The Impact of Context on Students' Framing and Reasoning about Fluid Dynamics

Tara Slominski,[†]* Warren M. Christensen,[‡] John B. Buncher,[‡] and Jennifer Momsen[†]
[†]Department of Biological Sciences and [‡]Department of Physics, North Dakota State University, Fargo, ND 58108

ABSTRACT

Contextual features of assessments can influence the ideas students draw from and the ways they assemble knowledge. We used a mixed-methods approach to explore how surface-level item context impacts student reasoning. In study 1, we developed an isomorphic survey to capture student reasoning about fluid dynamics, a crosscutting phenomenon, in two item contexts (blood vessels, water pipes), and administered the survey to students in two different course contexts: human anatomy and physiology (HA&P) and physics. We observed a significant difference in two of 16 between-context comparisons and a significant difference in how HA&P students responded to our survey compared with physics students. In study 2, we conducted interviews with HA&P students to explore our findings from study 1. Using the resources and framing theoretical framework, we found that HA&P students responding to the blood vessel protocol used teleological cognitive resources more frequently compared with HA&P students responding to the water pipes version. Further, students reasoning about water pipes spontaneously introduced HA&P content. Our findings support a dynamic model of cognition and align with previous work suggesting item context impacts student reasoning. These results also underscore a need for instructors to recognize the impact of context on student reasoning about crosscutting phenomena.

INTRODUCTION

Higher education plays a critical role in training the workforce to meet the growing demand for healthcare workers in the United States (Bureau of Labor Statistics, U.S. Department of Labor, 2021). Many students enter college with the goal of becoming healthcare professionals, and most of these students will need to complete the introductory human anatomy and physiology (HA&P) series. For those students, the HA&P series often serves as an early gatekeeper, regulating who can move on to their intended programs and, ultimately, their intended careers. Unfortunately for those undergraduate students with aspirations of pursing healthcare professions, the HA&P course series is notoriously a difficult gate to breach (Lindsay, 2020; Keller and Hughes, 2021). Further, physiology is an essential component of a biological literacy: national documents like *Vision and Change* (American Association for the Advancement of Science, 2011) and the *Next Generation Science Standards* (NGSS Lead States, 2013) include core concepts pertinent to physiology. Despite its important role, physiology education (and HA&P more specifically) is an area that lacks substantive research on teaching and learning.

The present work was motivated by this gap in the research and explores the role of teleological reasoning in students' learning difficulties. Our own classroom experiences and prior research suggests students are drawn to using teleological explanations in undergraduate physiology classes (Michael, 2007; Sturges and Maurer, 2013; Slominski *et al.*, 2019). Results from these earlier studies suggest both students and faculty perceive teleological explanations as interfering with students' ability to

Julia Gouvea, *Monitoring Editor*
Submitted Nov 4, 2021; Revised Jan 13, 2023; Accepted Jan 24, 2023
CBE Life Sci Educ June 1, 2023 22:ar15
DOI:10.1187/cbe.21-11-0312

*Address correspondence to: Tara Slominski (tara.slominski@gmail.com).

provide mechanistic explanations on physiology assessments. This, combined with our prior work on the impact of context on reasoning (Slominski *et al.*, 2020), led us to question whether the disciplinary context of HA&P (i.e., the human context) is especially prone to activating teleological explanations, thus explaining some of the difficulties that students report.

To determine whether the disciplinary context of HA&P is more likely to activate teleological explanations than other disciplinary contexts, we needed to identify a template system that we could then situate within a human context and a contrasting disciplinary context. Through discussions with physicists and engineers, we identified fluid dynamics as a crosscutting concept that could serve this purpose. We initially set out to explore our question using a survey instrument containing both forced-choice and open-response items (study 1). Students' reasoning was both diverse and vague, limiting our analysis of their explanations. We thus conducted an interview study (study 2) to better investigate the role of disciplinary context on student reasoning in HA&P.

The findings presented here highlight the complex impact context can have on student reasoning. While the disciplinary context of HA&P does seem to evoke teleological thinking, students' difficulties were not always clearly explained by a propensity toward teleological thinking. Our instruments were crafted to reveal student thinking about fluid dynamics, but the results of these studies serve as evidence in a broader sense and support of a more dynamic view of student cognition.

HA&P Is Difficult

Introductory HA&P courses typically serve as gatekeepers, regulating who can move on in their majors and, ultimately, their intended careers. In this gatekeeping role, HA&P courses are often plagued by high drop, withdrawal, and failure (DFW) rates (Harris *et al.*, 2004; Sturges *et al.*, 2016; Lindsay, 2020; Keller and Hughes, 2021); however, the factors contributing to such high DFW rates are complex.

One of the first studies to explore the factors contributing to HA&P's difficulty focused on faculty perceptions. Michael (2007) approached this question holistically by developing a survey that asked faculty to consider how the inherent disciplinary characteristics of HA&P (along with factors pertaining to student behaviors and student preparedness and instructional factors) may contribute to students' difficulty. Results from 56 instructors across the United States indicated that faculty attributed student difficulty in HA&P 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. Building from the findings from Michael's earlier work, Sturges and Maurer (2013) focused on student perspectives of HA&P's difficulty. Adopting Michael's survey (2007), Sturges and Maurer surveyed undergraduates enrolled in HA&P courses at a 4-year university in southeast Georgia. Consistent with faculty perceptions (Michael, 2007), students did not attribute their perceptions of difficulty to the way HA&P is taught, but instead to the inherent features of the discipline (Sturges and Maurer, 2013).

We recently conducted a replication study to verify the generalizability of results from Sturges and Maurer (2013) and Michael (2007). We sampled populations at 15 different institutions across the United States, which resulted in data from 17 instructors and four HA&P classes (Slominski *et al.*, 2019). Our results were consistent with those observed by Sturges and Maurer (2013) and Michael (2007): Students and faculty identify the discipline as inherently difficult to learn. As a replication study, these results confirm that students' perceptions of course difficulty are independent of variables like geographic region, institution type, class size, and prerequisite courses. Further, this research aligns with data from the nursing education research community, in which nursing students consider biology courses like HA&P to be especially challenging and, in some cases, more difficult than other courses in the nursing curriculum (Jordan *et al.*, 1999; Smales, 2010).

High DFW rates, findings from many empirical studies including our own, and conversations with students highlight a need to understand *why* the HA&P series is considered such a difficult series of courses, especially for pre-professional students. Our work builds on the findings of Michael (2007) and others (Sturges and Maurer, 2013; Slominski *et al.*, 2019), which attribute this difficulty to the discipline and less so to the instruction or to student behaviors or preparation. Specifically, we are interested in understanding how the disciplinary *context* of HA&P may impact the way students reason about the complex phenomena covered in HA&P courses. For the purposes of this work, we consider disciplinary context to represent the discipline-specific information (words, objects, phrases, phenomena, etc.) included in a problem or task that serves to contextualize that problem or task in a way that makes it relevant for students in a given discipline (e.g., biology or physics).

Teleological Thinking

Students in HA&P believe the nature of physiology concepts encourages them to think about phenomena and structures in terms of their purpose or goal (Sturges and Maurer, 2013; Slominski *et al.*, 2019). According to students, this tendency toward teleological thinking (or thinking about phenomena in terms of a need or a goal), is a main source of difficulty when trying to learn and succeed in HA&P (Sturges and Maurer, 2013; Slominski *et al.*, 2019). Students also report difficulty thinking about physiology phenomena in terms of cause and effect (Sturges and Maurer, 2013; Slominski *et al.*, 2019).

Evidence of students using teleological thinking can readily be found throughout HA&P and biology education literature (Bishop and Anderson, 1990; Michael, 1998, 2002; Modell, 2000; Cliff, 2006; Coley and Tanner, 2012, 2015; Badenhorst *et al.*, 2016; Richard *et al.*, 2017) researchers and educators the field has postulated ideas of why teleological thinking is problematic. When students focus on the outcomes of physiological mechanisms, as opposed to the physiological mechanisms themselves, students may then be limited in their propensity to use mechanistic thinking (Richardson, 1990; Tamir and Zohar, 1991; Kelemen, 1999a,b; Southerland *et al.*, 2001; Russ *et al.*, 2008; Trommler *et al.*, 2018). Additionally, some in biology education research (BER) argue that teleological thinking prohibits a student from incorporating important biological principles like variation and randomness into their mental models (Alters and Nelson, 2002). However, we caution, along with Gouvea and Simon (2018), that the presence of teleological thinking (often in the form of students' teleological remarks or agreement with teleological statements) should not necessarily be interpreted as students lacking mechanistic reasoning abilities, but rather as the absence of evidence of mechanistic reasoning.

There is debate as to why students are drawn to teleological reasoning. Some in BER and cognitive psychology consider students' tendency toward teleological reasoning to be the result of a problematic cognitive framework, one that is static and durable in nature (Keil, 1995; Kelemen, 1999a,b; Lombrozo and Carey, 2006; Coley and Tanner, 2012, 2015). Proponents of this stable model of cognition ascribe students' incorrect ideas to an underlying, pre-existing cognitive framework. These cognitive frameworks are believed to be deeply ingrained in our students and thus are indiscriminately applied across subject areas, resulting in numerous, deeply held misconceptions (Coley and Tanner, 2012, 2015). In the case of teleology, Kelemen and others argue the human mind has evolved in such a way that we have an innate tendency to view objects as having been intentionally designed for a specific purpose (Kelemen, 1999a,b), which has led to the establishment of a teleological cognitive construal (Coley and Tanner, 2015).

Dynamic Cognition

In contrast with the static model of cognition, others argue for a model that is dynamic, emergent, and situationally dependent (diSessa, 1993; Smith *et al.*, 1994; Gouvea and Simon, 2018). At its foundation, this perspective of cognition models knowledge as comprised of small, fine-grained ideas that are activated in response to a particular situation or context and compiled with other pieces of knowledge to form an explanation in real time (diSessa, 1988, 1993; Smith *et al.*, 1994; Hammer *et al.*, 2005; Harlow and Bianchini, 2020). Students accumulate these pieces of knowledge, or cognitive resources, as they make sense of the world around them (both inside and outside 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 as either 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.

Under this dynamic view of cognition and reasoning, the surface features used in articulating a problem or the setting in which the problem is asked can dictate how a student situates or frames the problem internally (Hammer *et al.*, 2005; Gouvea and Simon, 2018). When a student situates a problem using a particular frame, either subconsciously or consciously, it results in the activation and integration of particular conceptual resources. When conceptual resources are inappropriately selected or applied (e.g., they do not account for assumptions or limitations of the given scenario), a student is likely to provide an incorrect answer. In comparison to misconceptions, it is not students' conceptual resources that are wrong, but instead, the conceptual resources are misapplied in the given context. The same conceptual resource may be useful and productive for reasoning in a different context.

Proponents of a dynamic view of cognition argue that repeated coactivation of particular resources strengthens the associations between those resources, increasing the stability of a particular pattern of thinking (diSessa, 1988, 1993; Smith *et al.*, 1994; Gupta *et al.*, 2010; Gouvea and Simon, 2018). In the case of teleology, it may be that students' teleological explanations are the result of the repeated activation of particular cognitive resources (or resource patterns) in response to context cues that ultimately present as teleological reasoning. Southerland and colleagues (2001) identify one such possible resource as "need as a rationale for change," which posits "biological phenomena happen because the organism needs this adaptation/occurrence" (p. 344).

Southerland and colleagues (2001) leveraged diSessa's "knowledge in pieces" framework (1993) to explain students' spontaneous construction of explanations of biological phenomena. When asked to explain various biological phenomena in an interview setting (i.e., migration, growth, and color change), students offered teleological explanations more often than other reasoning categories (e.g., mechanistic ultimate, mechanistic proximate, anthropomorphic). Teleological explanations were the most prevalent reasoning category among all student groups (i.e., second-, fifth-, eighth-, and 12th-grade students), and among three of the four prompt versions (i.e., bean plant growth, ptarmigan color change, and duck migration). When students made use of multiple reasoning categories, Southerland and colleagues found students often situated their explanation to support teleological intentions before discussing any proximal mechanism. In one example, when asked *how* a ptarmigan's plumage goes from brown in the summer to white in the winter, a student began their explanation by describing how white plumage gives them greater protection from hunters. The student goes on to offer two insights the authors coded as mechanistic proximal before concluding with a statement about "nature taking over" (p. 339). Southerland and colleagues argue examples like this illustrate how the core intuition of an organism's need to adapt can direct the way a student constructs an explanation in real time. Southerland and colleagues specifically position this knowledge structure as operating as a phenomenological primitive (diSessa, 1993), that is "an organizing core intuition" that directs students' reasoning toward teleological formulations.

Extending this dynamic view of cognition to our work (namely the framing and resources framework; Hammer and Elby, 2003; Hammer *et al.*, 2005), we explore the possibility that the context of typical HA&P activities and assessments may cue students to frame those items in a way that results in students responding with teleological interpretations of a given phenomenon.

Dynamic Cognition and Contextual Effects

Due to the nature of HA&P content, it is reasonable to assume students enter the classroom with a wide array of pre-existing ideas, beliefs, and experiences surrounding how the human body functions. These pre-existing notions likely arise from the observations students have made about their own bodies (and those around them) as they have gone about their daily lives. Additionally, one could argue students are likely to associate their pre-existing 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 COVID-19 pandemic could all be associated with efforts to improve or maintain their own personal well-being or the well-being of others. Therefore, because students have robust experiences with the human body, they may be inclined to reason differently about complex scenarios if they are presented within the disciplinary context of the human body. Our work seeks to understand how the context of HA&P

may impact student reasoning and, ultimately, contribute to the challenges students report experiencing in this context (Sturges and Maurer, 2013; Slominski *et al.*, 2019). Gouvea and Simon (2018) argue that the contextual features of a problem, scenario, or activity influence the way students approach the task and the kinds of knowledge they employ. In this case, contextual features can refer to several different factors, including the physical environment in which the activity takes place, the disciplinary context used in the activity itself, or even the experiences a student has leading up to an activity. For the purposes of this paper, we focus on the disciplinary context included in a survey or questions that situates a task in a particular content area.

A growing body of literature from the BER community supports contextual effects impacting student thinking. One of the most recognized studies on contextual effects on student reasoning in biology comes from Nehm and Ha (2011). This study used 12 variations of an open-ended prompt to elucidate the effect of context on student reasoning about natural selection. The general format of the prompt versions remained consistent, but the contextual features differed in terms of trait direction (i.e., trait loss vs. train gain), organisms (locusts, rose, cheetah, etc.), and traits (resistance, thorns, running speed, etc.). Analysis of student responses revealed the accuracy of students' explanations of natural selection was impacted by the context included in the prompt. Most notably, analysis of contextual effects revealed students reason differently about prompts involving trait gain versus trait loss. The findings of Nehm and Ha (2011) have been supported by others, revealing multiple instances in which the type of taxa or trait direction used in a prompt or scenario have been found to impact student reasoning and students' explanations of natural selection (Opfer *et al.*, 2012; Heredia *et al.*, 2016; Göransson *et al.*, 2020).

These findings echo the work of others from across science, technology, engineering, and mathematics (STEM) disciplines who argue contextual features are especially impactful on novice students (Chi *et al.*, 1981; Krieter *et al.*, 2016; Bissonnette *et al.*, 2017). Novice students, like those enrolled in HA&P, are more likely to focus on the contextual features of a problem, which in turn, direct those students (either consciously or subconsciously) to a reasoning approach they associate with those surface features. More expert-like students look for underlying conceptual features (as opposed to the surface features) when determining how to approach a problem or scenario, leading them (either consciously or subconsciously) to employ reasoning strategies they consider appropriate for the underlying concepts.

Recently, Gouvea and Simon (2018) summarized an interdisciplinary body of research that suggests the contextual features of a system or problem (along with the environmental or behavioral context conditions the problem is administered in) influence the way a student approaches the task and the kinds of knowledge the student draws on or employs. Gouvea and Simon argue that "human cognition is generally dynamic and sensitive to context" p. 18 and issue a call for increased consideration of the context in which we probe and analyze student learning. Our work is a response to this call from Gouvea and Simon and others across STEM who have advocated for research on the impact of context on student learning.

One approach to exploring disciplinary contextual effects is through crosscutting concepts, or concepts that show up in more than one discipline (e.g., physics and biology). For example, our previous research (Slominski *et al.*, 2020) leveraged fluid dynamics to study how experts from different disciplines reason about a complex system. Using water in pipes and blood in vessels, we interviewed 10 individuals with expertise in fluid dynamics, including three from physics, three from engineering, and four from biology. Our analysis revealed physiology experts reasoned about complex systems through the lens of physiology, even when presented with a nonliving context (i.e., water and pipes). In contrast, physicists often removed the biological context (i.e., blood and vessels), seemingly favoring a more abstract mental model over the biological system we presented to them. By recontextualizing our prompt, experts from these different disciplines were more likely to activate a different suite of cognitive resources and, ultimately, come to different results. When asked to reason about a problem situated in a context outside their own disciplinary background, experts in our 2020 study focused on the underlying system at hand and less so on the disciplinary context in which it was presented. The findings from our earlier interdisciplinary work add to existing literature suggesting experts can see past disciplinary context when reasoning about a problem or scenario (Chi *et al.*, 1981; Krieter *et al.*, 2016; Bissonnette *et al.*, 2017). Our interdisciplinary approach to exploring contextual effects enabled us to observe disciplinary differences in the ways experts reason about complex systems.

Research Questions

Our goal in the present paper is to determine whether the context of HA&P impacts students' reasoning about fluid dynamics and to explore whether other factors play a role in students' difficulty with HA&P. We use isomorphic surveys to isolate the impact of contextual effects on student reasoning and leverage a crosscutting concept in physics and biology (fluid dynamics) along with research and theory from BER, physics education research, and cognitive psychology to describe students' reasoning.

We present two consecutive investigations (study 1 and study 2) in which we use a mixed-methods approach to better understand how context affects student reasoning in HA&P, both at the level of a course (research question 1) and at the level of individual items (research question 2). Study 1 makes use of isomorphic surveys to isolate the effect HA&P context has on student understanding 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 the human physiology context (blood and vessels) and a non-physiological context (water and pipes). In study 2, we used semistructured interviews to further examine the reasoning patterns students use in the context of fluid dynamics, leveraging the framing and resources theoretical framework to explain observed patterns in student reasoning.

To determine whether HA&P context impacts students' understanding of fluid dynamics, we collected data from students enrolled in both HA&P and physics. Our interdisciplinary study design enabled us to address the following questions:

TABLE 1. Student demographics[a]

		Introductory HA&P		Introductory Physics	
		Spring 2016	Spring 2018	Spring 2016	Spring 2018
Gender	Male	30.03% (103)	28.01% (93)	51.92% (108)	42.86% (66)
	Female	69.97% (240)	71.99% (239)	48.08% (100)	57.14% (88)
Race/ethnicity	White	88.34% (303)	87.35% (290)	87.50% (182)	84.42% (130)
	American Indian	1.75% (6)	0.00% (<5)	0.96% (<5)	0.65% (<5)
	Asian	1.75% (6)	3.92% (13)	1.92% (<5)	1.95% (<5)
	Black	1.75% (6)	1.81% (6)	2.40% (5)	4.55% (7)
	Hispanic	1.75% (6)	3.31% (11)	1.44% (<5)	2.60% (<5)
	Two or more	3.50% (12)	3.01% (10)	2.88% (6)	4.55% (7)
	Not specified	1.17% (<5)	0.60% (<5)	2.88% (6)	1.30% (<5)
First-generation status	Yes	14.29% (49)	15.36% (51)	15.87% (33)	11.69% (18)
	No	74.64% (256)	78.92% (262)	71.63% (149)	75.32% (116)
	Not reported	11.08% (38)	5.72% (19)	12.50% (26)	12.99% (20)
Pell Grant eligible		30.32% (104)	35.24% (117)	35.58% (74)	24.68% (38)

[a] Our demographic data reflect the data as collected by the NDSU registrar; we recognize these categorizations do not adequately represent gender nor do they recognize race and ethnicity as the distinct constructs they are.

1. Does *course* context (HA&P, physics) impact how students respond to items about fluid dynamics, a complex, interdisciplinary phenomenon?
2. Does *item* context impact how HA&P students and physics students respond to items about fluid dynamics?

STUDY 1

Methods

We used a previously developed isomorphic survey to isolate the effect of disciplinary context on students' reasoning concerning fluid dynamics (Slominski *et al.*, 2020); this let us disentangle the effects of HA&P's inherent focus on human-centric phenomena from its inherent focus on complex, dynamic systems. Our isomorphic fluids survey was designed to accommodate different disciplinary contexts while maintaining the underlying structure of the complex fluid system in question. We developed an HA&P version of our fluid survey that was situated in the context of blood and blood vessels (we refer to this version as the "BV" survey) and a non-biology version that was situated in the context of water and pipes (we refer to this version as the "WP" survey).

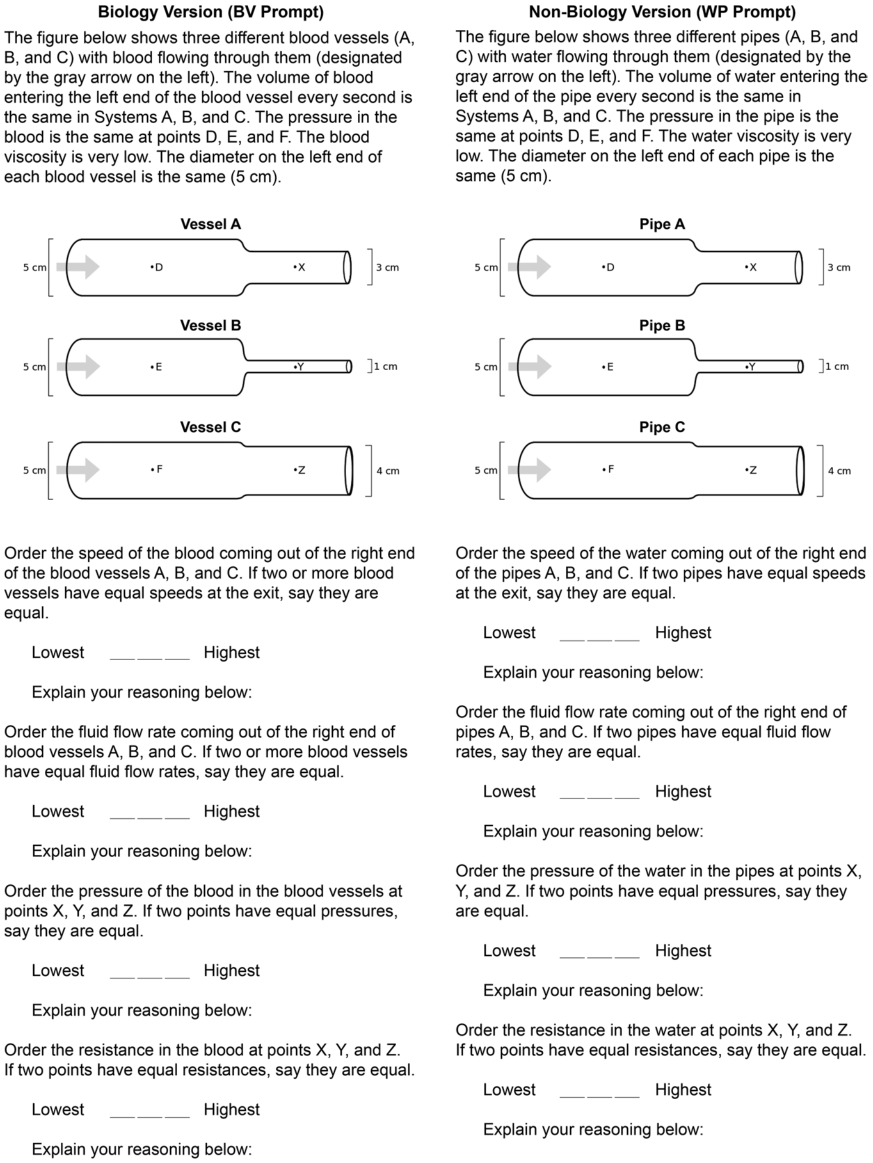
Study Participants and Course Context. This research was conducted at North Dakota State University (NDSU), a 4-year public doctoral university with high research activity located in the Midwest (Carnegie Classification of Institutions of Higher Education, 2021). NDSU is a primarily white institution (87%), 27% NDSU of students are Pell Grant eligible, and 11% report first-generation college student status. (Data were provided by the NDSU Office of Institutional Research and Analysis. Data values are recorded at official fourth week of term census dates.) We surveyed students enrolled in either introductory HA&P or introductory physics, as both courses include instruction on fluid dynamics. Our data were collected in Spring 2016 and 2018. The students enrolled in HA&P were similar to those enrolled in physics in terms of race and ethnicity, first-generation status, and Pell Grant status, but differed in terms of gender (Table 1).

The introductory HA&P course was the second course in a two-semester series and included the following body systems: endocrine, cardiovascular, lymphatic, immune, respiratory, digestive, urinary, and reproductive systems and development. Before enrolling in this course, students needed to complete the first course in the HA&P series (which covered the integumentary system, the skeletal system, joints, muscles and muscular system, nervous tissue and nervous system, and the special senses). The same instructor taught both semesters with total enrollments of 343 in 2016 and 332 in 2018.

The introductory physics course surveyed was the first semester of a two-semester algebra-based physics sequence. This course covers kinematics with constant acceleration, Newton's laws, energy, momentum, rotational dynamics, fluid flow, and thermodynamics. Before enrolling in this course, students were required to have completed a one-semester course in college algebra. The instructor for the 2018 physics course ($n = 154$) was not the same instructor who taught the course in 2016 ($n = 208$).

Survey Development. We developed an isomorphic survey with two versions: one version was contextualized in human physiology and one was contextualized in a non-physiological setting. These systems were chosen to isolate the effect of HA&P context on student understanding of fluid dynamics. The human physiology version was further contextualized to vascular content (blood vessels and blood) and the non-physiology version was contextualized to pipes and water (Figure 1). The isomorphic surveys asked students to rank the fluid speed, fluid flow rate (FFR, the volume of blood flowing through any tissue in a given period of time), pressure, and resistance at three locations in three different systems in one of two disciplinary contexts (blood vessels, water pipes). Students were also asked to explain their reasoning following each ranking item.

It is important to note our intent was not to evaluate the *correctness* of students' understanding of fluid dynamics, but rather how disciplinary context could affect a student's reasoning about fluid dynamics. For a thorough discussion of expert reasoning of fluid dynamics, we direct the reader to Slominski *et al.* (2020), in particular the supplemental materials.



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.

Lowest ___ ___ ___ Highest

Explain your reasoning below:

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.

Lowest ___ ___ ___ Highest

Explain your reasoning below:

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.

Lowest ___ ___ ___ Highest

Explain your reasoning below:

Order the resistance in the blood at points X, Y, and Z. If two points have equal resistances, say they are equal.

Lowest ___ ___ ___ Highest

Explain your reasoning below:

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.

Lowest ___ ___ ___ Highest

Explain your reasoning below:

Order the fluid flow rate coming out of the right end of pipes A, B, and C. If two pipes have equal fluid flow rates, say they are equal.

Lowest ___ ___ ___ Highest

Explain your reasoning below:

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.

Lowest ___ ___ ___ Highest

Explain your reasoning below:

Order the resistance in the water at points X, Y, and Z. If two points have equal resistances, say they are equal.

Lowest ___ ___ ___ Highest

Explain your reasoning below:

FIGURE 1. We developed isomorphic versions of our fluid flow survey, one situated in an HA&P disciplinary context with blood and vessels (BV) and the other (non-biology) situated in a physics disciplinary context of water and pipes (WP).

Our sampling approach included students from both HA&P and introductory physics, so our isomorphic surveys had to be suitable for both populations. While the overarching concept of fluid dynamics extends across disciplines, some of the technical terminology and applications associated with fluid dynamics do not, meaning words not typically encountered in both populations (at the introductory level) could not appear in either version of our survey. This constraint meant that some terms we might include in a traditional cardiovascular assessment (e.g., "gradient" or "compliance") were omitted, as they were not equally as relevant to an introductory physics student population. To ensure both versions of our survey were suitable for both HA&P students and introductory physics students, a biologist (T.S.) and a physicist (J.B.B.) worked together to construct our survey along with feedback from W.M.C., J.M., and additional experts in biology and physics. For more on survey development, pilot testing, and expected expert responses, see our earlier work exploring contextual effects on expert reasoning about fluid dynamics (Slominski *et al.*, 2020).

Survey Distribution. Our data were collected near the end of the Spring semester and shortly after students in both courses had received formal instruction on the topic of fluid dynamics. The two versions of the survey were randomly distributed, so approximately half of the students in each course were given the BV version and the other half the WP version (Figure 2). Surveys were administered in person, during class time, and participation was voluntary. 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 (in 2016, the second attempt occurred in HA&P, and in 2018, the second attempt occurred in physics).

After reviewing the data collected in Spring 2016, we observed many students providing answers that suggested they did not recognize the difference between FFR and speed (see *Results* for further description). In an attempt to alleviate this issue in 2018, we changed the order of the speed and FFR items. In the 2016 data collection, students were first asked about FFR and then speed; in the 2018 data collection, the order of these items was reversed.

Analysis. For each item on our survey, our interdisciplinary team of biologists and physicists compared the rankings provided by HA&P students with those provided by physics students, independent of the survey version. We used a Fisher's exact test to determine whether the proportions of the provided rankings were different across the two courses. Our data were collected over two semesters, so we used a Fisher's exact test to determine whether the responses provided by students in 2016 were similar to those collected in 2018 with respect to both class (physics/HA&P) and survey version (BV/WP).

To determine whether the survey version impacted how students responded, we compared the distribution of rankings provided by 2016 HA&P students in response to the BV version to the distribution of 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 whether the distribution 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

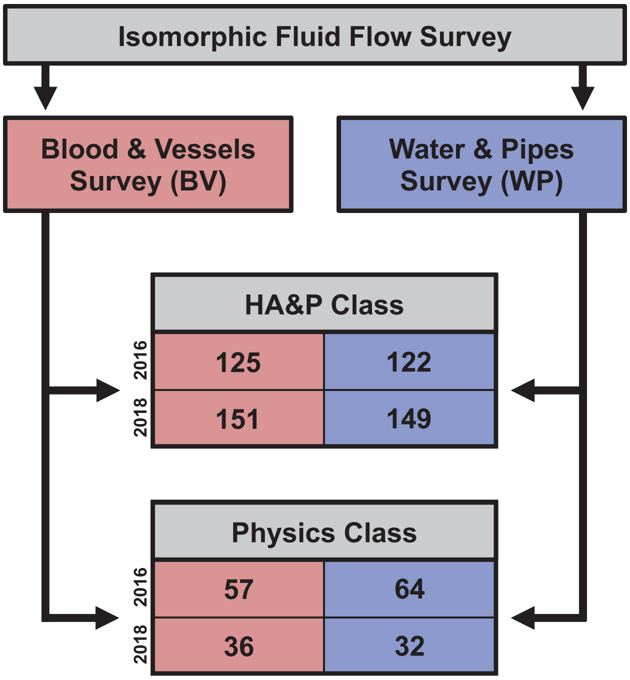


FIGURE 2. Survey distribution. We distributed the two isomorphic versions of our fluid flow survey across two course contexts, an HA&P course and an introductory physics course. The two versions of our survey were evenly distributed within each course to allow us to determine whether item context (BV or WP) impacted student responses within an individual course.

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, 2021).

To analyze the written explanations, we used thematic analysis (Braun and Clarke, 2006) with our interdisciplinary team of coders, two physicists (J.B.B., W.M.C.) and two biologists (T.S., J.M.). 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 our initial discussion of student responses, we had little agreement between biologists and physicists and were forced to abandon the thematic analysis. While we did find evidence of students' using teleological reasoning (e.g., "because the blood viscosity is very low, the vessels need to be smaller in order to move the blood faster and keep it from pooling up"), we did not feel confident in creating this as a distinct category. Therefore, we focus on discussing the challenges we faced and how they led, in part, to study 2.

Results

Differences across Years. To determine whether responses were similar across both years of data collection, we compared the distribution of rankings provided by students in 2016 with those collected in 2018. When comparing rankings collected from HA&P students in 2016 ($n = 247$) with those collected in 2018 ($n = 300$), irrespective of survey version, we found a difference in how students answered the FFR and speed items (Bonferroni-corrected p values < 0.05 and < 0.001, respectively, Fisher's exact test), but not the pressure and resistance items. When comparing responses provided by physics students in 2016 ($n = 121$) with those provided in 2018 ($n = 68$), irrespective of survey version, we found a difference in how students answered the FFR and pressure items (Bonferroni-corrected p values < 0.001 and < 0.001, respectively, Fisher's exact test), but not the speed and resistance items.

The differences in student responses to the FFR and speed items support our observations made after our initial data collection in 2016. In 2016, the speed item came after the FFR item. Based on the explanations students provided, we had reason to believe students were using the same reasoning to answer both the speed and FFR items. As an example, in 2016, a student in the physics course gave the ranking of C (lowest), A, B (highest) for the FFR item (WP) and said "the smaller diameter on the right would cause a faster stream" as their reasoning for this ranking. On the following speed item, this student provided the same ranking and said "again, smaller diameter on the right side = faster speed." In this example, and the many others like it, the reasoning provided for the FFR item does not explicitly include the term "flow rate" or mention of time, but it does explicitly include mention of speed or velocity. The students in this study may be more familiar with the concept of speed than the concept of FFR and therefore may be more inclined to make an error due to the ordering of these items. We thought that some students might be making the error of responding to the FFR item with speed in mind when they were presented with the FFR item first, but perhaps they would be less likely to conflate these concepts if they were presented with the (presumably) more familiar concept (speed) first.

To better characterize students' ranking and reasoning in response to the FFR item, we decided to switch the order of these two items in 2018. Because students, especially physics students, were likely more familiar with the concept of speed than they were FFR, we thought that, if students were presented with the speed item before the FFR item, they might be more likely to recognize that those items were asking students to reason about a different concept (i.e., FFR). It is also relevant to note that the instructor for the 2018 physics class was not the same as the 2016 physics class, and thus the observed differences may be the result of instructional differences.

Course Context Impacted How Students Answered Fluid Dynamics Items. We compared the distribution of student responses to investigate how students in different courses would answer a suite of interdisciplinary items (irrespective of assessment version) after receiving relevant instruction. In 2016, students in the HA&P course provided a different distribution of answers than the distribution of answers provided by physics students for the FFR, pressure, and resistance items, but not for the item about speed. In 2018, following the reordering of the speed and FFR items, students in the HA&P course provided a different distribution of answers compared with the distribution of answers provided by physics students for all four items.

TABLE 2. Examples of reasoning provided in response to the BV and WP prompts

Example	Course, version	Reasoning provided
A	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."
B	HA&P, WP	"Because that's what I think … resistance, pressure"
C	HA&P, WP	"Same reasoning as the one before"
D	HA&P, WP	"The more flow that is allowed through, the faster the liquid will go."
E	Physics, BV	"Smaller diameter = more pressure = faster speed."
F	Physics, BV	"The smallest diameter will have the highest speed because it is trying to compensate for the increased pressure."
G	HA&P, BV	"The friction against the walls of the vessel slow[s] down the flow."

In the case of FFR, more physics students predicted that the FFR would be equal (as opposed to predicting that a smaller diameter results in a lower FFR, a BAC ranking), especially in 2018. In 2018, more physics students provided a ranking that predicts that a smaller diameter results in a greater speed (a CAB ranking) than HA&P students. In both years, compared with HA&P students, more physics students said both the pressure and resistance in the blood/water at points X, Y, and Z would be equal.

Item Context Inconsistently Impacted How HA&P Students and Physics Students Responded to Items about Fluid Dynamics. In our comparison of patterns in student responses to our isomorphic, fluid flow surveys, we found item context inconsistently impacted the distribution of student responses. We found two instances in which student response patterns were significantly different across contexts. First, in 2016, the HA&P students who answered the BV version provided different ranking distributions for the FFR item compared with the HA&P students who answered the WP version. We found that, of those students who received the BV version of our assessment, more students responded with a ranking of BAC (smallest diameter to largest) compared with those students who received the WP version of our assessment. However, we found no evidence of an item contextual effect in 2018.

The second instance of item contextual effects was observed in 2018 in physics students in response to the resistance item. We found that of those students who received the WP version of our assessment, fewer students responded with a ranking of YXZ (smallest diameter to largest), and more students provided a ranking of equal compared with those students who received the BV version. This contextual effect was not found in 2016.

To summarize, in all but two cases, there was no evidence of item contextual effect in student ranking response patterns. However, in the two instances mentioned, there was a statistically significant difference in the distribution of ranking responses students provided when they were asked to reason about the BV version compared with the WP version.

Coding Students' Explanations Was Complicated. In study 1, we set out to capture student reasoning through their written responses to open-response items. Interpreting students' responses to open-ended prompts can be challenging and often requires that researchers make inferences about student cognition when attempting to categorize responses using an inductive coding strategy. Further, we often look to measures of interrater reliability (IRR) to validate our interpretations and coding of student responses. Therefore, our interdisciplinary research team used thematic analysis (Braun and Clarke, 2006) to characterize the reasoning students provided, using IRR to validate our coding efforts.

During the initial rounds of coding students' written explanations, we observed a great deal of variation in the kinds of responses students provided (Table 2). This variation occurred within and across courses, across survey versions and all four items (FFR, speed, pressure, resistance). Some students wrote responses that provided more detailed and specific insight into their thinking (Table 2, example A). However, many responses were minimal and provided little additional information or clarity on how or why students came to their respective conclusions (Table 2, example B). In addition, instead of describing their reasoning to each item, many students would explicitly refer to a previous response (Table 2, example C), resulting in superficial repetition and revealing very little of their reasoning approaches.

Further, while attempting to carry out our thematic analysis, several disagreements developed during our initial rounds of coding. We quickly discovered that our respective backgrounds in biology and physics impacted our interpretations of student responses; perhaps not surprisingly, context mattered. The most common disagreements seemed to result from the disciplinary assumptions we each brought to the coding process. For example, the biologists (T.S., J.M.) often hesitated to ascribe meaning to phrases that had a clear meaning to the physicists (J.B.B., W.M.C.). When students used the words "faster" or "slower" (Table 2, examples D and E), it was unclear to the biologists whether the students had an awareness of time, and therefore, the biologists did not feel confident in their ability to discern whether students were using ideas of speed or FFR in their explanations. Similarly, when students used phrases like "more blood" or "larger quantity," the biologists did not feel confident identifying those ideas as using FFR, as the students' responses did not explicitly address a rate. Conversely, there were times where the physicists attended to particular phrases that did not evoke a similar meaning to the biologists. For example, when students used symbols like arrows, "+", or "–", it was unclear to the biologists if they were implying a formula or equation or, alternatively, if they were representing a sort of a qualitative relationship. With no additional narrative provided, we could not confidently ascribe either meaning to students' responses. Similarly, biologists argued that, in some instances, students used the word "flow" in a manner to suggest they were thinking about volume and not rate

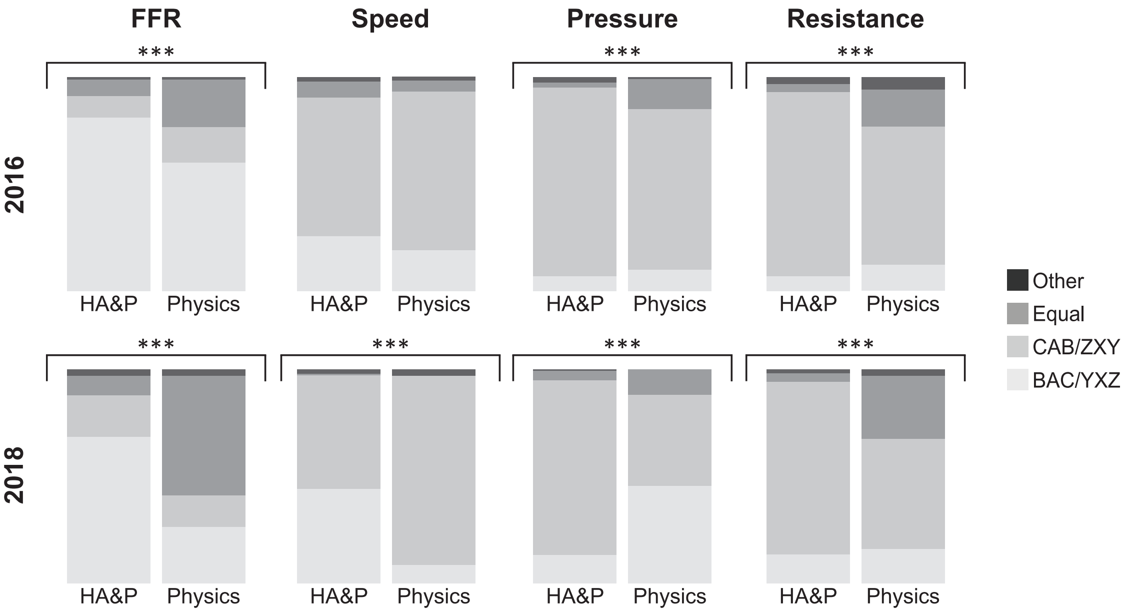


FIGURE 3. Comparison of rankings across course contexts. A Fisher's exact test was used to determine whether the proportions of the provided rankings were different across the two courses for data collected in the 2016 and 2018 semesters. A Bonferroni-adjusted alpha level of 0.004 (see *Methods*) was used to correct for multiple comparisons.

(Table 2, example D). 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. Due to the limitations of our survey design, we were unable discern whether students were using ideas of rate when reasoning about our survey items, and we could not confidently characterize students' use of the word "flow." In light of the focus of our research, this was a significant problem.

Despite mulitple attempts to reach consensus in our coding, we were unable to identify interpretive codes or patterns in the data and therefore could not achieve an acceptable level of IRR. We felt that students' written explanations could not be used to identify patterns in student reasoning. While we were hesitant to make substantive claims about student reasoning from such limited evidence, the conversation among the coders yielded valuable insights and served as the foundation for study 2.

Discussion

Distinct Differences across Disciplines. We consistently observed a significant difference in the way students in HA&P courses responded to our survey compared with students in physics courses (Figure 3). In 2016, we observed distinct differences in the way students in HA&P responded to the FFR, pressure, and resistance items compared with responses from students enrolled in physics. In 2018, we observed differences in response patterns between HA&P and physics students for all four items on our survey. Due to the challenges we encountered coding student explanations, we are limited in our ability to explain the differences we observed. We can, however, lean on insights from our previous work with experts (Slominski *et al.*, 2020) to provide some explanation as to why students in HA&P and physics would respond differently to the items in our survey.

We know from interviews with biologists, as well as our own experiences as instructors, that resistance is typically included in HA&P instruction and is recognized as a useful idea when thinking about FFR. In contrast to HA&P, resistance is not usually considered in an introductory physics course (at least as it pertains to fluids; Slominski *et al.*, 2020). Therefore, physics students may be relying on different resources to make their predictions than HA&P students. For example, the increased proportion of equal rankings in response to the FFR item could be due to physics students applying the continuity equation. Because our prompt states "volume of blood/water entering the left end of the blood vessel/pipe every second is the same in Systems A, B, and C," if a student is using the continuity equation to answer this prompt, we would expect them to say FFR would be the same at locations A, B, and C. Further, because physics students are not typically taught about resistance in the context of fluids, we also expect physics students may be relying on different ideas than HA&P students when answering the resistance item. Physics students are not taught about resistance (in the context of fluids), but they are taught about friction and viscosity. It may be that physics students are equating resistance to friction or viscosity and said they were equal across all three vessels/pipes because the text provided in our prompt states "the blood/water viscosity is very low."

In contrast to physics students, HA&P students are primarily instructed to consider vessel length, radius, and blood viscosity when reasoning about FFR. In the systems presented, the vessels/pipes are all the same length, and the viscosity of the blood/water is the same. The only difference across the scenarios is the radius. In a typical HA&P course, students will learn that the smaller the radius, the greater the resistance to flow (Slominski *et al.*, 2020). Operating under this knowledge, if the resistance increases (because of a decrease in vessel/pipe radius), the FFR would decrease. More HA&P students responded with a ranking consistent with this type of reasoning compared with physics students (Figure 3), andit is therefore likely that HA&P students are primarily focusing on the physical features of this system (i.e., diameter and length of the vessels/tubes) and are less likely to employ ideas like the continuity equation.

While our data cannot directly attribute these differences to instruction, our previous work (Slominski *et al.*, 2020) reveals distinct differences in the ways experts from biology and physics think about 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.

Looking across the FFR, pressure, and resistance items, there is a noticeable trend that seems to demonstrate a preference for "equals" answers among physics students (Figure 3). While our current study cannot fully explain this trend, we expect physics students are focusing more on the universal laws they perceive to be relevant (i.e., conservation laws) compared with HA&P students, who are focusing primarily on the physical features of the system and the differences across those features (i.e., vessel/pipe diameter). As described by Redish and Cooke (2013), biology (compared with physics) places greater value on describing the features of the system and emphasizes the importance of individual relationships found within individual systems. In contrast, the cultural norms of physics encourage one to simplify or abstract a system to form a complete understanding of phenomena, while emphasizing the universal laws and constraints that hold true, regardless of system-specific details (Redish and Cooke, 2013). It may be that HA&P students are more likely to frame these prompts (regardless of item context) as biology questions and, as a result, engage in the behaviors typical of the discipline (i.e., focus primarily on the perturbations of the physical features in the system); however, we are limited in our ability to explain this pattern as there is nothing explicit in the data (i.e., student explanations) that would definitively identify students as using this strategy.

Contextual effects Remain Unclear after Coding Extended Responses. While we observed some instances of students' response patterns being affected by item context, this result was inconsistent across our data (Figure 4): 14 of the 16 BV versus WP comparisons were not statistically different. Similarly, we observed instances where the ordering of our survey items appeared to impact student response patterns, but this effect appeared to be item context dependent at times (Figure 4). These findings align with previous works that claim an assessment's design and surface features impact student reasoning (Gouvea and Simon, 2018), especially for novice learners (Chi *et al.*, 1981).

However, the difficulty we experienced when attempting to interpret students' extended responses lessens the utility of our results. Students' explanations evoked teleological phases, although the wide range of specificity, clarity, and word count provided in students' responses made it difficult to confidently identify teleological reasoning (Table 2). Our study design limited our ability to make interpretive claims based on the reasoning students provided, and thus prompted our second study, which used interviews to more fully explore how disciplinary context impacted student reasoning surrounding fluid dynamics.

STUDY 2

Our review of student reasoning in study 1 suggested students may be using teleological or needs-based reasoning about our complex system (Table 2, example F). This observation aligns with data from earlier research 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 (Michael, 2007; Sturges and Maurer, 2013; Slominski *et al.*, 2019). Our initial observations of student explanations also aligns with work from the systems thinking body of literature, which argues that novice learners struggle with causality and emergence when reasoning about complex systems and look for agency in the system (Chi, 2005; Chi *et al.*, 2012; Levy and Wilensky, 2008; Grotzer *et al.*, 2017). 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 survey (study 1; Table 2, example A). This application of internalized ideas and experiences to a new setting may be similar to the ideas and notions presented in the resources and framing literature (Smith *et al.*, 1994; Hammer and Elby, 2003; Hammer *et al.*, 2005; Gupta *et al.*, 2010).

In study 2, we take a qualitative approach to understanding the role of item context on student reasoning in HA&P. We use semistructured, think-aloud interviews to unpack the explanations offered by students in study 1. We leverage the resource and framing literature to explain how the item context of our items may result in students activating differing knowledge structures and, as a result, reasoning about fluid dynamics in very different ways.

Methods

In response to the coding difficulties we experienced in study 1, we conducted think-aloud interviews with HA&P students to better capture their reasoning about fluid dynamics. We developed a semistructured interview protocol based on our fluid flow survey (study 1; Figure 1). As in study 1, we developed two versions of our interview protocol, one situated in the context of blood and vessels (BV) and a protocol situated in the context of water and pipes (WP). The interviews were conducted by T.S., a graduate researcher with a disciplinary background in biology and experience teaching HA&P at the undergraduate level.

Interview Participants. Because we were specifically interested in the impact of item context on HA&P student reasoning, we exclusively recruited from the introductory HA&P course. Students were solicited via email from the second course in the introductory HA&P series at NDSU, and each student received $20 as compensation for participating in our study.

A total of 18 HA&P students volunteered to participate in our interview study. One student who had taken a course taught by the interviewer (T.S.) was excluded from the study. Of the remaining 17 students, four students either did not respond to scheduling emails or had a scheduling conflict and were unable to participate in the interview study. We used the first interview time slot as a trial/pilot interview. Thus, we recruited a total of

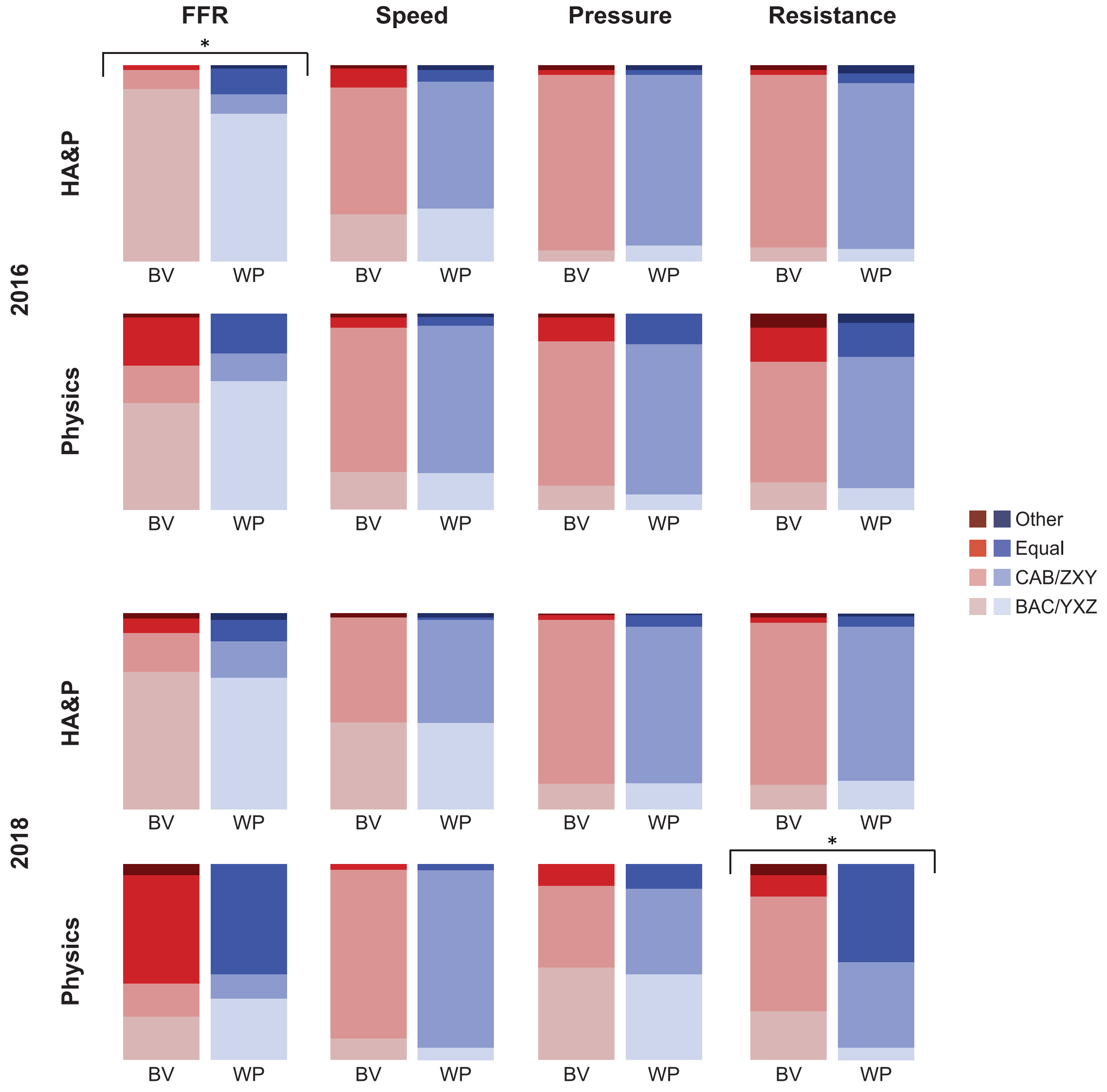


FIGURE 4. Comparison of rankings across item contexts within an individual course. A Fisher's exact test was used to determine whether the proportions of the provided rankings were different across the two item contexts within an individual course for data collected in the 2016 and 2018 semesters. A Bonferroni-adjusted alpha level of 0.004 (see *Methods*) was used to correct for multiple comparisons.

12 study participants, and we randomly assigned six participants to the BV version of our protocol and six to the WP version.

In relation to the HA&P instruction timeline, the interviews were conducted approximately 1 week after students had received relevant instruction on the topics and approximately 2 days before a summative exam containing that material. Data collection for study 2 occurred in Spring 2018, before data collection for study 1; all study 2 participants were removed from study 1, as they would have been primed by participating in the interview before taking the written diagnostic.

Interview Protocol. During the interview, students were presented with survey items one at a time and asked to provide an answer and then explain their reasoning. Students were also asked follow-up questions intended to help them elaborate on their explanations. All students were provided with a handout containing both the introductory text and explanatory figure of the BV or WP protocol to ensure they always had access to relevant information (pressure and flow comparisons). In light of our observations in study 1, we did make a small modification to the FFR item when converting our survey to an interview protocol. Because it was at times unclear if students were conflating speed and FFR, we decided to include a definition of FFR when asking students to provide a ranking for the FFR item:

Interviewer:	Okay. The next question I have is, can you order the fluid flow rate, and so by that I mean the volume of blood flowing per unit of time, coming out of the right side of the vessels. And then, again, if you think they're equal you can say that they're equal.

TABLE 3. Coding rubric developed through thematic analysis

Theme		Theme description	Example
Conceptual	Difficulty with fluid flow rate (DwFFR)	Participant may be unable to provide a definition of fluid flow rate. Participant may confuse fluid flow rate with speed or volume.	Referring to "fluid flow rate" as speed
	Difficulty with resistance (DwR)	Participant 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).	Referring to "resistance" using vague language or misusing terms like "friction," "push," "pull"
Epistemological	Direct relationship (DR)	Participant makes use of a direct relationship between two variables. Participant articulates 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."
	HA&P material (HAPM)	Participant may make explicit use of HA&P class material or resources (e.g., equations, definitions, instructor, etc.). Participant may make direct references to examples and analogies using HA&P content not provided by the prompt.	BV version: Student refers to the heart, capillaries, cardiac output, vasoconstriction, etc. WP version: Student refers to blood, vessels, heart, etc.
	Everyday examples (EE)	Participant makes use of examples and analogies that do not contain HA&P content.	Water hose, a dam, a balloon, etc.
	Physics and/or math (P/M)	Participant makes explicit use of material or resources from a physics or math class.	Equations, definitions, or course instructor
	Teleology (TEL)	Participant uses explanations that suggest they are thinking about phenomena in terms of their purpose, not in terms of causal mechanisms. Participant uses phrases that focus on the needs or goals of the broader system.	Phrases containing "needs to," "has to," "wants to," "in order to," etc.

All interviews were completed in under 25 minutes. The interviews were conducted by T.S. and both audio and video were recorded in the event students physically interacted with the BV or WP explanatory figure when explaining their reasoning. All interviews were transcribed using Rev Transcription software.

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

Analysis Phase 1: Initial Reading. Our analysis of the interview data began with an initial reading of all 12 interview transcripts by T.S., J.M., and W.M.C. During this initial reading, we independently read each of the 12 transcripts and took notes on our early observations, making 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 our notes to identify the similarities and differences of our initial observations. We clarified all differences that were disciplinary in nature and made note of early themes and patterns present in the transcripts.

Analysis Phase 2: Generalizing Themes. Phase 2 of our analysis was completed by T.S., J.M., and W.M.C. Using the insights gained from phase 1, T.S. generated a list of themes based on the early codes that emerged in phase 1. Through discussions, T.S., J.M. and W.M.C. refined those codes. Codes were sorted to identify potential relationships between individual and groups of codes. Identifying these relationships gave way to identifying 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, which resulted in nine 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, T.S. and W.M.C. read all 12 transcripts again and coded each transcript using the established rubric. J.M. also individually coded three transcripts and compared their coding results with those generated by T.S. and W.M.C. Any discrepancies in our coding were discussed until agreement was reached. These discussions 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 seven distinct themes (Table 3).

Results and Discussion

Our goal was to understand how surface-level, item context impacted HA&P students' reasoning about fluid dynamics. Through thematic coding of 12 interviews, we identified seven themes in student reasoning (Table 3). Early analysis of coding results revealed our themes describing student responses fell into two broad categories. First, two of our themes (DwFFR and DwR) indicated points during the interview when students struggled with the concepts themselves (we call these "conceptual themes"). Alternatively, five of our themes are more epistemological in nature (HAPM, EE, P/M, DR, TEL) and describe the kinds of knowledge and reasoning strategies we observed students using when answering our items (we call these "epistemological themes"). We use these categories to guide the presentation of our results and discussion. When presenting our results, we use brackets to indicate which version of the interview protocol students received.

TABLE 4. Coding results of student interviews—conceptual themes

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**
Prompt item	FFR					DwFFR				DwFFR			DwFFR
	Speed								DwFFR				
	Pressure												
	Resistance	DwR	DwR	DwR		DwR	DwR	DwR	DwR	DwR		DwR	DwR

Conceptual Themes. Thematic analysis revealed four of the 12 the HA&P students we interviewed conflated speed and FFR (DwFFR; Table 4), despite being provided a definition. Student P (BV) depicts this:

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 affect each other.

This finding is informative, because FFR is an important concept for understanding cardiovascular physiology in HA&P.

Similarly, four of the 12 students we interviewed struggled to use the concept of resistance (DwR; Table 4) and had difficulty describing resistance in a manner consistent with the definition provided by their HA&P textbook. We observed varying degrees of difficulty, with some students offering alternative descriptions of resistance (Students A, B, C, E, J, and Q) that used ideas like friction or "something" in their description. 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.

Interviewer: Okay. If you had to define resistance, what would you say it is?
Participant N (BV): It slows something down. It resists to whatever, resist to speed, resist to whatever it's resisting to.

While we did not observe an impact of disciplinary context on students' reasoning about the concept of resistance (Table 4), we did observe more students struggling with the concept of FFR in the context of water and pipes compared with blood and vessels. Therefore, disciplinary context may have had a small impact on conceptual difficulties, at least in terms of the concept of FFR.

Epistemological Themes. The remaining five themes we observed (HAPM, EE, P/M, DR, TEL) offer insight into the kinds of knowledge or epistemologies students were tapping into to make predictions throughout the interview (Table 5).

Everyday Examples. Five students in our interview study made use of everyday (or non-HA&P) examples when explaining their reasoning (Table 5). Many of these examples were focused on students' experiences with a water hose:

Student H (WP): 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.

The students we interviewed also made mention of other everyday experiences like living near a dam, filling up a water balloon, or pouring a bottle of wine. In all of these cases, students appeared to be 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 protocol, 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.

Physics and Math. We observed few instances of students making explicit mention of content or equations from their math or physics courses (P/M; Table 5). Two BV students and one WP student made mention of math or physics concepts. Student Q used knowledge and concepts acquired in math and physics

TABLE 5. Coding results of student interviews—epistemological themes

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**
Prompt item	FFR	DR	DR	DR TEL	DR	DR	P/M TEL	DR	DR HAPM	DR	DR EE	DR HAPM	
	Speed	DR EE	DR	DR P/M	DR	DR	P/M	DR HAPM	DR HAPM	DR P/M	DR EE	DR HAPM	DR HAPM
	Pressure	DR HAPM TEL	DR HAPM TEL	DR	DR HAPM TEL	DR TEL	DR P/M	DR EE TEL	DR	DR	DR EE	DR	DR
	Resistance	DR HAPM TEL	DR HAPM	DR HAPM	DR HAPM TEL	DR HAPM	DR HAPM P/M	DR EE	DR HAPM	DR	DR EE	DR EE	DR EE

courses extensively throughout the interview, though this student was atypical, having completed a bachelor of science degree and course work in physics, engineering, thermodynamics, and aerodynamics.

Student Q (BV): 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 [undergraduate institution].
Interviewer: Okay, so not in A&P?
Student Q: Nope.

In another instance, Student F explicitly stated that they were covering fluids in their physics course (Physics 211, the same course included in study 1) when presented with the BV prompt.

Student F (BV): Well, I'm taking physics right now, and we're going over fluid statics [in physics class], but I'm not very good at physics, so I could be very wrong, but I know we discussed … going over blood going through different areas, or, ah, fluid going through different areas, and how it's the same.

Direct Relationships. All 12 students interviewed made use of direct relationships while responding to our items and most of these students relied on these relationships for each of the four items in our interview (DR; Table 5). These direct and sequential relationships consisted of sequential associations between two structures or variables in the system (at the level of the tissue):

Student I (BV): 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 (WP): I would say the size of the exit is what's causing the resistance. The smaller the exit, the higher the resistance.

When probed further, nearly all students did not offer a mechanistic explanation and instead continued to identify how one quality of the system correlates with another:

Student E (BV): 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.

Student E did not identify the physical causes that result in the movement of blood or discuss the event at a microscopic grain (Russ *et al.*, 2008). Instead, Student E continued to rely on a direct relationship between the diameter of a vessel and the FFR of this system.

We observed one student, Student Q (BV), make use of more complex, indirect relationships:

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.

Instead of thinking about the relationship between two or three variables in isolation from the rest of the system, Student Q, who completed a BS degree in STEM, further contextualized our items as being part of an enclosed system. Similar to the characterizations of mechanistic reasoning put forth by Russ and colleagues (2008), we observed Student Q connect an important, relevant feature of the entire cardiovascular system structure (at the macro level) to two smaller components of that same system. We recognize Student Q's response does not necessarily resemble the mechanistic reasoning characterized by Russ and colleagues (2008) and others, but the explicit attention on enclosed systems was unique to this student.

Overall, analysis of our interview data revealed few instances of students articulating a mechanistic reasoning strategy in response to our prompts. The students we interviewed may have developed the necessary mechanistic reasoning abilities, but our prompts may have cued them to employ different reasoning strategies (i.e., causal reasoning or teleology). Most students did not appear to be reasoning about the whole system, but instead, components within that system (i.e., only the structures we presented to them). Therefore, it is likely that most students were not considering either indirect effects on the system or feedback to the system. Consistent with existing work on systems thinking, the students interviewed in this study rarely discussed causality and may have misinterpreted the emergent processes driving fluid dynamics as direct and linear (Chi, 2005; Chi *et al.*, 2012; Jacobson and Wilensky, 2006; Sommer and Lücken, 2010; Hmelo-Silver *et al.*, 2007; Scott *et al.*, 2018).

Teleological Language. The BV context prompted students to use teleological phrasing, while the WP context did not, as only one student (Student A) used teleological phrasing in response to the WP protocol (TEL; Table 5). Teleological responses were used more frequently in response to the pressure and resistance items compared with the FFR item. We did not observe any students using teleological phrasing in response to the speed item.

In most cases, students who received the BV version of our protocol used teleological phrasing to explain functions of the cardiovascular system[1]:

---

[1] The full text is provided for context and clarity; we underline portions of students' responses that were especially relevant in the coding rubric we present.

Student C (BV): If there's irregular resistance, it creates turbulence, so it doesn't go necessarily the direction you want to. It's 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.

When asked to explain these teleological phrases, Student C briefly mentioned a pressure gradient, but it is not clear whether the student is aware of the actual mechanisms driving blood flow. Student C used additional teleological phrases and continued providing an explanation that was goal driven. We consider this exchange (and others like it) as evidence of students' framing our items in a manner that evoked a teleological resource.

Consistent with previous literature on student difficulties in HA&P, our data suggest 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 (Cliff, 2006; Michael, 1998, 2002; Michael *et al.*, 1999; Modell, 2000; Sturges and Maurer, 2013; Badenhorst *et al.*, 2016; Slominski *et al.*, 2017, 2019). This focus on function resulted in students using language and phrases that assigned agency and intentions to individual components of the system, often in the form of teleology. When pressed on their teleological phrasings, students continued to describe direct associations between the system's components and rarely acknowledged the preceding, causal events when explaining the phenomena.

Impact of Disciplinary Context. We compared student responses to the BV protocol with the WP to elucidate the impact of item context on students' reasoning of fluid dynamics. The students who responded to the BV protocol noticed the biological content embedded in the interview items and then seemed to embrace that content, further contextualizing their thinking in HA&P content:

Student C (BV): So, in anatomy when you want pressure to go up, your blood vessels will constrict, so it will make it smaller, and then your blood pressure will go up. I know I should know more of the theory behind that, but I know that to be true. The smaller it is, the higher the pressure. So, it would be Y, X and Z [smallest diameter to largest].

Four out of the six students who were interviewed with the WP protocol 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, and at times very explicitly, as in this repsonse from Student A:

Student A (WP): 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 [pipe B].

In this case, Student A directly called the interviewer's attention to the introduction of HA&P content. Other students introduced HA&P content more subtly:

Student J (WP): The speed for water would be, pipe E would be going the fastest. Then D, then F [smallest diameter to largest].
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 [*sic*] 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 introduced the term "vessel" without any prior mention of HA&P content. We consider this voluntary inclusion of HA&P structures as evidence of Student J using an HA&P frame. Later in the interview, Student J made the framing more explicit and offered an HA&P example to aid in their articulation of their 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 [largest diameter to smallest].
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.

Student J introduced additional HA&P structures and functions, indicating they consider these to be applicable and useful 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.

Under the framing and resources framework (Hammer and Elby, 2003; Hammer *et al.*, 2005), the surface features used in articulating a scenario or a problem can dictate how a student situates or frames the problem internally (Gouvea and Simon, 2018). When a student situates a problem using a particular frame, either subconsciously or consciously, it results in the activation and integration of particular conceptual resources. If we apply the framing and resources theoretical framework to our observations, our coding suggests most of the students interviewed applied a frame where a student accessed a number of HA&P resources. The students who received the BV protocol noticed the embedded biological content 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 (BV):	Probably go Y, X, Z [smallest diameter to largest].
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 above exchange, 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), even including a nod to the function of the cardiovascular system with mention of "oxygen coming through the blood."

A hallmark of the framing and resource theoretical framework is the perspective that reasoning is dynamic in nature, rather than stable and constant, and students will activate different suites of conceptual resources based on how the task is framed (Gouvea and Simon, 2018). This aligns with the patterns we observed in all of our interviews—applying an HA&P frame often resulted in the introduction of teleological reasoning strategies (Table 5). We did not observe students in the WP group employing teleological reasoning strategies without first framing the problem with an HA&P frame. This emergence of teleological reasoning and only in conjunction with an 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 (Kelemen, 1999a,b; Coley and Tanner, 2012, 2015). 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). Further, our findings align with Southerland and colleagues' (2001) "need as a rationale for change" resource, as we observed students explaining phenomena in terms of what the blood or vessels must do to facilitate their function, which ultimately is necessary to sustain life in organisms with a cardiovascular system.

While teleological reasoning is not considered biologically accurate by many in the biology education community, others would argue that students' use of teleology is more nuanced than simply right or wrong (Zohar and Ginossar, 1998; Kampourakis, 2020; Trommler and Hammann, 2020). Counterproductive and biologically inaccurate teleological reasoning (sometimes referred to as "ontological") assumes that the structures and behaviors of a system exist to accomplish a particular goal or function. However, teleology can be a productive, epistemological tool to identify and describe biological phenomena and thus organize and construct accurate biological explanations, especially by experts (Trommler and Hammann, 2020). This epistemological utility could explain why teleological reasoning would be frequently activated and eventually become locally established in an HA&P frame.

We did observe students incorporating teleological language in somewhat different ways, which may indicate that teleology is serving differing roles among the students we interviewed. For some, teleological language was at the forefront of their explanations and appeared to serve a more explicit role in their rationales (Student C). For others, goal-oriented language was revealed only after probing their earlier responses (Student I). This difference could be the result of some students using teleology in a more direct, ontological sense, whereas other students are using teleology more as a productive, epistemological tool to organize their knowledge of the system or the way they communicate that knowledge (Trommler and Hammann, 2020). Given the complex role teleology can have in student understanding of biological phenomena, it is not surprising that students' language around teleology may be different, but their final rankings are not. Depending on the prompt, goal-oriented reasoning can lead students to select a "correct" answer, especially if that prompt fails to distinguish between the biological function and biological mechanism of a system.

We might wonder, however, what causes students who responded to the WP protocol to apply an HA&P frame when there were no disciplinary contextual features in the prompt that would explicitly cue 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 *other* feature of our protocol or the interview itself that subconsciously encouraged students to frame these items as a biology or HA&P prompt (Hammer *et al.*, 2005; Gouvea and Simon, 2018). 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 in the days before the interview. Students may even have 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 be contributing to a sort of recency effect, a theory from cognitive psychology suggesting students would be more likely to recall material they had most recently been presented with (Cowan *et al.*, 2002). It could be that students' experiences earlier that day (or week) 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 an HA&P frame in a non-biological context may be evidence of developing expertise, particularly since we observed experts applying an HA&P frame to the WP version of our protocol (Slominski *et al.*, 2020). Further qualitative work would be needed to determine with a large degree of certainty what encouraged students to apply an HA&P frame to the WP prompt.

We also observed instances when students appeared to be using a non-biological frame to reason about our items. As stated previously, Student Q had an atypical background compared with the other students interviewed in this study, and their response to our interview protocol (see *Physics and Math*) embodies those differences in experience.

In contrast 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 5) when responding to the questions regarding resistance. It is important to note that the term "resistance" is not used in relation to fluid dynamics in physics curricula (Slominski *et al.*, 2020), and it is therefore possible that the topic of resistance caused Student Q to reframe the problem in a way that aligns with their experiences and beliefs of that term (an HA&P frame).

Finally, every student in our study made use of simple relationships. The pervasiveness of this strategy suggests some contextual feature of our interview protocol may have encouraged this behavior. It is possible all students, even those previously identified as having applied an HA&P or non-biological frame, subconsciously (or even consciously) identified this as a sort of simple systems problem.

In our previous work (Slominski *et al.*, 2020), we found that experts initially focused on similar components of the system (e.g., changes in vessel diameter), which is to be expected due to the design of our prompt. Unlike most of the students we interviewed, experts typically went on to expand the scope of their reasoning to consider the entire system. As a result, experts considered other important features of the system (e.g., feedback) and the system's components (e.g., properties of the fluid).

By framing these tasks 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 (Jacobson and Wilensky, 2006; Hmelo-Silver *et al.*, 2007; Russ *et al.*, 2008; Sommer and Lücken, 2010; Chi *et al.*, 2012; Scott *et al.*, 2018). This expectation aligns with our observations of the data (Table 5), suggesting HA&P students may use a simple systems frame when faced with any problem that, regardless of surface-level, item context, focuses on a complex system.

Study 2 Summary. Across our interview data, we observed several impacts of disciplinary context on student reasoning about fluid dynamics. First, we found that the students who received the BV version of our protocol were more likely to use teleological phrasing than those students who received the WP version (Table 4). Second, students who received the WP version were more likely to use non-HA&P examples than those students who received the BV protocol. Finally, item-level disciplinary contextual effects did not appear to affect students' use of direct relationships, as all students in our study demonstrated this type of reasoning strategy at various stages during the interview.

GENERAL IMPLICATIONS

Context Matters

In study 1, while we did not find strong evidence that disciplinary context impacted students' rankings of items related to fluid dynamics, we found evidence that course context impacted student rankings. Our earlier interdisciplinary work with experts (Slominski *et al.*, 2020) revealed distinct differences in the ways experts from biology and physics think about fluid dynamics; our present research extends this finding to students: Students in HA&P responded to our survey in significantly different ways from students enrolled in physics.

The results of study 2 align with previous works that suggest item context can impact student reasoning (Smith *et al.*, 1994; Gouvea and Simon, 2018). Our work demonstrates the value of the resources and framing theoretical framework to BER, as we found evidence for an HA&P-like frame, which was associated with teleological resources. Our interview study revealed that item context can evoke ideas and explanations (i.e., teleology) that may otherwise go unmentioned in a different (non-biological) context, and our findings support others in the BER community who advocate for a dynamic view of cognition.

Implications for Research

Cross-disciplinary Implications. To our knowledge, there have been few studies using an interdisciplinary approach to investigate student understanding of crosscutting STEM concepts at the undergraduate level. In the research presented here, we focused on one specific crosscutting 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 crosscutting concepts have in introductory instruction and work to repeat our approach, focusing on additional crosscutting concepts as defined by national documents (NGSS Lead States, 2013).

The data for both study 1 and study 2 come from the same institution, and it is unclear if the patterns we observed in student reasoning are unique to our institution or indicative of the broader STEM undergraduate population. Replication research studies would be essential in determining whether the differences in understanding of fluid dynamics between HA&P and physics students are specific to our university or if they persist more broadly. If these differences are representative of the broader undergraduate population, it is essential efforts be made to better understand how these differences in student understanding of fluid dynamics impact students' learning at later points in their undergraduate careers. Our previous work indicates the instructors of these courses may also differ in their approaches to solving problems about fluid dynamics (Slominski *et al.*, 2020), although 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 among all other STEM disciplines.

Our work also 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 varies with context. This framework has had limited use outside physics education research but, as our work demonstrates, can be used to explain how students reason about biological phenomena.

Implications for Research on Student Reasoning. The findings from study 1 and study 2 also add to a growing body of research that indicates disciplinary contextual 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. Researchers should consider how the context embedded in their research tools impacts the pre-existing knowledge structures students are calling upon. We recognize this is a large task for BER, as our prompts are often highly contextualized, making the role of item context an important question to consider.

We also encourage biology education researchers to consider the role of students' pre-existing knowledge and resources in students' reasoning and to consider the affordances of those existing knowledge structures to student reasoning. By systematically unpacking students' reasoning, especially in the case of "wrong answers," we can identify students' useful pre-existing conceptions and begin to understand how to support activation of these conceptions in a way that aligns with a more expert-like mental model (Hammer, 1996). In the case of teleology, while it is often the case that teleology can lead students to form a biologically inaccurate mental model of a system, it is also possible students are using this reasoning strategy in a way that helps them accurately identify and describe the relationships present in a biological system. Undergraduate HA&P students, regardless of student demographics and instructional settings, are drawn to using teleological reasoning (Sturges and Maurer, 2013; Slominski *et al.*, 2019), so more work is needed to understand how to help students productively lean in and benefit from the epistemological affordances of teleology while also deterring them from falling into the conceptual snares of a biologically inaccurate, ontological application. We believe a fruitful next step would be to explore strategies that encourage novice learners to be more attentive of their use of early, intuitive ideas, especially when reasoning about complex, biological systems.

Methodological Implications. This work also highlights the methodological limitations of relying exclusively on students' constructed responses as evidence of students' reasoning. As demonstrated in Table 2, students' explanations varied greatly in the amount of insight into student thinking they revealed. While some responses illustrated student thinking quite well (Table 2, example A), many responses left us questioning the ideas students used when interpreting our prompt and how they assembled those ideas to form an explanation (Table 2, examples B, C, and E). Because we sought to understand how item context impacts the explanations students generate, we believed the limitations of analyzing constructed-response items would greatly hinder our ability to make claims regarding student reasoning. Therefore, in study 2, we chose to leverage the affordances of semistructured interviews. While the effort required to conduct, transcribe, and analyze interview data typically limits a study's sample size, the ability to further clarify and probe participants' responses in real time can yield insights that are often unattainable from traditional constructed-response instruments. This was especially apparent in study 2, as students' teleological language and ideas were only revealed after a series of follow-up questions.

When considered together, the findings of study 1 and study 2 highlight the benefits of a mixed-methods approach. Study 1 enabled us to identify a course context effect, but the approach obscured the nuances of student reasoning. The qualitative design of study 2 enabled us to focus solely on probing student reasoning, allowing us to reveal patterns in student reasoning not captured in our earlier, quantitative study (study 1). Leveraging mixed-methods approaches enabled us to characterize student cognition more robustly.

Implications for Instruction

Our results have several implications for instruction. First, one of the most noteworthy findings of this work is that, after instruction, students in our HA&P courses and introductory physics courses have very different ideas regarding fluid dynamics. This observation is concerning when we consider how many students are required to complete both courses (sometimes simultaneously) before they can move on to their professional programs. Those students may compartmentalize their knowledge of physics from HA&P and struggle to develop a coherent understanding of fluid dynamics.

Our research also indicates students are likely receiving somewhat conflicting instruction regarding these topics, especially as it pertains to the concepts of resistance and FFR. Our findings here, as well as our earlier work with experts (Slominski *et al.*, 2020), demonstrate the different value these concepts hold across biology and physics. In the case of resistance, biology students and experts frequently made use of this concept in the context of fluid dynamics. However, the concept of resistance is seemingly confined in physics curricula to electric circuits. We have no knowledge of whether and how students reconcile these conflicting ideas to generate a productive mental model of fluid dynamics. As such, biology and physics instructors need to be aware of this stark difference across curricula, and interdisciplinary efforts are needed to provide targeted support to students to help them reconcile concepts that lie at the intersection of biology and physics (e.g., the Hagen-Poiseuille equation; Redish and Cooke, 2013).

Further, if students receive conflicting instruction on the topic of fluid dynamics between HA&P and physics courses, it is possible there are other crosscutting concepts that are misaligned between the various STEM disciplines. Administrators and instructors need to work toward 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, we advocate educators move away from the more traditional notion of misconceptions and embrace a dynamic view of student difficulties. Recognizing that students 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 (Nehm and Ha, 2011; Heredia *et al.*, 2016; Gouvea and Simon, 2018; Göransson *et al.*, 2020; Lira and Gardner, 2020), 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 contextual effects.

GENERAL CONCLUSIONS

We used a mixed-methods approach to understand how HA&P students reason about fluid dynamics and whether that reasoning was affected by surface-level, disciplinary context. By sampling students from HA&P and physics courses, we were able to control for disciplinary effects and explore the role disciplinary 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 disciplinary contextual features may impact student reasoning when they are asked to reason about complex systems. Through a series of interviews, we found evidence to suggest HA&P students frame fluids problems using a lens that situates those problems as HA&P problems, 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 phrases. We also found evidence to suggest HA&P students rarely employ mechanistic reasoning strategies when reasoning with fluid dynamics and, instead, rely on linear, surface-level relationships.

This research adds to the growing body of work that recognizes the impact disciplinary contextual features can have on student reasoning surrounding biological questions. 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 BER.

ACKNOWLEDGMENTS

This investigation was conducted in compliance with the Institutional Review Board regulations (protocols no. SM18224, no. SM20237, and no. SM15258). We thank the students who participated in our study. Without their participation, this study could not have been conducted. We thank members of the Momsen lab for many valuable discussions. We also thank the University of Maryland Physics Education Research Group, especially Edward (Joe) Redish, for their insightful discussions and feedback on this project. We thank Rachel Barker and Hanna Berger for their contributions made during the NDSU REU program. This study was supported by the NDSU Graduate School through the STEM Education PhD Fellowship, the National Science Foundation (DUE 1560142), and the North Dakota Experimental Program to Stimulate Competitive Research Infrastructure Improvement Program–Doctoral Dissertation Assistantship.

REFERENCES

Alters, B. J., & Nelson, C. E. (2002). Perspective: Teaching evolution in higher education. *Evolution*, *56*(10), 1891–1901. Retrieved October 15, 2021, from https://onlinelibrary.wiley.com/doi/abs/10.1111/j.0014-3820.2002.tb00115.x

American Association for the Advancement of Science. (2011). *Vision and change in undergraduate biology education*. Washington, DC. Retrieved October 15, 2021, from http://visionandchange.org

Badenhorst, E., Mamede, S., Abrahams, A., Bugarith, K., Friedling, J., Gunston, G., … & Schmidt, H. G. (2016). First-year medical students' naïve beliefs about respiratory physiology. *Advances in Physiology Education*, *40*(3), 342–348. Retrieved October 15, 2021, from https://journals.physiology.org/doi/full/10.1152/advan.00193.2015

Bishop, B. A., & Anderson, C. W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching*, *27*(5), 415–427. https://doi.org/10.1002/tea.3660270503

Bissonnette, S. A., Combs, E. D., Nagami, P. H., Byers, V., Fernandez, J., Le, D., … & Tanner, K. D. (2017). Using the Biology Card Sorting Task to measure changes in conceptual expertise during postsecondary biology education. *CBE—Life Sciences Education*, *16*(1), ar14. https://doi.org/10.1187/cbe.16-09-0273

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Bureau of Labor Statistics, U.S. Department of Labor. (2021, August 21). *Healthcare. Occupational outlook handbook*. Retrieved November 2, 2021, from www.bls.gov/ooh/healthcare/home.htm

Carnegie Classification of Institutions of Higher Education. (2021). *About Carnegie Classification*. Retrieved January 8, 2021, from http://carnegieclassifications.iu.edu

Chi, M. T. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences*, *14*(2), 161–199. https://doi.org/10.1207/s15327809jls1402_1

Chi, M. T., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, *5*(2), 121–152. https://doi.org/10.1207/s15516709cog0502_2

Chi, M. T. H., Roscoe, R. D., Slotta, J. D., Roy, M., & Chase, C. C. (2012). Misconceived causal explanations for emergent processes. *Cognitive Science*, *36*(1), 1–61. https://doi.org/10.1111/j.1551-6709.2011.01207.x

Cliff, W. H. (2006). Case study analysis and the remediation of misconceptions about respiratory physiology. *Advances in Physiology Education*, *30*(4), 215–223. https://doi.org/10.1152/advan.00002.2006

Coley, J. D., & Tanner, K. (2012). Common origins of diverse misconceptions: Cognitive principles and the development of biology thinking. *CBE—Life Sciences Education*, *11*(3), 209–215. https://doi.org/10.1187/cbe.12-06-0074

Coley, J. D., & Tanner, K. (2015). Relations between intuitive biological thinking and biological misconceptions in biology majors and nonmajors. *CBE—Life Sciences Education*, *14*(1), ar8. https://doi.org/10.1187/cbe.14-06-0094

Cowan, N., Saults, J. S., Elliott, E. M., & Moreno, M. V. (2002). Deconfounding serial recall. *Journal of Memory and Language*, *46*(1), 153–177. Retrieved October 15, 2021, from https://psycnet.apa.org/doi/10.1006/jmla.2001.2805

diSessa, A. A. (1988). *Knowledge in pieces*. Retrieved October 15, 2021, from www.citeulike.org/group/9538/article/4441459

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, *10*(2/3), 105–225. Retrieved October 15, 2021, from www.jstor.org/stable/3233725

Göransson, A., Orraryd, D., Fiedler, D., & Tibell, L. A. (2020). Conceptual characterization of threshold concepts in student explanations of evolution by natural selection and effects of item context. *CBE—Life Sciences Education*, *19*(1), ar1. https://doi.org/10.1187/cbe.19-03-0056

Gouvea, J. S., & Simon, M. R. (2018). Challenging cognitive construals: A dynamic alternative to stable misconceptions. *CBE—Life Sciences Education*, *17*(2), ar34. https://doi.org/10.1187/cbe.17-10-0214

Grotzer, T. A., Derbiszewska, K., & Solis, S. L. (2017). Leveraging fourth and sixth graders' experiences to reveal understanding of the forms and features of distributed causality. *Cognition and Instruction*, *35*(1), 55–87. https://doi.org/10.1080/07370008.2016.1251808

Gupta, A., Hammer, D., & Redish, E. F. (2010). The case for dynamic models of learners' ontologies in physics. *Journal of the Learning Sciences*, *19*(3), 285–321. https://doi.org/10.1080/10508406.2010.491751

Hammer, D. (1996). Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions. *Journal of the Learning Sciences*, *5*(2), 97–127. Retrieved October 15, 2021, from https://psycnet.apa.org/doi/10.1207/s15327809jls0502_1

Hammer, D., & Elby, A. (2003). Tapping epistemological resources for learning physics. *Journal of the Learning Sciences*, *12*(1), 53–90. Retrieved October 15, 2021, from https://psycnet.apa.org/doi/10.1207/S15327809JLS1201_3

Hammer, D., Elby, A., Scherr, R. E., & Redish, E. F. (2005). Resources, framing, and transfer. In Mestre, J. P. (Ed.), *Transfer of learning from a modern multidisciplinary perspective* (pp. 89–120). Greenwich, CT: Information Age Publishing.

Harlow, D. B., & Bianchini, J. A. (2020). Knowledge-in-pieces—Andrea A. diSessa, David Hammer. In *Science education in theory and practice* (pp. 389–401). Cham, Switzerland: Springer.

Harris, D. E., Hannum, L., & Gupta, S. (2004). Contributing factors to student success in anatomy & physiology: Lower outside workload & better preparation. *American Biology Teacher*, *66*(3), 168–175. https://doi.org/10.2307/4451650

Heredia, S. C., Furtak, E. M., & Morrison, D. (2016). Exploring the influence of plant and animal item contexts on student response patterns to natural selection multiple choice items. *Evolution: Education and Outreach*, *9*(1), 10. https://doi.org/10.1186/s12052-016-0061-z

Hmelo-Silver, C. E., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *Journal of the Learning Sciences*, *16*(3), 307–331. Retrieved February 11, 2021, from https://psycnet.apa.org/doi/10.1080/10508400701413401

Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *Journal of the Learning Sciences*, *15*(1), 11–34. https://doi.org/10.1207/s15327809jls1501_4

Jordan, S., Davies, S., & Green, B. (1999). The biosciences in the pre-registration nursing curriculum: Staff and students' perceptions of difficulties and relevance. *Nurse Education Today*, *19*(3), 215–226. https://doi.org/10.1016/S0260-6917(99)80007-0

Kampourakis, K. (2020). Students' "teleological misconceptions" in evolution education: Why the underlying design stance, not teleology per se, is the problem. *Evolution: Education and Outreach*, *13*(1), 1–12. https://doi.org/10.1186/s12052-019-0116-z

Keil, F. C. (1995). The growth of causal understandings of natural kinds. In *Causal cognition: A multidisciplinary debate* (pp. 234–267). Oxford: Clarendon Press/Oxford University Press.

Kelemen, D. (1999a). Function, goals and intention: Children's teleological reasoning about objects. *Trends in Cognitive Sciences*, *3*(12), 461–468. https://doi.org/10.1016/S1364-6613(99)01402-3

Kelemen, D. (1999b). Why are rocks pointy? Children's preference for teleological explanations of the natural world. *Developmental Psychology*, *35*(6), 1440. Retrieved February 11, 2021, from https://psycnet.apa.org/doi/10.1037/0012-1649.35.6.1440

Keller, K. L., & Hughes, F. P. (2021). Does a student's academic major influence their perceptions of a human anatomy and physiology course and ultimately their success in the course? *HAPS Educator*, *25*(2), 13–29.

Krieter, F. E., Julius, R. W., Tanner, K. D., Bush, S. D., & Scott, G. E. (2016). Thinking like a chemist: Development of a chemistry card-sorting task to probe conceptual expertise. *Journal of Chemical Education*, *93*(5), 811–820. https://doi.org/10.1021/acs.jchemed.5b00992

Levy, S. T., & Wilensky, U. (2008). Inventing a "mid level" to make ends meet: Reasoning between the levels of complexity. *Cognition and Instruction*, *26*(1), 1–47. https://doi.org/10.1080/07370000701798479

Lindsay, K. G. (2020). A multilevel binary logistic regression model of success in Anatomy and Physiology I: A retrospective analysis. *International Journal of Research in Education and Science*, *6*(2), 361–368. https://doi.org/10.46328/ijres.v6i2.835

Lira, M., & Gardner, S. M. (2020). Leveraging multiple analytic frameworks to assess the stability of students' knowledge in physiology. *CBE—Life Sciences Education*, *19*(1), ar3. https://doi.org/10.1187/cbe.18-08-0160

Lombrozo, T., & Carey, S. (2006). Functional explanation and the function of explanation. *Cognition*, *99*(2), 167–204. https://doi.org/10.1016/j.cognition.2004.12.009

Michael, J. (1998). Students' misconceptions about perceived physiological responses. *Advances in Physiology Education*, *19*, 90–98. https://doi.org/10.1152/advances.1998.274.6.S90

Michael, J. (2002). Misconceptions—What students think they know. *Advances in Physiology Education*, *26*(1), 5–6. https://doi.org/10.1152/advan.00047.2001

Michael, J. (2007). What makes physiology hard for students to learn? Results of a faculty survey. *Advances in Physiology Education*, *31*(1), 34–40. https://doi.org/10.1152/advan.00057.2006

Michael, J., Richardson, D., Rovick, A., Modell, H., Bruce, D., Horwitz, B., … & Williams, S. (1999). Undergraduate students' misconceptions about respiratory physiology. *Advances in Physiology Education*, *22*, 127–135. https://doi.org/10.1152/advances.1999.277.6.S127

Modell, H. I. (2000). How to help students understand physiology? Emphasize general models. *Advances in Physiology Education*, *23*(1), 101–107. https://doi.org/10.1152/advances.2000.23.1.S101

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

NGSS Lead States. (2013). *Next Generation Science Standards*. Retrieved October 15, 2021, from www.nextgenscience.org

Opfer, J. E., Nehm, R. H., & Ha, M. (2012). Cognitive foundations for science assessment design: Knowing what students know about evolution. *Journal of Research in Science Teaching*, *49*(6), 744–777. https://doi.org/10.1002/tea.21028

R Core Team. (2021). *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing. Retrieved November 3, 2021, from www.R-project.org

Redish, E. F., & Cooke, T. J. (2013). Learning each other's ropes: Negotiating interdisciplinary authenticity. *CBE—Life Sciences Education*, *12*(2), 175–186. https://doi.org/10.1187/cbe.12-09-0147

Richard, M., Coley, J. D., Tanner, K. D., & Sevian, H. (2017). Investigating undergraduate students' use of intuitive reasoning and evolutionary knowledge in explanations of antibiotic resistance. *CBE—Life Sciences Education*, *16*(3), ar55. https://doi.org/10.1187/cbe.16-11-0317

Richardson, D. R. (1990). A survey of students' notions of body function as teleologic or mechanistic. *American Journal of Physiology*, *258*(6 Pt 3), S8–10. https://doi.org/10.1152/advances.1990.258.6.S8

Russ, R. S., Scherr, R. E., Hammer, D., & Mikeska, J. (2008). Recognizing mechanistic reasoning in student scientific inquiry: A framework for discourse analysis developed from philosophy of science. *Science Education*, *92*(3), 499–525. https://doi.org/10.1002/sce.20264

Scott, E. E., Anderson, C. W., Mashood, K. K., Matz, R. L., Underwood, S. M., Sawtelle, V., & Sevian, H. (2018). Developing an analytical framework to characterize student reasoning about complex processes. *CBE—Life Sciences Education*, *17*(3), ar49. https://doi.org/10.1187/cbe.17-10-0225

Slominski, T., Fugleberg, A., Christensen, W. M., Buncher, J. B., & Momsen, J. L. (2020). Using framing as a lens to understand context effects on expert reasoning. *CBE—Life Sciences Education*, *19*(3), ar48. https://doi.org/10.1187/cbe.19-11-0230

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. https://doi.org/10.1152/advan.00040.2018

Slominski, T. N., Momsen, J. L., & Montplaisir, L. M. (2017). Drawing on student knowledge of neuroanatomy and neurophysiology. *Advances in Physiology Education*, *41*(2), 212–221. https://doi.org/10.1152/advan.00129.2016

Smales, K. (2010). Learning and applying biosciences to clinical practice in nursing. *Nursing Standard*, *24*(33), 35–39. https://doi.org/10.7748/ns2010.04.24.33.35.c7716

Smith, J. P., diSessa, A. A., & Roschelle, J. (1994). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences*, *3*(2), 115–163. https://doi.org/10.1207/s15327809jls0302_1

Sommer, C., & Lücken, M. (2010). System competence—Are elementary students able to deal with a biological system? *Nordic Studies in Science Education*, *6*(2), 125–143. https://doi.org/10.5617/nordina.255

Southerland, S. A., Abrams, E., Cummins, C. L., & Anzelmo, J. (2001). Understanding students' explanations of biological phenomena: Conceptual frameworks or p-prims? *Science Education*, *85*(4), 328–348. https://doi.org/10.1002/sce.1013

Sturges, D., & Maurer, T. (2013). Allied health students' perceptions of class difficulty: The case of undergraduate human anatomy and physiology. *Internet Journal of Allied Health Sciences and Practice*, *11*(4). https://doi.org/10.46743/1540-580X/2013.1460

Sturges, D., Maurer, T. W., Allen, D., Gatch, D. B., & Shankar, P. (2016). Academic performance in human anatomy and physiology classes: A 2-yr study of academic motivation and grade expectation. *Advances in Physiology Education*, *40*(1), 26–31. https://doi.org/10.1152/advan.00091.2015

Tamir, P., & Zohar, A. (1991). Anthropomorphism and teleology in reasoning about biological phenomena. *Science Education*, *75*(1), 57–67. https://doi.org/10.1002/sce.3730750106

Trommler, F., Gresch, H., & Hammann, M. (2018). Students' reasons for preferring teleological explanations. *International Journal of Science Education*, *40*(2), 159–187. https://doi.org/10.1080/09500693.2017.1404658

Trommler, F., & Hammann, M. (2020). The relationship between biological function and teleology: Implications for biology education. *Evolution: Education and Outreach*, *13*(1), 1–16. https://doi.org/10.1186/s12052-020-00130-y

Zohar, A., & Ginossar, S. (1998). Lifting the taboo regarding teleology and anthropomorphism in biology education—heretical suggestions. *Science Education*, *82*(6), 679–697. https://doi.org/10.1002/(SICI)1098-237X(199811)82:6<679::AID-SCE3>3.0.CO;2-E