to describe the system in question. One version (referred to as the BV version) used an HA&P surface context (i.e. blood and vessels) and the other version (referred to as the WP version) used a non-biological surface context (i.e. water and pipes).

To be able to isolate the effect of context on student responses, we needed to control for students' ability to answer questions about fluid dynamics. Fluids and fluid dynamics are routinely included in the introductory physics curriculum, therefore, we considered students enrolled in the introductory algebra-based physics course to be an appropriate population for our study. We gave our isomorphic assessments to students enrolled in HA&P and students enrolled in the introductory algebra-based physics course at a large, Midwest research institution in Spring 2016 and 2018. The two versions of the assessment were distributed so approximately half of the students in each course were given the BV version and the other half the WP version (Table 9). Students voluntarily completed our task in each class after receiving formal instruction on the topic of fluid dynamics. Several students (25 students in 2016 and 34 students in 2018) were simultaneously enrolled in HA&P and physics; we removed their second attempt at this task.

Table 9. Sample Sizes and Version Distribution by Year for Each Course.

Course	2016		2018	
	BV version	**WP version**	**BV version**	**WP version**
HA&P	125	122	151	149
Physics	57	64	36	32

After reviewing the data collected in Spring 2016, we noticed a large number of students providing answers that suggested a failure to recognize the difference between fluid flow rate (FFR) and speed. In an attempt to aleviate this issue in 2018, we made a minor modification to the assessment and changed the order of the speed and fluid flow rate questions. In the 2016 version, students were first asked about fluid flow rate and then speed. In the 2018 version, the order of these items was reversed.

Analysis

We compared the rankings provided by HA&P students to all prompt items to the rankings provided by physics students, independent of version. We used a Fisher's exact test to determine if the proportions of the provided rankings were different across the two courses. To determine if prompt version impacted the way students responded, we compared the rankings provided by 2016 HA&P students in response to the BV version to the rankings provided by 2016 HA&P students in response to the WP version. We repeated this comparison for each course included in our study. We used a Fisher's exact test to determine if the proportions of the provided rankings were different across the two versions within each course. The 2016 and 2018 data sets each underwent their own suite of comparisons with 12 tests conducted within each data set (four comparisons across courses, four comparisons within the HA&P course, and four comparisons within the physics course). To correct for multiple comparisons, a Bonferroni-adjusted alpha level of 0.004 (0.05/12) was used. All statistical analyses were conducted using the R statistical environment (R Core Team, 2018).

To analyze the written explanations, we used thematic analysis (Braun & Clarke, 2006) with an interdisciplinary team of coders (two from physics, two from biology). Each of the four coders began by individually reading 40 assessments completed by HA&P students (20 BV and 20 WP) and 40 assessments completed by physics students (20 BV and 20 WP). Each member of the coding team took notes on their initial thoughts while reading each assessment and the team met to compare their initial observations. During this initial meeting, there were very few similarities in the observations made by the biologists compared to those made by the physicists. The biologists often placed more value on the phrasing and vocabulary students used when crafting their responses while physicists focused on the various equations or principles included in student responses. These differences were heightened by the variation in response quality and a concern that students seemed to be using shortcuts when writing out their explanations. Despite numerous attempts at working through our coding differences, we were unable to generate initial coding themes. Because there were such stark differences in the ways coders interpreted student explanations, we did not feel it was appropriate to use those explanations (and our coding of those explanations) as evidence of student reasoning.

Results

Comparing Responses Across Courses

We compared student responses to our isomorphic assessment to investigate how students in different courses would answer a suite of interdisciplinary questions (irrespective of assessment version) after receiving relevant instruction. In 2016, students in the HA&P course (n = 247) provided different answers than the answers provided by physics students (n = 121) for the FFR, pressure, and resistance questions (Figure 7a). In 2018, students in the HA&P course (n = 300) provided different answers compared to the answers provided by physics students (n = 68) for all four questions.

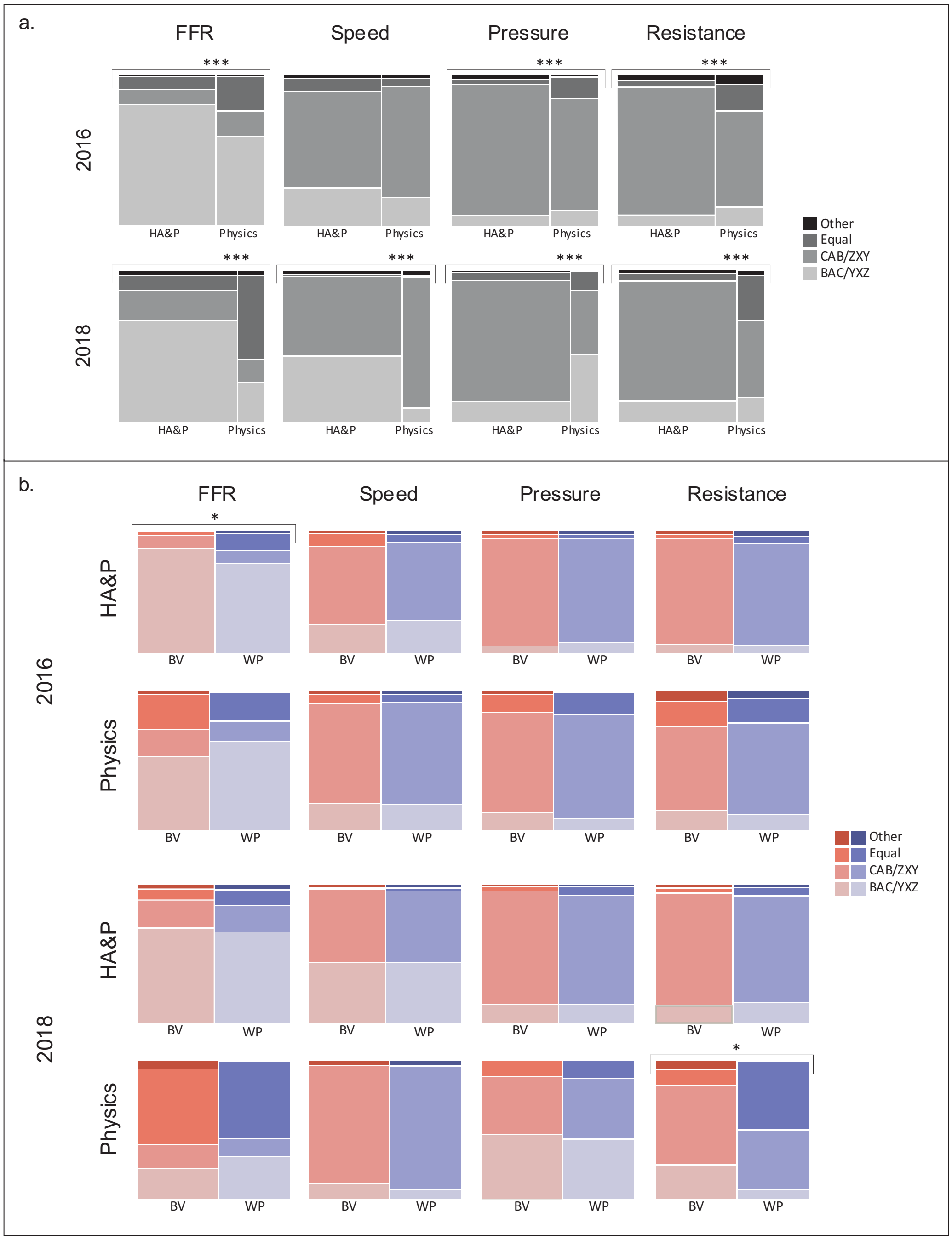

Figure 7. Student Ranking Responses to the FFR, Speed, Pressure, and Resistance Questions. The widths of the bars in these mosaic plots represent the proportions of students that (in Figure 7a.) were enrolled in either HA&P or physics and (in Figure 7b.) received either a BV or a WP version of our prompt. The heights of the bars represent the proportions of each ranking response (Other, Equal, CAB/ZXY, and BAC/YXZ) given in each population. Figure 7a. Comparing student ranking responses collected from HA&P students to responses collected from physics students within the same year, irrespective of assessment version. *P* values determined by two-sided Fisher's exact test with a Bonferroni corrected alpha level of 0.004 (***, $P < 0.001$). Figure 7b. Comparing student ranking responses collected from students given the BV version to responses collected from students given the WP version within the same class. *P* values determined by two-sided Fisher's exact test with a Bonferroni corrected alpha level of 0.004 (*, $P < 0.05$).

In 2016, the speed question came after the FFR. Based on the explanations students provided, we had reason to believe students were using the same reasoning to answer both the speed and FFR questions. We decided to switch the order of these two questions in 2018. Because students were likely more familiar with the concept of speed than they were FFR, we thought that if students were presented with the speed question after the FFR question, they may be more likely to recognize that those questions were asking students to reason about different concepts.

To determine how this order impacted student responses, we compared student responses to the speed question from the 2016 HA&P course with responses from the 2018 HA&P course (irrespective of prompt version) using a Fisher's exact test with a Bonferroni correction (alpha level of 0.004). We found that HA&P students in 2018 did provide significantly different responses than students in the 2016 course ($P < 0.0001$). We compared responses to the speed question from the 2016 physics students to responses from 2018 physics students and after correcting for multiple comparisons, there was no significant difference in responses observed (*unadjusted* $P = 0.038$, *adjusted* $P = 0.45$).

Comparing Responses Across Versions

We compared student responses to two versions of an isomorphic assessment to investigate how context would affect student responses. In 2016, the HA&P students that answered the BV version provided different rankings to the FFR question compared to the HA&P students that answered the WP version (Figure 7b). We found that of those students who received the BV version of our assessment, more students responded with a ranking of BAC compared to those students who received the WP version of our assessment. The second instance of a context effect was observed in 2018 with the physics students. We found that of those students who received the WP version of our assessment, fewer students responded with a ranking of YXZ and more students provided a ranking of equal compared to those students who received the BV version (Figure 7b). To summarize, in all but two cases, there was no evidence of a context effect in student responses. However, in the two instances mentioned above, there was a significant difference in the responses students provided when they were asked to reason about the BV version compared to the WP version.

Coding Student Explanations

During our initial coding, we observed a great deal of variation among the reasoning students provided (Table 10). This variation occurred within and across courses and assessment versions and was indicative of all four sub-questions (FFR, speed, pressure, resistance). Some students wrote substantial responses that did provide valuable insight into student thinking (Table 10, Example F). However, many responses were minimal in nature and we were hesitant to make any interpretive claims of student thinking from such limited evidence (Table 10, Example A).

Table 10. Examples of Reasoning Provided in Response to the Speed Question, Observed During Initial Phase of Coding (40 HA&P, 40 physics).

Example	Course, Version	Stated Reasoning
A	HA&P, WP	“because that’s what I think…resistance, pressure”
B	HA&P, BV	“the friction against the walls of the vessel slow down the flow”
C	HA&P, WP	“the more flow that is allowed through, the faster the liquid will go”
D	Physics, BV	“smaller diameter = more pressure = faster speed”
E	Physics, BV	“the smallest diameter will have the highest speed because it is trying to compensate for the increased pressure”
F	Physics, WP	“It’s like with a hose. If you just let it run, it just flows but if you put your thumb over the end of the hose the water comes and faster w/ a greater force.”

Further, while attempting to carry out our thematic analysis, a number of disagreements developed during those initial rounds of coding. For example, there were multiple instances where the biologists and physics disagreed on how students were using the word “flow”. Biologists argued that in some instances, students used the word “flow” in manner to suggest they were thinking about a volume and there was no evidence to suggest they had an awareness of a rate (Table 10, Example C). Physicists argued that students were likely taking shortcuts while writing their explanations and when they used the word “flow” it was reasonable to assume they were cognizant of a rate.

Because of the considerable variation in the quality of student responses and the multiple disagreements persisting within our interdisciplinary coding team, we felt as though these explanations collectively could not be used as evidence of student reasoning. While we were unable to make substantive claims about student reasoning, the conversation among the coders yielded valuable insights and serves as the foundation for subsequent qualitative investigations (see Study 2, Chapter 3 and Slominski et al., *in revision*).

Discussion

Differences Across Courses

There was a significant difference in the way students in HA&P responded to our prompt compared to the way students in physics responded in nearly every instance across the two years of data collection (Figure 7a). Our data was collected after students had received formal instruction on the topic of fluid dynamics and after students had completed over 2/3 of their respective course. Therefore, our data suggests students leaving an introductory HA&P course have different ideas about fluid dynamics than students leaving an introductory physics course or they framed the problem differently. While our evidence cannot directly attribute these differences to instruction, our previous work (Chapter 3 and Slominski et al., *in revision*) does reveal distinct differences in the ways experts from biology and physics think about the basic ideas that govern fluid dynamics. Knowing that experts from biology and physics rely on different ideas and types of knowledge when solving these problems, it is reasonable to hypothesize that students in these introductory courses are being introduced to at least some disparate ways of reasoning about fluid dynamics.

We also found evidence to suggest students in HA&P struggle to see the difference between speed and fluid flow rate. After switching the order of the speed and FFR questions on our prompt for the 2018 data collection, we saw a significant difference in the ways students in HA&P responded. To our knowledge, there was no substantial changes made in the HA&P instruction from 2016 to 2018 and the student population remained the same in regard to course pre-requisites and majors served. We draw two conclusions from this finding. First, even after instruction, students in HA&P have difficulty discerning the concept of rate. This claim comes from students providing the same rankings and reasoning to questions that ask for speed and FFR. Students also provided language to suggest they considered ‘flow’ to be representative of a volume, not a rate (Table 10, Example C). Secondly, our data align with previous works that claim an assessment’s design and surface features impact student reasoning (Gouvea & Simon, 2018).

Context Effects on Novice Reasoning

We observed few instances of student reasoning being affected by item context (Figure 7b). Of the 16 possible comparisons, only two indicated a significant context effect. We interpret this finding to mean context does impact student reasoning of fluid dynamics, but its effect varies depending on situational factors. In our 2016 dataset, HA&P students were affected by context when answering the FFR question, however, we did not see a similar pattern in the 2018 dataset. Bearing in mind that students struggled to discern the difference between speed and FFR, it is possible that a substantial proportion of HA&P students were confused by the concept of FFR and hence, their reasoning was more likely to be swayed by the surface context of our assessment (BV or WP context).

Similarly, physics students' responses to the resistance question were also significantly different across versions in 2018. Those students who received the BV version provided responses more similar to those provided by HA&P students. Findings from our previous work indicate physics experts do not teach the concept of resistance in conjunction with fluid dynamics (Chapter 3 and Slominski et al., *in revision*). Further, the reasoning physics students provided often indicated students were unclear on what was meant by the term 'resistance'. Therefore, we can deduce physics students had limited formal knowledge of resistance when completing our assessment and thus, were more likely to be impacted by the context included in our assessment.

Taken together, these findings suggest students are more likely to be impacted by context effects when they have less knowledge about a particular topic. This claim aligns with earlier work that suggests novice students are more likely to be impacted by surface context than more expert-like students (Chi et al., 1981).

Interpreting Student Reasoning

While attempting to code student explanations, we observed what appeared to be a number of patterns across the data. In addition to the observations described above, we saw evidence of what could be interpreted as teleological or needs-based reasoning (Table 10, Example E). In our coding discussions, the biologists often found the language and phrasing students used to be reminiscent of teleology, though because of the diversity of quality and effort observed across responses and the limitations of students' metacognition reflection abilities, we felt unable to quantify the extent to which students use teleological reasoning with completing our assessment. In contrast, the physicists did not observe nearly as many teleological explanations during their individual reading of the data.

In addition to teleological ideas, many students also seemed to draw on real-world examples or their own experiential knowledge when explaining their reasoning (Table 10, Example F). These kinds of explanations were not highly observed in our initial analysis, though when students used these examples, they were often quite explicit with their ideas.

We also observed many students articulating relationships between variables like diameter, speed, pressure, etc. (Table 10, Example D). Sometimes these relationships encompassed two variables, other times, students would include three or four variables. In many cases, students appeared to be using shortcuts while writing out these relationships and those shortcuts made it difficult to discern if the students were aware of the mechanisms driving those relationships.

In the scenarios described above, we had some evidence to suggest students were using ideas of teleology, superficial relationships, and real-world knowledge to complete our prompt. However, we felt our study design limited our ability to make interpretive claims based on the reasoning students provided.

While our initial analysis of student explanations cannot confidently answer our second research question, it does better situate our question in the existing body of discipline-based education research literature. Our early analysis of student reasoning suggests students are using a teleological or needs based form of reasoning about our complex system (Table 10, Example E). This observation aligns with data from earlier works exploring student difficulty in HA&P, that assert students feel inclined to use teleological sense-making when reasoning with HA&P content and struggle with causality (Chapter 2 and Slominski et al., 2019; Sturges & Maurer, 2013; Michael, 2007). Our early analysis of student explanations also aligns with work from the systems thinking body of literature that argues novice learners struggle with causality and emergence when reasoning about complex systems and look for agency in the system (Grotzer et al., 2017; Chi et al., 2012; Levy & Wilensky, 2008; Chi, 2005). We also observed students calling to mind their experiences with the natural world and applying them to the somewhat different scenario we depicted in our prompt. This application of internalized ideas and experiences to a new setting may be similar in nature to the ideas and notions presented in the phenomenological primitive and resource literature (Hammer et al., 2005; Hammer & Elby, 2003; diSessa, 1993; 1988).

In order to better understand how our early observations fit within these existing bodies of work, we need to better capture student thinking while they move through our assessment. In Study 2, we used semi-structured think-aloud interviews in an attempt to unpack the explanations offered by students in Study 1. More specifically, we used these interviews to describe the ideas and reasoning strategies HA&P students employ when thinking about fluid dynamics. We also explore how the activation of those ideas may be different when students are asked to reason about fluid dynamics in two different contexts, a HA&P context (blood and vessels) and a non-HA&P context (water and pipes).

Study 2

Methods

To determine the effect of item context on student reasoning, we conducted 12 semi-structured think-aloud interviews using our fluid flow prompt (Figure 6) in the spring of 2018. Because this dissertation focuses on student difficulties in HA&P (and not physics), we designed our interview study to investigate HA&P student reasoning only. Further, all the explanation patterns of interest observed in Study 1 were observed amongst the HA&P population. Therefore, omitting the physics students from our study would not impact the likelihood of those themes emerging in our interview population. Students were solicited via email from the second course in the introductory HA&P series at a large, Midwest research institution. In relation to the HA&P instruction timeline, the interviews were conducted approximately one week after students had received relevant instruction on the topics and approximately two days prior to a summative exam containing that material. In Spring 2018, data collection for Study 2 occurred before data collection for Study 1 and all Study 2 participants were removed from Study 1 as they would have been primed by participating in the interview prior to taking the written diagnostic.

Six undergraduate participants were randomly assigned the BV version of our prompt and the other six were assigned the WP version of our prompt. All students were provided with a handout containing both the introductory text and explanatory figure of the BV or WP prompt to ensure students always had access to the situational variables articulated in our prompt. During the interview, students were asked to first provide an answer to one of the four sub-questions (i.e. speed, fluid flow rate, pressure, and resistance) and then explain their reasoning. Students were then asked follow-up questions intended to get students to elaborate on the explanations they provided. This process was repeated for each of the four sub-questions.

The interviews also contained an unrelated task and the data presented here were collected during the first half of the interviews. Each student was given $20 as compensation for their participation in our study and all interviews were completed in under 25 minutes. The interviews were conducted by TS and both the audio and video was recorded in the event students physically interacted with the BV or WP prompt when explaining their reasoning. All transcripts were transcribed using Rev Transcription.

Analysis

We used thematic analysis (Braun and Clarke, 2006) to identify broad themes in our transcript data. Below we describe each phase of our analysis.

Analysis Phase 1: Initial Reading

Our analysis of the interview data began with an initial reading of all 12 interview transcripts by TS (biology expert), JM (biology expert), and WC (physics expert). During this initial reading, we independently read each of the 12 transcripts and took notes on our early observations. In particular, we made note of the salient terms, phrases, and relationships students used in their explanations. After individually reading and taking notes on all 12 transcripts in their entirety, we came together to compare notes. We discussed our individual observations and compared across our notes to identify the similarities and differences of our initial observations. We clarified all differences that were disciplinary in nature and we made note of early themes and patterns present in the transcripts.

Analysis Phase 2: Generalizing Themes

Phase 2 of our analysis was completed by TS, JM, and WC. Using the insights gained from Phase 1, TS generated a list of themes based on the early codes that emerged in Phase 1. TS, JM and WC refined those codes. Codes were sorted to identify potential relationships between individual and groups of codes. Identifying these relationships gave way to identifying the broader themes across the data. This initial sorting resulted in 10 initial coding themes. During our group discussion, we modified the initial list of themes and combined two themes to result in 9 themes. We crafted descriptions for each of these themes and constructed a coding guide.

Analysis Phase 3: Evaluating Themes

Once a list of themes was generated, TS and WC read all 12 transcripts again and coded each transcript using the established rubric. JM also individually coded three transcripts and compared their coding results with those generated by TS and WC. Any discrepancies in our coding were discussed until we reached an agreement. These discussions often resulted in 1) slight modifications to our theme descriptions, 2) the combining of two themes into one theme, and 3) the removal of one theme. Our final coding rubric resulted in 7 distinct themes (Table 11).

Results

Through thematic analysis of 12 interviews, we identified seven patterns in student reasoning. Below, we briefly expand on each pattern as presented in Table 12.

Table 11. Coding Rubric Developed Through Thematic Analysis.

Theme	Theme Description	Example
Difficulty with Fluid Flow Rate	Students may be unable to provide a definition of fluid flow rate. Students may confuse fluid flow rate with speed or volume.	Examples include referring to resistance as a push, friction, pulling, etc.
Difficulty with Resistance	Students may be unable to provide a definition of resistance or may provide a definition that does not align with the HA&P textbook (a force that opposes movement).	Examples include referring to resistance as a push, friction, pulling, etc.
Human Anatomy & Physiology	Students may make explicit use of HA&P class material or resources (e.g. equations, definitions, instructor, etc.). Students may make direct references to examples and analogies using HA&P content not provided by the prompt.	If given BV version, student may refer to the heart, capillaries, cardiac output, vasoconstriction, etc. If given the WP version, student may refer to blood, vessels, heart, etc.
Non-Human Anatomy & Physiology	Students make use of examples and analogies that do not contain HA&P content.	Examples include a water hose, a dam, a balloon, etc.
Physics and/or Math	Students make explicit use of material or resources from a physics or math class	Examples include equations, definitions, or course instructor.
Simple Relationship	Student responses make use of a simple relationship between two or three variables. Students articulate that a change in one variable results in a change in another variable. These relationships do not include a mechanistic relationship.	"if you increase ____, the ____ would decrease" "the wider the opening, the slower it comes out"
Teleology	Students use explanations that suggest they are thinking about phenomena in terms of their purpose, not in terms of causal mechanisms. Students use phrases that focus on the needs or goals of the broader system.	Examples include phrases containing "needs to", "has to", "wants to", "in order to", etc.

Table 12. Coding Results of Student Interviews.

	Student	**C**	**E**	**F**	**I**	**P**	**Q**	**A**	**B**	**D**	**H**	**J**	**N**
	Prompt Version	**BV**	**BV**	**BV**	**BV**	**BV**	**BV**	**WP**	**WP**	**WP**	**WP**	**WP**	**WP**
Themes observed*	**Speed**	N_HA&P SR	SR	P/M SR	SR	SR	P/M	HA&P SR	DwFFR HA&P SR	P/M SR	N_HA&P SR	HA&P SR	HA&P SR
	FFR	SR	SR	SR TEL	SR	DwFFR SR	P/M TEL	SR	HA&P SR	DwFFR SR	N_HA&P SR	HA&P SR	DwFFR
	Pressure	HA&P SR TEL	HA&P SR TEL	SR	HA&P SR TEL	SR TEL	P/M SR	N_HA&P SR TEL	SR	SR	N_HA&P SR	SR	SR
	Resistance	DwR HA&P SR TEL	DwR HA&P SR	DwR HA&P SR	HA&P SR TEL	DwR HA&P SR	DwR HA&P P/M SR	DwR N_HA&P SR	DwR HA&P SR	DwR SR	N_HA&P SR	DwR N_HA&P SR	DwR N_HA&P SR

*Our coding only recognized the presence of each theme in the responses to each of the four sub-questions - our approach did not account for frequency of each theme.

DwFFR – Difficulty with Fluid Flow Rate
DwR – Difficulty with Resistance
HA&P – Human Anatomy & Physiology
N_HA&P – Non-Human Anatomy & Physiology
P/M – Physics and/or Math
SR – Simple Relationship
TEL – Teleology

Difficulty with Fluid Flow Rate – Four of the twelve students interviewed struggled with the concept of FFR. All of these students gave responses to indicate they consider FFR and speed to be the same concept.

Difficulty with Resistance – Ten of the twelve students interviewed struggled to use or describe resistance in a manner consistent with the definition provided by their HA&P textbook (a force that opposes movement). We observed varying degrees of difficulty, with some students offering alternative descriptions of resistance (Students A, B, C, E, J, and Q), offering description that used words like friction or "something". Some students explicitly stated they did not know what was meant by the term resistance (Students D, F, N, and P) and later offered an alternative description of the term.

Human Anatomy and Physiology – All students that received the BV prompt incorporated additional HA&P content when responding to the prompt. These students often included structures like the heart and capillaries or introduced new functions to the system like vasoregulation. For those students who received the BV prompt, the inclusion of HA&P content did not occur until the second half of the interview after reaching either the pressure or resistance question. Four out of the six students who received the WP prompt also spontaneously introduced HA&P content despite being asked to reason about water and pipes. When these four students introduced the HA&P content, they did so at the start of the interview. We observed these students introduce the HA&P in one of two ways, either making an explicit attempt to use HA&P context as an example, or more subtly using HA&P language (e.g. vessel) as a replacement for the WP language (e.g. pipe).

Non-Human Anatomy and Physiology – Only one BV student used a non-HA&P example when explaining their reasoning (Student C). Four WP students used non-HA&P examples when explaining their reasoning, some more than others. For example, Student H used these examples at every point in the interview whereas Students J and N only used these examples at the end of the interview. Overall, these examples and analogies were used more often when responding to the resistance question, compared to the other three sub-questions. At no point did any student use both a non-HA&P example and HA&P content in response to the same sub-question.

Physics and/or Math – We found few instances of students making explicit mention of content or resources from their math or physics courses. Two BV students made mention of math or physics concepts and one WP student. Student Q used knowledge and resources acquired in math and physics courses extensively throughout the interview, though this student was atypical as they had already completed a bachelor of science degree and had completed coursework in physics, engineering, thermodynamics, and aerodynamics.

Simple Relationship - Students used simple relationships in nearly all of their responses. We observed no effect of prompt version on student use of simple relationships. We only observed one student, Student Q, make use of use what appeared to be a more complex, mechanistic systems thinking approach. Instead of thinking about the relationship between two or three variables in isolation from the rest of the system, this student articulated how these relationships emerge from other relationships that exist throughout the system.

Teleology - Students were more likely to use teleological reasoning when presented with the BV prompt. Every student that received the BV prompt used teleological reasoning at least once during the interview. Only one student (Student A) used teleological reasoning in response to the WP prompt. Teleological responses were used more frequently in response to the pressure and resistance questions compared to the FFR question. We did not observe any students using teleological reasoning in response to the speed question.

Discussion

We conducted think-aloud interviews to investigate how HA&P students reason about fluid dynamics. Thematic analysis revealed the HA&P students we interviewed struggled to reason with the concept of FFR, an important concept for understanding cardiovascular physiology in HA&P (Table 12). Similarly, HA&P students experienced difficulty using the concept of resistance. Despite receiving formal instruction on both of these concepts prior to completing this interview, students still had trouble using these concepts during our interview.

To determine how item context effects student reasoning, we used two versions of an isomorphic interview protocol, one describing a system with blood and vessels and the other describing a system with water and pipes. We found that the students that received the BV version of our prompt were more likely to use teleological reasoning than those students who received the WP version of our prompt. Students who received the WP version of our prompt were more likely to use non-HA&P examples and analogies when reasoning about our prompt than those students who received the BV prompt. Context effects did not appear to affect students' use of simple relationships, as all students in our study demonstrated this type of reasoning strategy at various stages during the interview. The results of this study align with previous works that suggest item context can impact student reasoning (Gouvea & Simon, 2018; Smith et al., 1994).

General Discussion

We used a mixed methods approach to gather more insight into how HA&P students reason about fluid dynamics and how context features may affect that reasoning. Thematic analysis revealed a number of parallels between the reasoning observed in the interview setting and our review of the written responses students provided in Study 1.

Difficulty with Fluid Flow Rate

Our review of the written explanations in Study 1 suggested H&P students struggle with the concept of FFR. Our coding of student interviews confirmed this: students do have difficulty interpreting and applying the concept of FFR when reasoning about a complex system (Table 12). The interview setting enabled us to gain deeper insight into the reasoning behind student predictions and we observed multiple instances of students confusing FFR with speed:

Interviewer: "Is there a difference between speed and fluid flow rate?"

Student P: "I'd say yes."

Interviewer: "Okay, what would the difference be?"

Student P: "Well ... maybe not. I feel like they kinda are the same. They effect each other."

The quotes above indicate Student P struggled to differentiate between FFR and speed. The insights gained from students P, B, D, and N align with the context effect observed in Study 1 (Figure 7b.) – there was an effect of item context on student rankings for the FFR question. The data presented here indicate HA&P students are not proficient in their use of FFR (even after instruction) and because previous research suggests novice learners are more likely to be affected by item context (Chi et al., 1981), we conclude the differences we observed in Study 1 were the result of a context effect.

Teleological Reasoning

We also found ample interview evidence to suggest the patterns we observed in our review of the student explanations collected in Study 1 (teleological reasoning, real-world examples, and simple relationships; Table 10) were representative of common strategies students use when reasoning about fluid dynamics. All students who received the BV prompt used teleological reasoning at some point during the interview (Table 12). When interpreting the written explanations, we were unable to probe student thinking and determine if the teleological phrases were strongly held ideas. In the interview setting, we were able to ask follow-up questions that challenged the teleological phrases students used to better understand if these phrases were merely the product of conversational norms (Trommler et al., 2018) or if they were indicative of the way students conceptualize the phenomena:

Student C: “…if there's irregular resistance, it creates turbulence, so it doesn't go necessarily the direction you want to. It kind of like, circular currents that slow it down.”

Interviewer: “If you had to define resistance, what would you say?”

Student C: “Well, we're talking about resistance in regards to blood flow, so I say resistance ... Well, in this case, I would say it's almost friction. Resistance is an inverse force, because we were going in one direction and we want to go in the other direction. Anything that would slow down blood.”

Interviewer: “Okay. When you said, we want the blood to go in other direction. What causes that? Or, why does that happen?”

Student C: “Well, the heart pumps, there's a pulmonary circuit and a systemic circuit. What causes it to go one direction?”

Interviewer: “Just to clarify, what do you mean by the blood wants to go in one direction?”

Student C: “Well, we want ... because it goes to arteries, to capillaries, to veins. So you want blood to move away from the heart. And it goes with the pressure gradient, so it's moving away from the heart. And it's moving to all your tissues to exchange products with them.”

In the example above, Student C uses multiple teleological phrases (underlined). When asked to explain these teleological phrases, Student C does not offer a non-teleological alternative or give any indication they are aware of the actual mechanisms driving blood flow. Instead, Student C uses additional teleological phrases and continues an explanation that is goal-driven. We consider this exchange (and others like it) as evidence of students' strongly-held, teleological views of physiological phenomena. Consistent with previous literature on student difficulties in HA&P, our data suggests students do reason about fluid dynamics (a complex system) in a manner that prioritizes the resulting function or goal of the system as opposed to the underlying causal mechanisms from which the function emerges (Chapter 2 and Slominski et al., 2019; Slominski et al., 2017; Badenhorst et al., 2016; Sturges & Maurer, 2013, Cliff, 2006; Michael et al., 2002; 1999; Modell, 2000; Michael, 1998).

Real-World Examples

Five students in our interview study made use of real-world (or non-HA&P) examples when explaining their reasoning (Table 12). Similar to written explanations from Study 1, many of these examples were focused on students' real-world experiences with a water hose:

> Student H: "Honestly, for me I thought about cleaning off cars with a hose. The smaller the area that you have, the more pressure shoots out, and then the faster it will come out. The wider the opening, the slower it comes out, because it's not as much built up pressure trying to get out."

Interview students also made mention of other real-world experiences like living near a dam, filling up a water balloon, or pouring a bottle of wine. In all of these cases, students were drawing on their previous experiences with the natural world to explain the problem at hand. Due to the prevalence of this experiential knowledge in our interview transcripts, especially in those given the WP prompt, we consider the examples provided in the written responses to be reflective of the kinds of informal knowledge structures students rely on when reasoning about fluid dynamics.

Simple Relationships

All of the twelve students interviewed made use of simple relationships while responding to our prompt and most of these students relied on these relationships for each of the four questions in our interview (Table 12).

Student I: “Because the diameter on vessel C is bigger, so it will have more blood coming through since the diameter is bigger. And then X is in the middle, because it has 3 cm, and then Y is last because the diameter is the smallest.”

Student N: “I would say the size of the exit is what's causing the resistance. The smaller the exit, the higher the resistance.”

The examples above are representative of transcript passages coded as containing a simple relationship. Similar to responses in Study 1 (Table 10), analysis of our interviews revealed students making superficial associations between two or three structures or variables in the system (at the level of the tissue). When probed further, most all students failed to offer a mechanistic explanation and continued to articulate a more surface-level understanding of the system at hand:

Student E: “I'd say vessel C would have the most because it has the largest diameter that it opens, so more would be rushing out faster.”

Interviewer: “Okay. Then what would be causing it to rush out faster?”

Student E: “I guess just since it has a bigger opening, I feel like it would just have to come out the fastest.”

Interviewer: “Okay. What do you mean it would have to?”

Student E: “I guess the most fluid would come out just because there's a bigger opening.”

Despite being prompted, Student E fails to offer any reasoning that would suggest a mechanistic understanding of the system. This student is unable to identify the physical causes that results in the movement of blood nor do they discuss the event at a microscopic grain (Russ et al., 2008). These results indicate HA&P students are likely limited in their systems thinking abilities. Consistent with existing work on systems thinking, the students interviewed in this study struggled with causality and appear to have misinterpreted the emergent processes driving fluid dynamics as direct and linear (Scott et al., 2018; Chi et al., 2012; Sommer & Lücken, 2010; Hmelo-Silver et al., 2007; Jacobson & Wilensky, 2006; Chi, 2005). Due to the similarities between the interview transcripts and student responses from Study 1, it is likely students in both our sample populations lack systems thinking skills and an ability to reason mechanistically about a complex system.

The Impact of Context and Framing on Student Reasoning

Our coding revealed interview students introduced new HA&P content in response to both versions of our prompt (Table 12). Applying the framing and resources theoretical framework to our observations, our coding suggests most of the students interviewed applied a HA&P-like frame at some point during our interview. The students that received the BV prompt noticed the biological content embedded in the prompt and then seemed to embrace that content, further contextualizing their thinking in HA&P content:

Interviewer: “Okay. So the next question I have is, can you order the pressure of the blood in the vessels at points X, Y, and Z?”

Student I: “Probably go Y, X, Z.”

Interviewer: “Okay, and why do you say that?”

Student I: “Since D, E, and F are all the same with pressure, since it's getting smaller the blood's still going to want to go through at the same pressure, so it's going to go up with Y because it doesn't have as much room. And then, the flow rate at Z is going to be more fluent, so it won't have as much pressure going through the vessel.”

Interviewer: “Okay, and what did you … what do you mean by the blood is going to want to go through?”

Student I: “Well, starting from the left side to right side, it's going to want to continue to come from left to right, so it will still have to travel. But, since Y is the smallest, the pressure's going to be the highest.”

Interviewer: “Okay, and what's making it have to travel?”

Student I: “I don't know. Oxygen coming through the blood, I mean like the blood viscosity and the pressure of the blood.”

Hammer and colleagues (2005) describe framing a scenario or problem as the act of interpreting that scenario in terms of the expectations and behaviors an individual has formed based on previous experience with similar events. Near the end of the exchange above, Student I introduced a new functional component to the system in the form of oxygen exchange. For Student I, applying this HA&P

frame resulted in them further situating this problem in the physiology content and expanded the system to encompass more aspects of the cardiovascular system (Hammer et al., 2005).

A hallmark of the framing and resource theoretical framework is the perspective that reasoning is dynamic in nature (as opposed to stable and constant), meaning students will activate different suites of conceptual resources based on how the task is framed (Gouvea and Simon, 2018). This belief aligns with the patterns we observed in all of our interviews - applying a HA&P frame often resulted in the introduction of teleological reasoning strategies (Table 12). We did not observe students in the WP group employ teleological reasoning strategies without first framing the problem with an HA&P frame. This emergence of teleological reasoning and only in conjunction with a HA&P frame indicates that contrary to much of the existing work on teleological reasoning, students do not have a stable teleological cognitive construal that would be activated anytime they are faced with a complex system (Coley & Tanner, 2012; 2015; Kelemen, 1999a; 1999b). Instead, our results indicate teleological reasoning may operate in a manner similar to what is understood of conceptual resources - activating again and again and ultimately becoming locally coherent in relation to biological frames (Hammer et al., 2005).

For those students who received the WP version of our prompt, we did see evidence of them utilizing a HA&P frame, though this frame revealed itself in a slightly different way. Instead of waiting until the pressure or resistance questions to make their HA&P framing more explicit (Table 12), the WP students that used an HA&P frame revealed that frame at the start of the interview. For some students, the introduction of HA&P content to the interview was explicit, like that presented by Student A:

> Student A: “I'm trying to remember ‘cause I remember we were talking about this like with blood vessels. Like that's what it makes me think of. I want to say that the middle one's the fastest.”

In this case, Student A directly called the interviewers attention to their introduction of HA&P content. Other students introduced HA&P more subtlety:

> Student J: “The speed for water would be, pipe E would be going the fastest. Then D, then F.”
>
> Interviewer: “Okay. Why do you say E is the fastest?”
>
> Student J: “Its diameter is the smallest, so the pressure is higher.”

Interviewer: “Okay. What does pressure and speed have to do with one another? What's that relationship?”

Student J: “The relationship?”

Interviewer: “Yeah. Why does the pressure being higher matter?”

Student J: “The smaller the vessel, the higher the pressure usually is.”

Despite being asked about water and pipes, Student J introduces the term ‘vessel’ without any prior mention of HA&P content or any direct mention of using that frame. However, later in the interview Student J makes his framing more explicit and offers an HA&P example to aid in his articulation of his reasoning:

Interviewer: “Order the pipe scenarios based on their fluid flow rate. Fluid flow rate meaning the volume of water flowing per unit of time.”

Student J: “Okay. Pipe F would have the most volume going out. Then pipe D and then E.”

Interviewer: “Okay. Why do you say that?”

Student J: “It's kind of.. I'll compare it to the heart, and, are you familiar with the heart?”

Interviewer: “Yeah. Tell me how it works into your example.”

Student J: “Call the first part of the pipe the left ventricle. Then when it contracts, call that the aorta. The aorta takes a large amount of blood out. Once it contracts, there's not much blocking it. The aorta, it expands when it needs to. Then if it didn't expand, there'd be less blood going out.”

Similar to the HA&P framing observed in the BV students, Student J introduces additional HA&P structures and functions as they are considered applicable and important for the scenario at hand. In conjunction with the framing and resources framework, Student J’s introduction of and reliance on HA&P content as a means of directing their reasoning may indicate they have framed this problem as a biological problem.

If the WP students did frame our interview prompt using a HA&P frame, the question remains, what caused these students to apply a HA&P when there was no surface context encouraging them to do so? While our data cannot answer this question directly, previous work on context and framing would suggest there could have been some feature (other than the surface context of blood and vessels or water and pipes) of our prompt or the interview that subconsciously encouraged students to frame this prompt as a biology or HA&P prompt (Gouvea et al., 2019; Hammer et al., 2005). Perhaps it was something about the visual we used to depict our system or maybe the focus on fluids reminded them of the instruction they had received in HA&P class the days prior to the interview. Students may had HA&P class earlier that day or they may have been studying HA&P material before coming to the interview. These recent experiences with HA&P content could result in students being more likely to see similarities between HA&P content and a non-biological system question. It is also possible that these HA&P students are emerging experts in HA&P and biology more broadly. In this case, the adoption of a HA&P frame in a non-biological context may be evidence of developing expertise. Further qualitative work would be needed to determine with a large degree of certainty what encouraged students to apply a HA&P frame to the WP prompt.

We also observed instances where students appeared to be using a non-biological frame to reason about our prompt. As stated previously, Student Q had an atypical background compared to the other students interviewed in this study and their response to our interview prompt appears to embody those differences in experience:

Student Q: “Terminal end, the fastest is vessel B, second fastest is vessel A, third fastest is vessel C.”

Interviewer: “Okay, and why did you say that ranking?”

Student Q: “Because of the dead white guy's principles that says as liquid … conservation of volume flow of liquids, volumetric flow of liquids through enclosed systems, and so the speed of flow, velocity of flow must increase as the radius of the vessel decreases.”

Interviewer: “Okay. Where did you learn that?”

Student Q: “In thermodynamics class at the US Naval Academy.”

Contrary to the other students in our interview study, Student Q articulated a focus on principles and theories. This behavior could be the product of Student Q applying a non-biological frame, likely a frame closely associated with physics or engineering. Interestingly, later in the interview Student Q made direct use of HA&P content (Table 12) when responding to the questions regarding resistance. It is important to note, the term resistance is not used in relation to fluid dynamics in physics curricula (Chapter 3 and Slominski et al., *in revision*) and thus, it is possible that the topic of resistance has caused Student Q to reframe the problem in a way that aligns with their experiences and beliefs of that term (an HA&P frame).

Lastly, every student in our study made use of simple relationships when reasoning about our prompt. The pervasiveness of this strategy suggests some contextual feature of our prompt may have encouraged students to frame this prompt in a similar manner. Due to the nature of our prompt, it is possible all students, even those previously identified as having applied a HA&P or non-biological frame, subconsciously (or even consciously) recognized this as a sort of simple systems problem. By framing this as a simple systems problem, students would likely apply the set of expectations and beliefs they typically ascribe to simple systems problems (Hammer et al., 2005). If those expectations, beliefs, and behaviors were similar to those of an individual with limited system thinking skills, we would expect an emphasis on linear, surface-level relationships (Chi et al., 2012) as opposed to a focus on the causal and emergent mechanisms actually occurring within the system (Scott et al., 2018; Chi et al., 2012; Sommer & Lücken, 2010; Russ et al., 2008; Hmelo-Silver et al., 2007; Jacobson & Wilensky, 2006). This expectation aligns with our observations of the data (Table 12), suggesting HA&P students may have and employ a simple systems frame when faced with any problem that, regardless of surface context, focuses on a complex system.

Implications for Research

To our knowledge, there have been few studies to an interdisciplinary approach to investigate student understanding of cross-cutting STEM concepts at the undergraduate level. In the research presented here, we focused on one specific cross-cutting concept, fluid dynamics, and uncovered a stark difference in the ways students in HA&P and physics reason about fluid dynamics after receiving formal instruction. Future research should recognize the role cross-cutting concepts have in introductory instruction and work to repeat our approach focusing on additional cross-cutting concepts as defined by national documents (National Research Council, 2012).

Due to our sampling procedure, it is unclear if the patterns we observed in student reasoning is unique to our institution or indicative of the broader STEM undergraduate population. Future work is needed to determine if the differences in understanding of fluid dynamics between HA&P and physics students is specific to our university or if it persists more broadly. If these differences are representative of the broader university system, it is essential efforts be made to better understand how these differences in student understanding of fluid dynamics impact their learning at later points in their undergraduate career. Our previous work indicates the instructors of these courses may also differ in their approach to solving problems about fluid dynamics (Chapter 3 and Slominski et al., *in revision*) though we know very little about how fluid mechanics is taught in these courses. More work is needed to determine the cause of students' reasoning differences and better gauge how many other conceptual and instructional differences reside between HA&P and physics and between all other STEM disciplines.

The findings from Study 1 and Study 2 add to a growing body of research that indicates context features can impact student reasoning. We encourage future research on student difficulties to recognize the impact context can have on student thinking, and thus, the implications it can have for our interpretation of student difficulties research.

Our work emphasizes the importance of interdisciplinary collaborations across STEM education researchers. An interdisciplinary team was crucial for our study as all stages of this research relied heavily on insights gained from both disciplinary backgrounds. For example, the framing and resources theoretical framework is a useful tool for understanding how student reasoning varied with context. This framework has had little use outside of physics education research but, as our work demonstrates, can be used to explain how students reason about biological phenomena.

Implications for Instruction

Taken together, the results from Studies 1 and 2 have a number of implications for instruction. First, one of the most glaring findings of this work is that after instruction students in our HA&P courses and students in our introductory physics courses have very different ideas regarding fluid dynamics. This observation is concerning considering how many students are required to complete both of these courses (sometimes simultaneously) before they are able to move on to their professional programs. We know students struggle to reason about complex systems, but it seems we may be making it even more challenging by giving them conflicting instruction. We urge instructors to recognize this potential for conflicting instruction and check in with their students to see if and how they are able to reconcile the knowledge the gained in their physics courses with the that of their HA&P courses (and vice versa).

Our research also indicates students are likely receiving somewhat conflicting instruction regarding these topics (Chapter 3 and Slominski et al., *in revision*). We have no knowledge of whether and how students reconcile these conflicting ideas to generate a productive mental model of fluid dynamics. Further, if students receive conflicting instruction on the topic of fluid dynamics between HA&P and physics courses, it is possible there are other cross-cutting concepts that are misaligned between the various STEM disciplines. Administrators and instructors need to work towards breaking down the silos in which our respective disciplines are housed and begin to establish open lines of communication and collaboration between STEM instructors, especially those teaching at the introductory level.

Focusing more specifically on HA&P instruction, our research advocates for educators to move away from the more traditional notion of misconceptions and embrace a more dynamic view of student difficulties. Recognizing student may not be completely committed to a particular idea or reasoning strategy means instructors need to be more cautious when attempting to ascribe students' inaccurate responses to a particular reasoning approach. On a related note, our research, along with a growing collection of other works, suggests the language instructors use in their assessments can have substantial implications for the strategies students use to reason about those assessments and, ultimately, their overall performance. Instructors should be cognizant of the impact item context can have on student reasoning and recognize students' inaccurate responses may be the product of these context effects.

Conclusion

We used a mixed methods approach to understand how HA&P students reason about fluid dynamics and whether that reasoning was affected by item surface context. By sampling students from HA&P and physics courses, we were able to control for instruction effects and explore the role item context had on student reasoning using two versions of an isomorphic assessment. Our results indicate students in HA&P and physics reason about fluid dynamics very differently, even after formal instruction. We also found evidence to suggest context features may impact student reasoning when they are asked to reason with concepts they are struggling to master. Through a series of interviews, we found evidence to suggest HA&P students frame problems in a manner consistent with their experiences in HA&P and thinking about systems, even if those problems do not contain biological content. For those students asked to reason about biological content, this framing resulted in the application of teleological reasoning strategies. We also found evidence to suggest HA&P students are limited in their mechanistic understanding of fluid dynamics and rely on linear, surface-level relationships when reasoning about fluid systems.

This research adds to the growing body of work that recognizes the impact context features can have on student reasoning. Our work aligns with previous research that advocates for a dynamic-context sensitive view of student cognition and advocates for the framing and resources theoretical framework as a tool for understanding student reasoning in biology education research.

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CHAPTER 5. CONCLUSION

This goal of this dissertation research was to understand why students struggle to succeed in HA&P. Contrary to the common trend of research conducted in HA&P education, my research does not focus on specific difficulties students experience in learning one particular concept or unit. Instead, my research takes a wholistic approach, seeking a common thread that may underly the specific student difficulties we observe in the classroom and in the HA&P education literature. My pursuit of this research was informed by frameworks from biology education research, physics education research, and cognitive psychology, resulting in investigation of four potential sources of student difficulty in HA&P: teleological reasoning, context effects, framing and resources, and systems thinking.

Few studies have investigated students' perception of the cause of student difficulty in HA&P. To my knowledge, none of those studies have used a multi-site approach, and thus, are limited in their generalizability. It is unclear if the student challenges reported by researchers like Sturges and Maurer (2013) were population specific or due to the unique environmental effects at play at that single institution. Therefore, the first step in my investigation into student difficulties was to determine if the challenges students experience in HA&P are unique to any given institution or curriculum. In Chapter 2, I present the results of my replication study which explored both student and faculty perceptions of the difficulties in learning physiology (Slominski et al., 2019). By sampling fifteen different institutions from across the U.S., I was able to capture the perceptions of a broad population of students and faculty.

My results reinforce those reported by Sturges and Maurer (2013) as all the students in our sample identified the discipline as the primary driver of difficulty when learning physiology. More specifically, the students in our study and those sampled by Sturges and Maurer (2013) report both being inclined to use teleological reasoning and struggling to use causal reasoning as the two greatest barriers to their learning. Together these students reflect five different institutions which differ in class size, prerequisite requirements, and demographics; this diversity of institutions implies that the common difficulties students report (avoiding teleological reasoning and accurately applying causal reasoning) are likely not unique to any given curricula or instructional approach. Further, these results speak to a need to explore students' reasoning more broadly, rather than focusing on developing interventions for specific content pieces.

When considering what aspect of HA&P as a discipline might drive students towards teleological reasoning and away from causality, one might to consider that the context of humans sets HA&P courses apart from other STEM courses. Students have extensive personal experience with the human body and those experiences are often tied to an implicit goal of survival. Previous literature has established that surface features or the situational context used to articulate a problem or scenario can impact how a student reasons about that problem (Gouvea et al., 2019; Gouvea & Simon, 2018; Heredia et al., 2012; Nehm & Ha, 2011; Hammer et al., 2005; Smith et al., 1994). Therefore, I hypothesized that human physiology context itself may be impacting how students reason about the complex phenomena found in a HA&P course, and thus, encouraging the use of teleological reasoning over causal reasoning strategies.

To investigate this hypothesis in Chapter 4, I worked with an interdisciplinary team of discipline-based education researchers from biology and physics to develop two versions of an isomorphic prompt that could reveal the role of human physiology surface context features on student reasoning about a complex system. In order to isolate the effect of context on student responses, I needed to control for students' ability to answer questions about fluid dynamics. Students enrolled in the introductory algebra-based physics course receive formal instruction on fluid dynamics, making them an ideal contrasting study population to students enrolled in the introductory HA&P course. The initial results from this study (Chapter 4, Study 1) showed mixed support for the context hypothesis, with only two instances of surface context impacting student results.

However, because evaluating student answers to a written assessment is only a proxy for characterizing authentic student reasoning, I conducted a qualitative follow-up study (Study 2) that used think-aloud interviews to probe the effect of surface context on student reasoning. Thematic analysis of student interviews revealed patterns in student reasoning and, with the application of the framing and resources theoretical framework, I observed evidence of differential framing in response to the contextual differences of our interview prompts. I found evidence to suggest students frame a problem differently when it is presented using HA&P context versus non-biological context (Figure 8). I also found evidence to suggest that by framing a problem or scenario with a HA&P frame, students are more likely to employ teleological reasoning strategies. This finding goes against earlier works that argue students have a stable, teleological cognitive construal and would activate that reasoning approach anytime they are faced with a complex system (Coley & Tanner, 2015; 2012; Kelemen, 1999a; 1999b). Instead, this research suggests teleological reasoning may function more like an epistemological or conceptual resource and be likely to activate in conjunction with a HA&P frame (Hammer et al., 2005) (Figure 8).

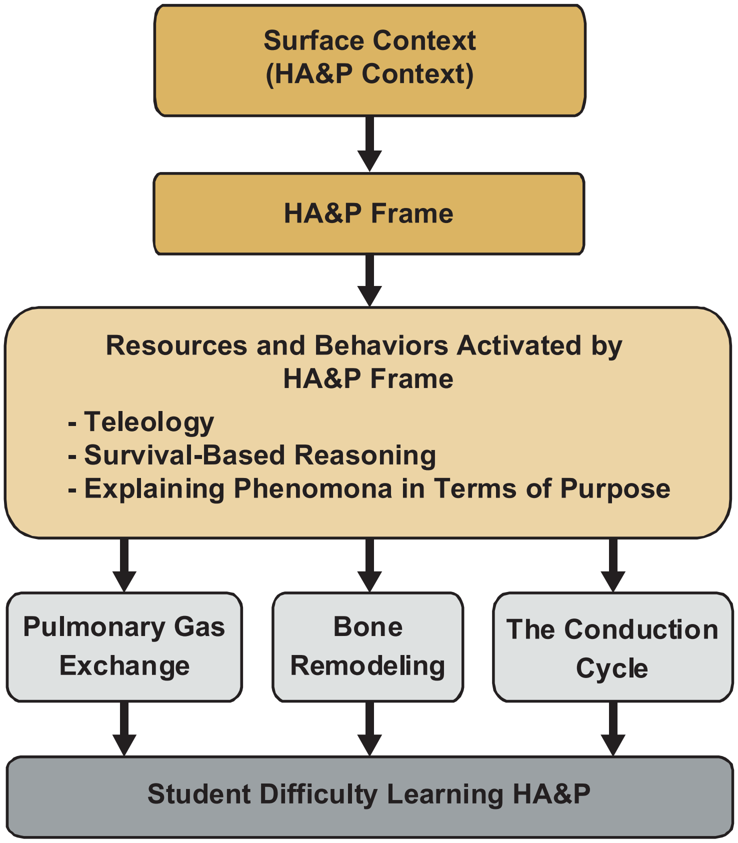

Figure 8. Explanatory Model Depicting How Surface Context Features in HA&P Could Lead to the Application of a HA&P Frame and Ultimately, Student Learning Difficulties.

In addition, I found evidence to suggest HA&P students may have access to a simple systems frame, as every student in our interview study utilized similar strategies and behaviors when presented with our complex system. This finding is in alignment with the centralized mindset theory which posits that students may be inclined to apply a simple systems frame whenever encountering a complex system (Figure 9). Similar to the claims made by the centralized mindset research, if students apply a simple systems frame, they would likely activate the resources commonly associated with that frame. The resulting reasoning and behaviors would likely be non-mechanistic and linear in nature.

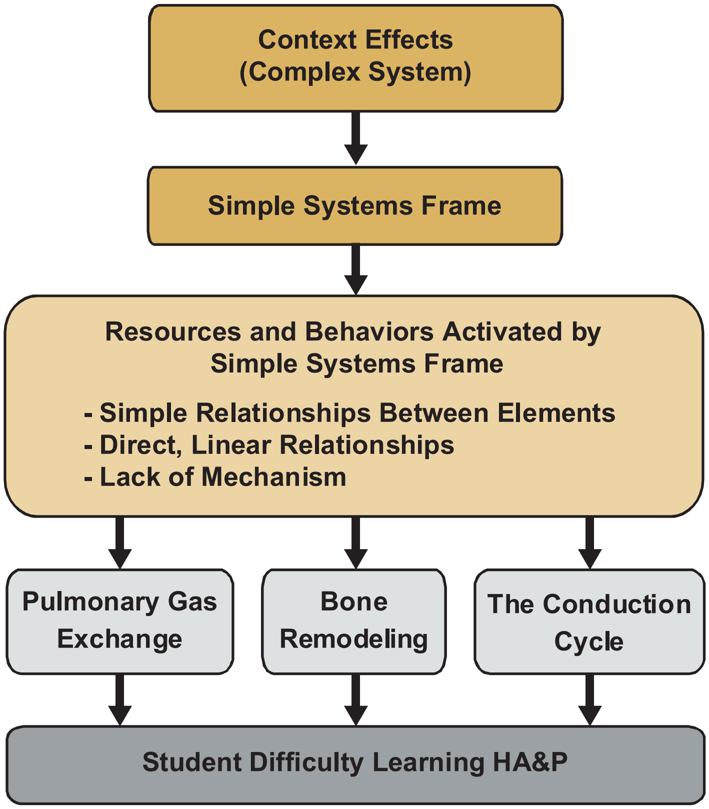

Figure 9. Explanatory Model Depicting How the Presence of Complex Systems in HA&P Curriculum Could Lead to the Application of a Simple Systems Frame and Ultimately, Student Learning Difficulties.

Implications for Research

I found evidence to indicate the surface context used in HA&P problems may make students more inclined to use teleological reasoning. To strengthen this claim, future studies should investigate the role of context in HA&P using additional body systems and other cross-cutting concepts. I also found evidence to suggest students are inclined to using reasoning strategies that are indicative of having limited systems thinking skills (Chapters 2 and 4). However, I did not formally asses students' thinking skills outside of a physiology context, and thus, it remains unknown how students that are proficient with mechanistic reasoning and systems thinking skills would be impacted by HA&P context. To expand on our findings, I argue future efforts should be made to better understand the impact item context has on student reasoning in HA&P and how that impact is influenced by a student's system thinking skills.

The research presented in this dissertation advocates for the recognition and consideration of framework and theories originating outside of a researcher's home discipline. For example, the framing and resources theoretical framework provided a meaningful way to interpret the patters we observed in student responses. Applying this framework to our research enables us to more readily extend our findings to other student difficulties in the HA&P education research community as well as the broader biology education research community. While at times challenging, the intense conversations had between our interdisciplinary team proved to be imperative for the success of this research. I strongly recommend discipline-based education researchers recognize the untapped potential interdisciplinary collaborations can hold and work to foster those collaborations, especially those education researchers focusing on issues pertinent to introductory STEM undergraduates.

Implications for Instruction

One of the unexpected results of this dissertation research was the realization that students leaving an introductory HA&P course have drastically different ideas about fluid dynamics compared to students leaving an introductory algebra-based physics course (Chapter 4). This result is especially troubling when one considers how many students are expected to complete both of these courses (perhaps even simultaneously) before they are allowed on to their professional program. One way to understand where this difference in understanding comes from is to better understand how experts in these respective field approach these topics, as these expert strategies can be good indicators of how these courses are taught. The study presented in Chapter 3 did just that. I conducted a study investigating how experts from biology, physics, and engineering reason about fluid dynamics and how that reasoning might be impacted by context features. I found that experts from these different disciplines had distinctly different ways of reasoning about fluid dynamics, especially comparing across biology and physics, and they ultimately provided different answers in response to our interview prompt. Despite being asked to reason about a context outside of their own discipline, experts appeared to have framed the problem in ways that aligned with their disciplinary background and thus activated conceptual resources connected to that frame. This study also revealed stark epistemological differences across these disciplines, consistent with previously presented work (Redish & Cooke, 2013).

Because experts may be inclined to teach ways that align with their disciplinary frames, it is likely students in HA&P and introductory physics courses are receiving conflicting instruction on the topic of fluid dynamics. Unfortunately, I have no evidence that speaks to if students are able to reconcile this conflicting instruction or how (or even if) they might be integrating these two disciplinary models of fluid dynamics to form one function mental model. Further, we have no knowledge of how these differences in instruction may be impacting students in their later courses.

The inherent disciplinary segregation of the higher education system means very little instructional collaboration across STEM disciplines. Our research demonstrates the importance of breaking down the silos that isolate our disciplines and advocates for intentional conversations between instructors, especially those teaching introductory course, to better understand how cross-cutting concepts are being taught in our respective disciplines.

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Heredia, S., Furtak, E. M., & Morrison, D. (2012). Item context: How organisms used to frame natural selection items influence student response choices. *Proceedings of the National Association for Research in Science Teaching (NARST) Annual Conference*. Indianapolis, IN. http://spot.colorado.edu/~furtake/NARST_2012_final.pdf

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Nehm, R. H., & Ha, M. (2011). Item feature effects in evolution assessment. *Journal of Research in Science Teaching, 48*(3), 237-256.

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Slominski, T., Grindberg, S., & Momsen, J. (2019). Physiology is hard: A replication study of students’ perceived learning difficulties. *Advances in Physiology Education, 43*(2), 121–127.

Smith, J. P., III, diSessa, A. A., & Roschelle, J. (1994). Misconceptions Reconceived: A Constructivist Analysis of Knowledge in Transition. *The Journal of the Learning Sciences, 3*(2), 115–163.

Sturges, D., & Maurer, T. (2013). Allied Health Students’ Perceptions of Class Difficulty: The Case of Undergraduate Human Anatomy and Physiology. *The Internet Journal of Allied Health Sciences and Practice, 11*(4), 9.

APPENDIX A. COMPLETE LIST OF SURVEY ITEMS

	What is it about the subject matter of A&P that makes it hard to learn? [Discipline]	
1.	Understanding physiology is based (built upon) an understanding of physics and chemistry.	**SD D N A SA**
2.	Physiological phenomena need to be understood at a number of different organizational levels simultaneously (from the molecular to the whole organism).	**SD D N A SA**
3.	Understanding physiology requires the ability to reason causally (mechanistically).	**SD D N A SA**
4.	Understanding physiology requires at least some limited ability to think about dynamic systems.	**SD D N A SA**
5.	Physiology, like other life sciences, seems to encourage teleological thinking (thinking about things in terms of their purpose).	**SD D N A SA**
6.	Much of our understanding of physiological mechanisms is communicated graphically or in other mathematical ways.	**SD D N A SA**
7.	The language of physiology is a mixed one, with many commonly used words taking on specific, scientific meanings that are different from (sometimes opposite from) their lay meanings.	**SD D N A SA**

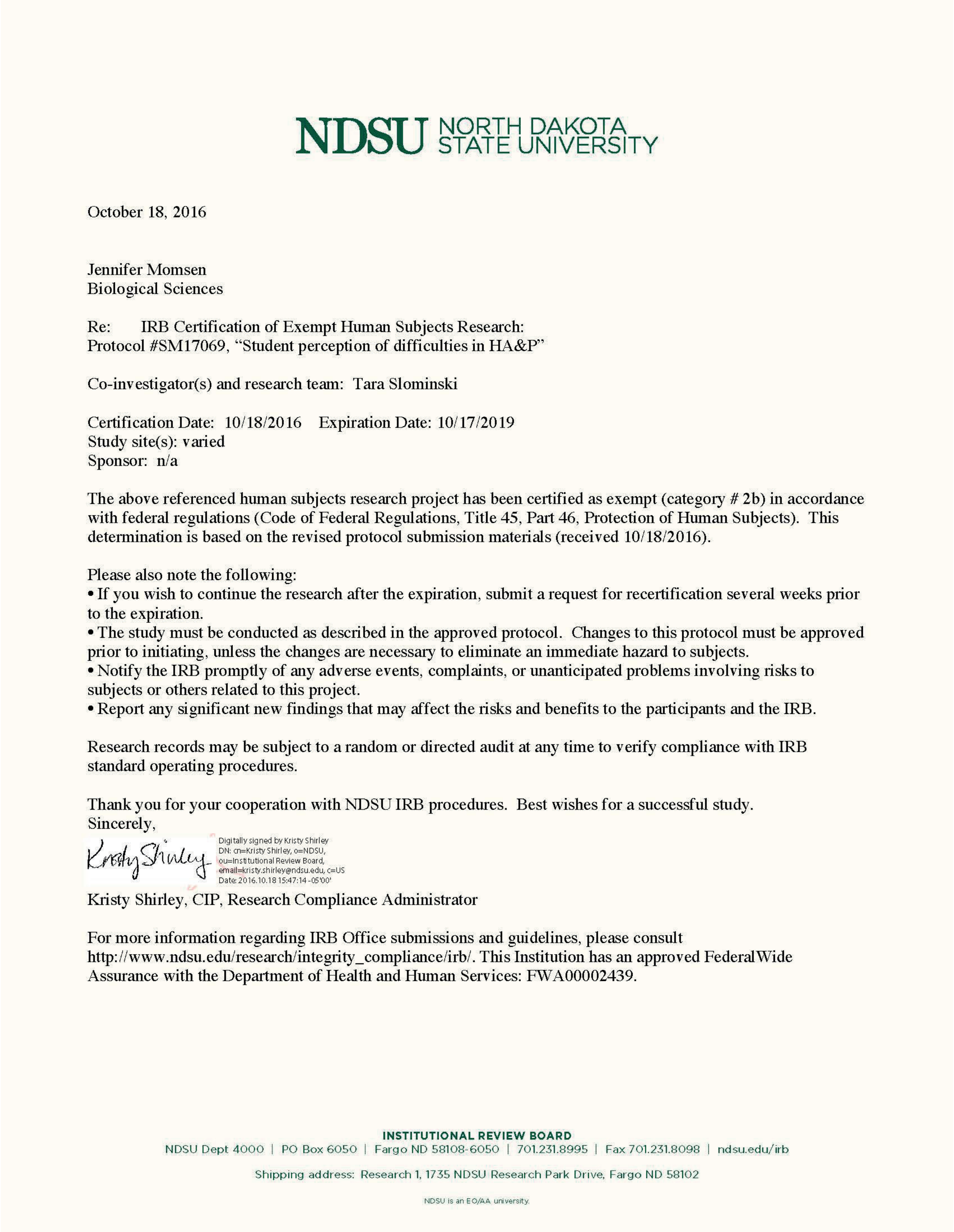
	What is it about the way A&P is taught that makes it hard to learn? [Teaching]	
8.	Textbooks are typically descriptive compendia of facts, not mechanistic descriptions of phenomena or concepts.	**SD D N A SA**
9.	Neither authors nor teachers stress the commonalities of function across organ systems ("common themes" or general models).	**SD D N A SA**
10.	Teachers do a poor job of defining and communicating our learning objectives (what students should be able to do at the end of the class).	**SD D N A SA**
11.	Teachers expect too many memorized facts and too little understanding at the same time.	**SD D N A SA**
12.	Teachers and authors use language imprecisely, use too much jargon, and use too many acronyms, all to the detriment of learning.	**SD D N A SA**
13.	Teachers talk (physiology) too much and students talk (physiology) too little.	**SD D N A SA**

	What is it about the way students attempt to learn A&P that makes it hard? [Students]	
14.	Students believe that "learning" is the same thing as "memorizing".	**SD D N A SA**
15.	Students compartmentalize (pigeon-hole) everything, failing to look for, or see, commonalities across organ systems or phenomena.	**SD D N A SA**
16.	Students fail to appreciate the integrative nature of physiological mechanisms; e.g. they don't want to think about the respiratory system now (while learning acid/base balance) because they studied it months ago and have already passed the test on that subject.	**SD D N A SA**
17.	Students assume that ALL physiological responses must benefit the organism.	**SD D N A SA**
18.	Students tend to ignore graphs, tables and figures, and when they attempt to use them they don't understand the meaning to be found there.	**SD D N A SA**

APPENDIX B. STUDENT DEMOGRAPHICS BY INSTITUTION

	Student Demographics	Institution			
		A	B	C	D
Ethnicity	Asian American	6.67	4.11	7.5	-
	Black or African American	-	1.9	2.5	43.64
	Hispanic/Latino	13.33	0.32	15	5.45
	Native American or Alaskan Native	-	1.9	-	-
	Native Hawaiian or Other Pacific Islander	-	-	-	-
	White/Caucasian	80	89.56	70	49.09
	Other	-	1.27	1.25	1.82
	Prefer not to say	-	0.95	3.75	-
Undergraduate Semesters Completed	0	0	4.11	0	9.09
	1 to 2	13.33	43.35	21.25	32.73
	3 to 4	26.67	32.28	35	29.09
	5 to 6	40	14.24	26.25	20
	7 or more	20	6.01	17.5	9.09
Undergraduate GPA (Self-reported)	less than 2.00	0	0.32	3.75	0
	2.00 to 2.49	13.33	0.95	8.75	12.73
	2.50 to 2.99	6.67	10.13	30	30.91
	3.00 to 3.49	13.33	27.85	27.5	27.27
	3.50 to 4.00	66.67	60.76	30	29.09

APPENDIX C. IRB DOCUMENT FOR CHAPTER 2 RESEARCH



NDSU NORTH DAKOTA
STATE UNIVERSITY

October 18, 2016

Jennifer Momsen
Biological Sciences

Re: IRB Certification of Exempt Human Subjects Research:
Protocol #SM17069, "Student perception of difficulties in HA&P"

Co-investigator(s) and research team: Tara Slominski

Certification Date: 10/18/2016 Expiration Date: 10/17/2019
Study site(s): varied
Sponsor: n/a

The above referenced human subjects research project has been certified as exempt (category # 2b) in accordance with federal regulations (Code of Federal Regulations, Title 45, Part 46, Protection of Human Subjects). This determination is based on the revised protocol submission materials (received 10/18/2016).

Please also note the following:

- If you wish to continue the research after the expiration, submit a request for recertification several weeks prior to the expiration.
- The study must be conducted as described in the approved protocol. Changes to this protocol must be approved prior to initiating, unless the changes are necessary to eliminate an immediate hazard to subjects.
- Notify the IRB promptly of any adverse events, complaints, or unanticipated problems involving risks to subjects or others related to this project.
- Report any significant new findings that may affect the risks and benefits to the participants and the IRB.

Research records may be subject to a random or directed audit at any time to verify compliance with IRB standard operating procedures.

Thank you for your cooperation with NDSU IRB procedures. Best wishes for a successful study.
Sincerely,

Kristy Shirley

Digitally signed by Kristy Shirley
DN: cn=Kristy Shirley, o=NDSU,
ou=Institutional Review Board,
email=kristy.shirley@ndsu.edu, c=US
Date: 2016.10.18 15:47:14 -05'00'

Kristy Shirley, CIP, Research Compliance Administrator

For more information regarding IRB Office submissions and guidelines, please consult http://www.ndsu.edu/research/integrity_compliance/irb/. This Institution has an approved FederalWide Assurance with the Department of Health and Human Services: FWA00002439.

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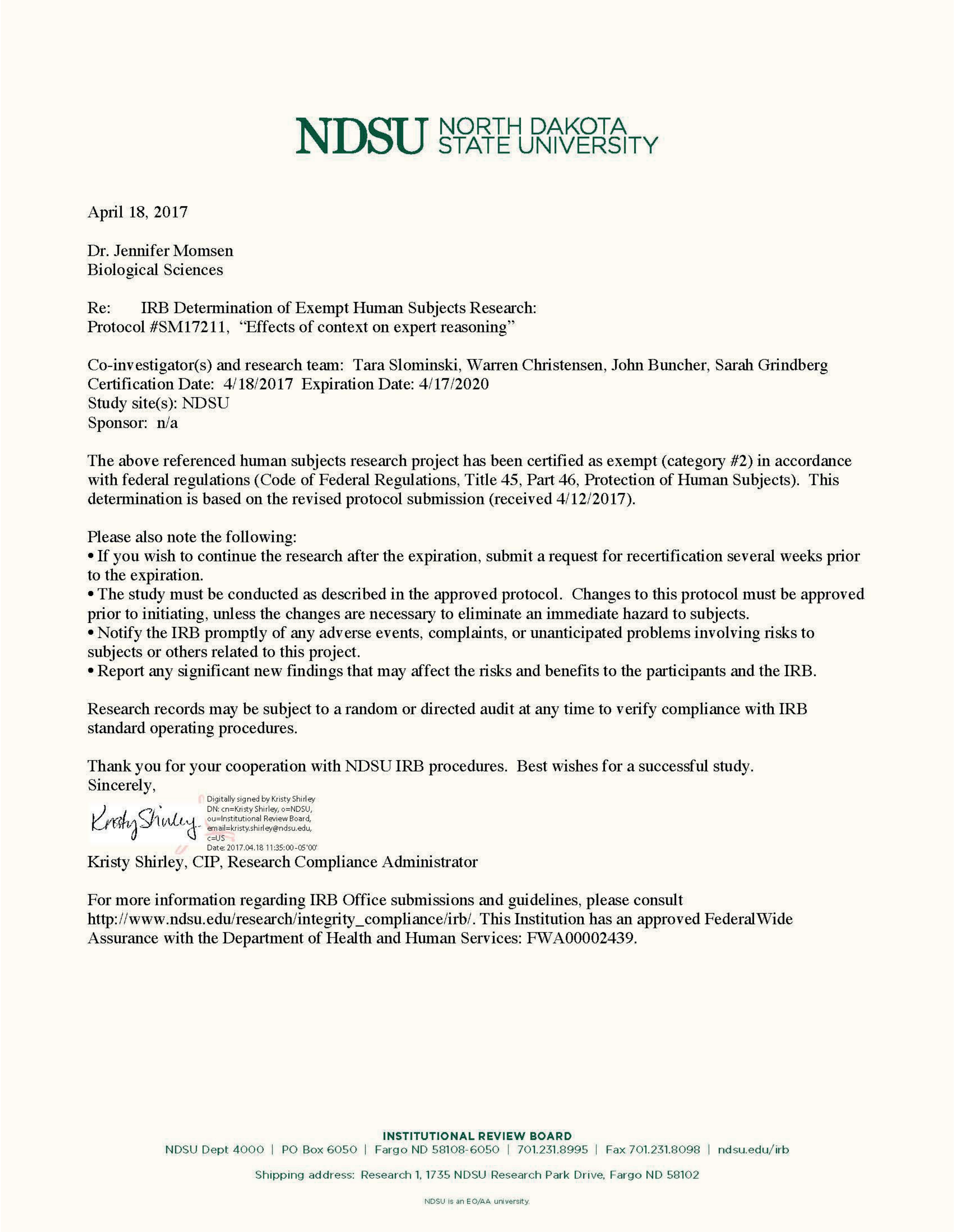
Shipping address: Research 1, 1735 NDSU Research Park Drive, Fargo ND 58102

APPENDIX D. IRB DOCUMENT FOR CHAPTER 3 RESEARCH



NDSU NORTH DAKOTA STATE UNIVERSITY

April 18, 2017

Dr. Jennifer Momsen
Biological Sciences

Re: IRB Determination of Exempt Human Subjects Research:
Protocol #SM17211, "Effects of context on expert reasoning"

Co-investigator(s) and research team: Tara Slominski, Warren Christensen, John Buncher, Sarah Grindberg
Certification Date: 4/18/2017 Expiration Date: 4/17/2020
Study site(s): NDSU
Sponsor: n/a

The above referenced human subjects research project has been certified as exempt (category #2) in accordance with federal regulations (Code of Federal Regulations, Title 45, Part 46, Protection of Human Subjects). This determination is based on the revised protocol submission (received 4/12/2017).

Please also note the following:

- If you wish to continue the research after the expiration, submit a request for recertification several weeks prior to the expiration.
- The study must be conducted as described in the approved protocol. Changes to this protocol must be approved prior to initiating, unless the changes are necessary to eliminate an immediate hazard to subjects.
- Notify the IRB promptly of any adverse events, complaints, or unanticipated problems involving risks to subjects or others related to this project.
- Report any significant new findings that may affect the risks and benefits to the participants and the IRB.

Research records may be subject to a random or directed audit at any time to verify compliance with IRB standard operating procedures.

Thank you for your cooperation with NDSU IRB procedures. Best wishes for a successful study.
Sincerely,

Kristy Shirley
Digitally signed by Kristy Shirley
DN: cn=Kristy Shirley, o=NDSU, ou=Institutional Review Board, email=kristy.shirley@ndsu.edu, c=US
Date: 2017.04.18 11:35:00 -05'00'

Kristy Shirley, CIP, Research Compliance Administrator

For more information regarding IRB Office submissions and guidelines, please consult http://www.ndsu.edu/research/integrity_compliance/irb/. This Institution has an approved FederalWide Assurance with the Department of Health and Human Services: FWA00002439.

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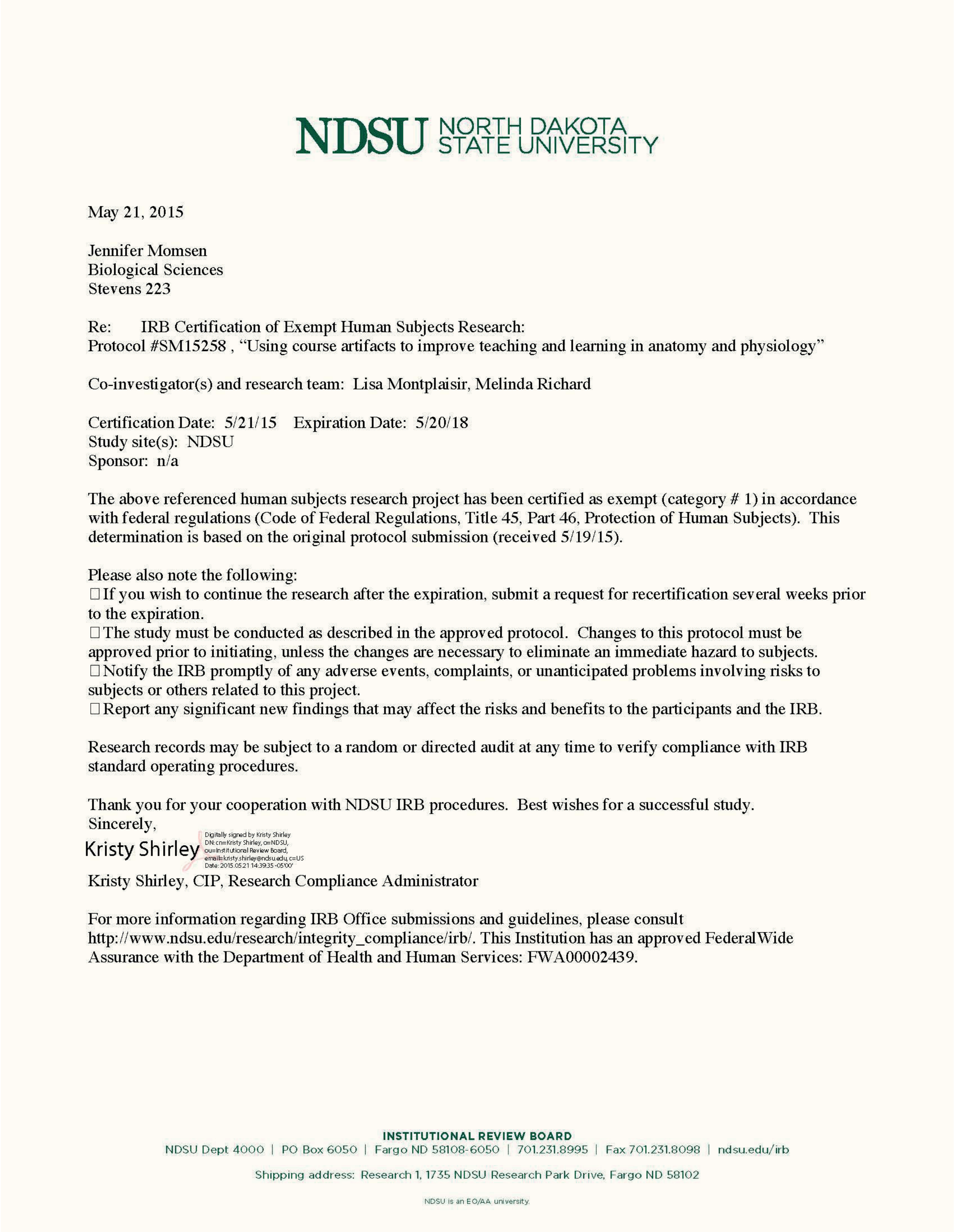
Shipping address: Research 1, 1735 NDSU Research Park Drive, Fargo ND 58102

APPENDIX E. IRB DOCUMENT FOR CHAPTER 4 RESEARCH – HA&P RESPONSES



NDSU NORTH DAKOTA STATE UNIVERSITY

May 21, 2015

Jennifer Momsen
Biological Sciences
Stevens 223

Re: IRB Certification of Exempt Human Subjects Research:
Protocol #SM15258 , "Using course artifacts to improve teaching and learning in anatomy and physiology"

Co-investigator(s) and research team: Lisa Montplaisir, Melinda Richard

Certification Date: 5/21/15 Expiration Date: 5/20/18
Study site(s): NDSU
Sponsor: n/a

The above referenced human subjects research project has been certified as exempt (category # 1) in accordance with federal regulations (Code of Federal Regulations, Title 45, Part 46, Protection of Human Subjects). This determination is based on the original protocol submission (received 5/19/15).

Please also note the following:
☐ If you wish to continue the research after the expiration, submit a request for recertification several weeks prior to the expiration.
☐ The study must be conducted as described in the approved protocol. Changes to this protocol must be approved prior to initiating, unless the changes are necessary to eliminate an immediate hazard to subjects.
☐ Notify the IRB promptly of any adverse events, complaints, or unanticipated problems involving risks to subjects or others related to this project.
☐ Report any significant new findings that may affect the risks and benefits to the participants and the IRB.

Research records may be subject to a random or directed audit at any time to verify compliance with IRB standard operating procedures.

Thank you for your cooperation with NDSU IRB procedures. Best wishes for a successful study.
Sincerely,
Kristy Shirley
Digitally signed by Kristy Shirley
DN: cn=Kristy Shirley, o=NDSU,
ou=Institutional Review Board,
email=kristy.shirley@ndsu.edu, c=US
Date: 2015.05.21 14:39:35 -05'00'

Kristy Shirley, CIP, Research Compliance Administrator

For more information regarding IRB Office submissions and guidelines, please consult http://www.ndsu.edu/research/integrity_compliance/irb/. This Institution has an approved FederalWide Assurance with the Department of Health and Human Services: FWA00002439.

INSTITUTIONAL REVIEW BOARD
NDSU Dept 4000 | PO Box 6050 | Fargo ND 58108-6050 | 701.231.8995 | Fax 701.231.8098 | ndsu.edu/irb

Shipping address: Research 1, 1735 NDSU Research Park Drive, Fargo ND 58102

NDSU is an EO/AA university.

APPENDIX F. IRB DOCUMENT FOR CHAPTER 4 RESEARCH – PHYSICS RESPONSES

NDSU NORTH DAKOTA STATE UNIVERSITY

April 6, 2020

Dr. John Buncher
Physics

Re: IRB Determination of Exempt Human Subjects Research:
Protocol #SM20237, "Using Course Artifacts to Improve Teaching & Learning in Introductory Physics"

NDSU Co-investigator(s) and research team: Warren Christensen, Jennifer Momsen, Tara Slominski
Date of Exempt Determination: 4/6/2020 Expiration Date: 4/5/2023
Study site(s): NDSU Funding Agency: n/a

The above referenced human subjects research project has been determined exempt (category 1) in accordance with federal regulations (Code of Federal Regulations, Title 45, Part 46, Protection of Human Subjects). This determination is based on the original protocol received 4/2/2020.

Please also note the following:
- If you wish to continue the research after the expiration, submit a request for recertification several weeks prior to the expiration.
- The study must be conducted as described in the approved protocol. Changes to this protocol must be approved prior to initiating, unless the changes are necessary to eliminate an immediate hazard to subjects.
- Notify the IRB promptly of any adverse events, complaints, or unanticipated problems involving risks to subjects or others related to this project.
- Report any significant new findings that may affect the risks and benefits to the participants and the IRB.

Research records may be subject to a random or directed audit at any time to verify compliance with IRB standard operating procedures.

Thank you for your cooperation with NDSU IRB procedures. Best wishes for a successful study.
Sincerely,

Kristy Shirley

Kristy Shirley, CIP, Research Compliance Administrator

For more information regarding IRB Office submissions and guidelines, please consult https://www.ndsu.edu/research/for_researchers/research_integrity_and_compliance/institutional_review_board_irb/. This Institution has an approved FederalWide Assurance with the Department of Health and Human Services: FWA00002439.

INSTITUTIONAL REVIEW BOARD
NDSU Dept 4000 | PO Box 6050 | Fargo ND 58108-6050 | 701.231.8995 | Fax 701.231.8098 | ndsu.edu/irb

Shipping address: Research 1, 1735 NDSU Research Park Drive, Fargo ND 58102

APPENDIX G. IRB DOCUMENT FOR CHAPTER 4 RESEARCH – HA&P STUDENT INTERVIEWS

NDSU NORTH DAKOTA
STATE UNIVERSITY

April 6, 2018

Dr. Jennifer Momsen
Biological Sciences

Re: IRB Determination of Exempt Human Subjects Research:
Protocol #SM18224, "Effects of item context on student reasoning"

Co-investigator(s) and research team: Tara Slominski, Sarah Grindberg, Andrew Fugleberg
Date of Exempt Determination: 4/6/2018 Expiration Date: 4/5/2021
Study site(s): area schools
Sponsor: n/a

The above referenced human subjects research project has been certified as exempt (category #1) in accordance with federal regulations (Code of Federal Regulations, Title 45, Part 46, Protection of Human Subjects). This determination is based on the original protocol submission (received 3/29/2018) and updated consent (received 4/6/2018).

Please also note the following:

- If you wish to continue the research after the expiration, submit a request for recertification several weeks prior to the expiration.
- The study must be conducted as described in the approved protocol. Changes to this protocol must be approved prior to initiating, unless the changes are necessary to eliminate an immediate hazard to subjects.
- Notify the IRB promptly of any adverse events, complaints, or unanticipated problems involving risks to subjects or others related to this project.
- Report any significant new findings that may affect the risks and benefits to the participants and the IRB.

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Thank you for your cooperation with NDSU IRB procedures. Best wishes for a successful study.
Sincerely,

Kristy Shirley

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NDSU is an EO/AA university.