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Work in Progress: How Spatial Concepts are Embedded and Discussed in an Undergraduate Civil Engineering Fluids Class

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Hayden Wulf is a master's student in civil engineering, specializing in structural engineering, with over three years of experience in engineering education research. Hayden's past research has focused heavily on observing changes in classroom environments and instructional practices over time, particularly during disruptions such as the COVID-19 pandemic. Her current research uses an anti-deficit perspective to examine how visuo-spatial skills are taught or perceived with the goal of broadening participation in engineering programs. Following the completion of her master's degree, Hayden plans to work towards a Ph.D in engineering education and pursue a career as a structural engineering professor.

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Abstract

A Civil Engineer is often required to “see” and “imagine” a structure or system that they are designing. Being able to “see” and “imagine” is often referred to as spatial visualization. Spatial visualization skills have been correlated to degree attainment in engineering. Spatial visualization techniques can be used to improve student understanding of complex engineering concepts by supporting the process of visually imagining and interacting with physical or virtual forms in an accurate manner. Despite the importance of spatial visualization within engineering, instructors and students alike are often unaware of the ways spatial information is conveyed within concepts in the classroom and embedded throughout the curriculum. Previous studies have focused on the way spatial concepts are communicated in various STEM contexts, including geology and chemistry, but there is a lack of research focused on how spatial concepts are embedded and discussed within specific engineering disciplines. Thus, the purpose of this pilot study was to identify how spatial concepts are embedded in an undergraduate Civil Engineering fluids course and to characterize the ways the instructor conveyed this information. This work in progress paper is part of a larger study aimed at understanding spatial visualization in Civil Engineering from a pedagogical and student perspective. The research team conducted classroom ethnographic-inspired observations of an accelerated 5-week, 3 credit hour fluid mechanics course in summer 2025 at a R1 university in the Midwest. Data was collected using an observation template based on prior research and was further refined through classroom observations in a different discipline and by watching YouTube videos of instructors teaching engineering. Adapting a spatial concept categorization framework developed by education researchers in geological sciences, it was found that spatial concepts within the fluids course largely focused on describing the interactions between two or more objects, either statically (e.g. the pressure water exerts on a dam wall) or dynamically (e.g. water flowing through a pipe). When conveying these ideas, the instructor relied primarily on verbal descriptions – either of the literal scenario or by providing a metaphor to a simpler analogous phenomenon. The instructor often utilized computer-generated diagrams or hand drawings to convey complex visuospatial information. While language and diagrams were used frequently to convey spatial information, the instructor rarely used gestures or interactive physical/virtual models to demonstrate visuospatial concepts to students. Future work will focus on refining the observation template and observing additional Civil Engineering courses to identify the concepts that are inherently spatial in nature and to describe how these concepts are discussed.

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Introduction

The continued growth of a competent engineering workforce is vital to the U.S.'s ability to remain competitive on a global scale and continue addressing the world's issues [1], [2]. Engineering educators are tasked with supporting the success of engineering students in order to maintain the growth of this workforce. Historically, research has focused on supporting this success by identifying skills that are connected to success in engineering and producing methods for training students to acquire those skills throughout their college programs. One skill that has been correlated with success in engineering is spatial visualization [3] – the ability to produce and manipulate mental imagery of three-dimensional objects [4]. Because engineering students are often asked to utilize spatial visualization skills to complete tasks such as producing sketches or visualizing cross-sections, previous studies have focused on training these skills through avenues such as computer-aided design (CAD) modeling [5] or virtual reality exercises [6]. These methods, however, put students who enter engineering with lower spatial visualization skills, often including women and individuals from lower socioeconomic backgrounds [7], [8], [9], at an inherent disadvantage by focusing on a skill "deficit" among these students, which discourages these students from pursuing STEM degrees [10], [11]. The work discussed here is part of a larger project which aims to evaluate and redesign the curriculum used in civil engineering courses in order to allow students to focus on developing their understanding of new concepts rather than allocating effort towards producing mental imagery in the classroom environment. Thus, the following research questions guide this work:

1. In what ways are spatial concepts embedded in an undergraduate civil engineering fluids course?
2. What methods are used by the instructor of an undergraduate civil engineering fluids course to convey spatialized information?

Literature Review

Spatial Visualization Skills. Spatial visualization skills describe students' abilities to accurately imagine and represent three-dimensional objects, including producing manipulations of these objects such as cross-sections and rotations [4]. These skills, which are often considered elements of a student's broader cognitive abilities, have been identified in previous studies as being particularly relevant in engineering [12], [13]. Engineering students are often asked to use spatial visualization skills during practices such as sketching 3-D objects, conceptualizing object deflections and cross-sections, and understanding object movements. ***Spatial Skills in STEM.*** Previous studies have identified correlations between students' spatial visualization skills and their success in various STEM fields. Spatial visualization skills have served as key predictors of additional skills that are relevant in engineering, such as knowledge acquisition [14] and word problem representation [15]. Additional studies have also identified correlations between students' spatial visualization skills and their success in scientific disciplines, particularly engineering, at the collegiate level [3], [16]. The findings from each of these studies provide evidence that spatial skills are closely connected to a student's ability to succeed in engineering. ***Spatial Skills Disparities.*** However, there are disparities in the presence of spatial visualization skills among varying groups of engineering students. Spatial visualization skills are particularly relevant among novices, who often rely on mental imagery to solve problems, as opposed to experts, who appear to rely more heavily on analytical strategies [14], [17]. Additionally, studies have identified differences between the spatial skills of male and female students, as well as between students from varying socioeconomic backgrounds [7], [8], [9]. However, strategies for developing spatial skills have shown to be equally beneficial for different genders [18] and have even demonstrated the potential to eliminate gender disparities [19]. In alignment with the demand for attracting talent from a variety of backgrounds to STEM fields [2], it is vital that research continues to explore how this disparity can be addressed in engineering education environments.

Methods

To answer the research questions and develop an in-depth understanding of the instructional dynamics of this civil engineering fluids course, an ethnographic-inspired approach was taken.

Fundamentally, ethnography allows for researchers to develop a "detailed day-to-day picture of events" and create a "record" of the "behaviors and beliefs" of a cultural sharing group [20]. This picture of events is compiled through "long-term access to a culture sharing group" (p. 474) and involves the researcher embedding themselves into the environment being studied, collecting observations, writing field notes, and compiling documents and other artifacts [20]. While this study was inspired by the basic data collection structure of ethnography, we chose to focus solely on describing instructional strategies rather than create descriptions of classroom cultural or social dynamics.

Data collection consisted primarily of classroom observations in an accelerated 5-week undergraduate fluid mechanics course at an R1 university in the Midwest. The class was taught in a hybrid format between two campuses, with the instructor splitting time between both classrooms. Therefore, the instructor was teaching in person at Campus A every Tuesday with Campus B having the lecture streamed to their classroom and vice versa on Thursday. Due to this, in-person teaching was observed once a week and the remote lecture was observed on the other day. The observation template was created by the research team, refined through a literature review, and piloted and further refined with videos of prerecorded civil engineering lectures. Resulting from this process, eleven potential methods of content delivery were defined and included as part of the observation template (Table 1).

Table 1: Categories used to classify delivery methods in observations

Category	Definition
Text	Written or typed descriptions of a concept or information about a concept/scenario
Vocal	Spoken words about the concept being visualized
Audio	Use of non-verbal sounds to assist visualization
Video	Use of a video or GIF to assist with the visualization of a concept [21]
Image	Photographs depicting a real-world scene (not drawings or diagrams) including AI generated images depicting real world scenes [21]
Diagram	Computer-generated drawings or depictions of a concept/scenario [22]
Drawing	Digital or physical *hand-drawn* depictions of a concept/scenario (either pre-drawn or made during class) [22]
Deictic Gesture	Gestures indicating toward or emphasizing specific portions of other forms of imagery (e.g. pointing to part of a diagram, underlining a word) [23]
Iconic Gesture	Gestures representing or imitating a physical concept/attribute (e.g. pointing to imitate a vector, holding hand flat to represent a plate) [23]
Physical Model	*Interactive* real-world modeling of a concept using physical props or tools [24]
Virtual Model	*Interactive* virtual modeling of a concept using computer software [25]

Author 1 completed all course observations, attending all nine of the four-hour lectures. Observations captured both an instructor's delivery method and a summary of the spatial content being conveyed (example given in Figure 1). After lectures, Author 1 refined observation notes by expanding on shorthand and inserting images and figures the instructor used from lecture notes. Additionally, Author 1 maintained a field notes journal, recording their thoughts and experiences during data collection. Exploratory data analysis was conducted by Authors 1 and 2 under the supervision of Author 3. Authors 1 and 2 first developed a concept inventory using the syllabus from this and three other fluids courses to understand how delivery methods varied by concept, if at all. This concept inventory consisted of 14 items covering both fundamental topics (e.g. Fluid Properties) and complex applied topics (e.g. Using Energy balances to solve fluid problems). In initial coding, Authors 1 and 2 coded observations into the applicable topic(s) independently, before meeting to develop a consensus. This study, while providing a unique insight into a single fluids course, is limited in that it looks at a single course and instructor in an accelerated course context. Thus, it is difficult to make any major conclusions about instructor behavior or teaching methods in the broader civil engineering context.

Results

A total of 195 examples of visuo-spatial information were recorded over the nine-lecture accelerated course, summarized in Figure 2.

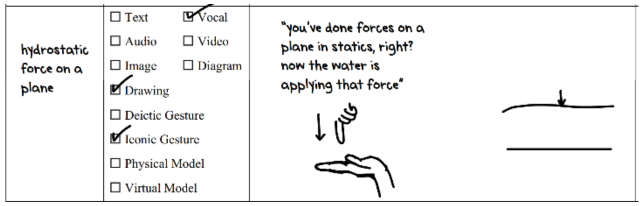

Figure 1: Example of an observation recorded during a lecture

Looking at the frequency of delivery method used (Figure 2A), we see that the instructor relied primarily on vocal explanations, diagrams, and drawings to convey spatialized information to students. Verbal delivery was the most prevalent in the lecture-driven classroom. Verbal explanations were occasionally utilized alone (e.g. verbally explaining the difference between laminar and turbulent flow) but were typically employed in conjunction with another delivery method. For example, the instructor would frequently show students a diagram or drawing, and then verbally walk students through the physical situation being represented (e.g. the direction of fluid flow in a system, the way flow might develop at a boundary layer, etc.). Verbal delivery was also heavily intwined with instructor gesturing. Iconic gesturing (such as using hands to mimic the flow of water) was used during verbal instruction to create a physical manifestation of the phenomena the instructor was discussing, such as holding a hand up to mimic a static wall. Iconic gesturing was used to mimic the movement of fluids and energy in a system, impart a sense of scale onto students (for example the difference in a short versus long pipe), and represent force vectors in a system. Deictic gestures (such as pointing) largely served to draw students' attention to specific areas or diagrams that were being discussed, for example pointing to one of four diagrams showing different flow regimes. In contrast, the instructor rarely made use of videos and physical or virtual models during instruction. Videos, for example, were only used three times in the course and served to highlight concepts that were both spatialized and time dependent – such as the differences between streaklines, streamlines, and pathlines. Interactable physical and virtual models were also seldomly used in the course, but allowed students to directly interact with physical phenomena, such as a virtual model that allowed students to experiment with how buoyancy was affected by object shape and fluid properties. Although both videos and models provide benefits to demonstrating spatial and temporal information, they also require an instructor to invest a significant amount of time into screening content or developing activities. This barrier may prevent instructors from fully implementing these methods despite their benefits.

Next, we examined delivery method by topic (Figure 2B). Most topics were largely delivered via text or verbal methods, aligning with a lecture-based course. Iconic gesturing was used most when explaining hydrostatics (forces applied to forms, planes, and surfaces in contact with fluids), static pressure (inherent properties of pressure in non-moving fluids), and flow classification (defining different types of fluid movement over space and time). Interestingly, these three topics are rooted in the physical interaction of objects suggesting gesturing was utilized in demonstrating these types of relationships. For example, when discussing hydrostatics, the instructor would frequently gesture to indicate the relative direction of force vectors acting on an object. Similarly, in discussing flow characterization, the instructor would use his hands to represent the movement of fluid particles in different flow conditions. These methods allowed the instructor to convey both movement and location information to students in all three dimensions rather than have students extrapolate these features from two-dimensional drawings or diagrams. Another notable variation is in the instructor's use of computer-generated diagrams and handmade drawings. While both were frequently used, computer-generated diagrams were used when a detailed depiction of a spatial phenomenon was warranted. This is most clear when discussing how moving fluids interact with physical boundaries (Boundary Layers). The instructor relied heavily on diagrams that depicted features such as pipe curves, valves, and entrances and the way these features impacted fluid streamlines. While these features could be drawn, diagrams provide a higher level of precision and clarity than a hand drawing. On the other

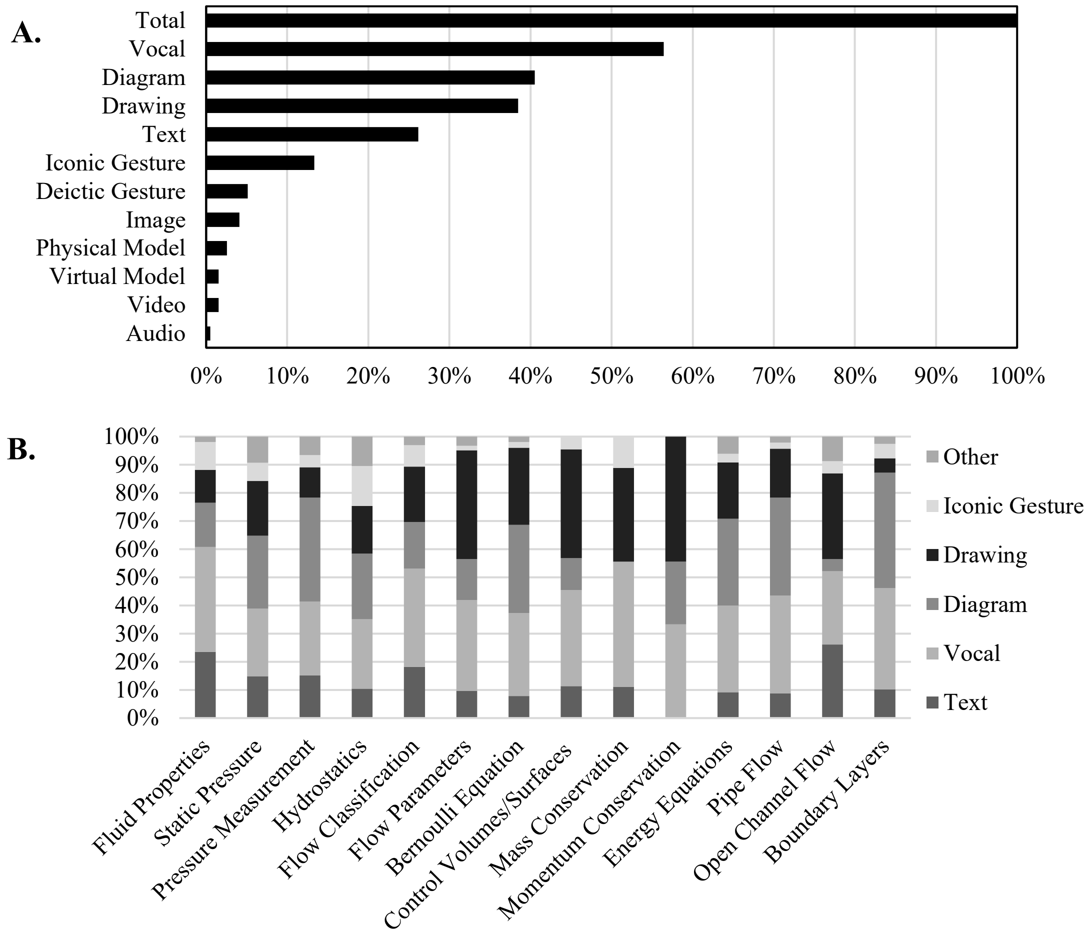

Figure 2: Summary of observational data. **A.** Percentage of delivery methods used over the 9-week accelerated course **B.** Summary of top five delivery methods used by course topic.

hand, drawings allowed the professor flexibility in making quick representations of phenomena being discussed or in creating simplified representations capturing only the key components of a particular problem.

Discussion & Recommendations

To contextualize the results of our preliminary analysis we turned to Cognitive Load Theory (CLT) [26]. In CLT, two main sources of load occupy working memory resources: the inherent difficulty associated with a particular task (intrinsic load) and the additional load generated by instructional practices, particularly those that are nonoptimal (extraneous load) [27]. The leftover working memory not occupied by these loads is devoted to the learning and internalizing of the presented information (gemane load) [27]. Thus, the goal is to optimize the learning process by reducing the amount of working memory capacity that students are required to allocate to extraneous activities, such as producing and manipulating mental imagery, when learning [28]. We suspect that some methods of delivery of spatial content place a higher load on students than others, forcing students to devote working memory to trying to visualize a situation over learning the material at hand. This in turn places additional burden on students with less spatial visualization experience, who must devote even more working memory toward visualizing these scenarios. As student interviews have not yet been conducted, we cannot assert with any certainty the impact of different delivery methods. However, we can turn to current literature on student cognitive load in STEM. Paas & Van Merriënboer [29] and Castro-Alonso et al. [30] provided a variety of methods by which the principles of cognitive load theory could be integrated into STEM classrooms. Findings from their summaries, as well as the results of additional cognitive load studies, informed the recommendations listed in Table 2 below. These recommendations can benefit all students but will be particularly helpful for students with lower spatial visualization skills – closing the gaps observed between gender and socio-economic status. Strategies such as providing diagrams and drawings when possible and avoiding the split attention effect may be helpful in freeing up working memory for these students.

Table 2. Recommendations for supporting spatial visualization through curriculum preparation

Recommendation	Justification
Provide imagery in the form of photographs, diagrams, or drawings to support instruction where possible.	Providing visual representations of concepts has been shown to support learning when compared to instruction that lacks visual imagery [31].
Utilize interactive virtual and physical models when explaining *complex* ideas that involve the interaction of several concepts or elements.	Studies have found that both physical and virtual interactive models can support learning of complex concepts when intentionally planned and integrated into instructional activities [32], [33]
Plan for slower or adjustable pacing when presenting visual information in lectures.	Adjusting the pacing at which visuo-spatial information is presented to students helps to ensure that students have adequate time to process visual information before it is removed from their eyesight [34].
Accompany visualizations during instruction with intentional *vocal* explanations, as opposed to written text, when possible.	Several previous studies have found that vocal explanations support learning by preventing interference with visual processing when imagery is used during instruction [35], [36].
Prepare gestures to mimic shapes (iconic gestures) or bring attention to important elements of images or diagrams (deictic gestures) throughout the instructional process.	Research has shown that gestures may help reduce cognitive load by supplementing portions of working memory [37], [38] and highlighting critical information [39] during the learning process.
Draw students' attention to one integrated source of visual information at a time (e.g. ensuring students are looking towards the lecturer before using gestures, integrating explanatory text within diagrams rather than separating verbal/visual explanations).	Spatial split attention effect establishes that providing multiple sources of new information at once creates a higher cognitive demand for students, reducing learning capabilities [40], [41].
Facilitate collaboration when having students complete cognitively demanding spatial visualization tasks.	Evidence suggests that collaborative activities help to divide the cognitive load placed on individual students when learning highly-demanding concepts, supporting the acquisition and retention of new knowledge [42]
When asking students to create mental imagery of physical concepts, support this visualization by reducing visual and audible distractions (e.g. having students close their eyes, limiting speaking to descriptions of the visualization).	Previous studies have established that excessive environmental distractions can negatively impact cognitive load when learning new concepts [43] and having students close their eyes when visualizing can increase available working-memory resources [44].

Future Work and Conclusion

This work in progress study demonstrates the varied ways in which an instructor utilized different delivery methods to convey spatialized information in a fluids course. The instructor relied on delivery mechanisms associated with traditional lecture style instruction - verbal explanations and the use of static drawings and diagrams – rather than strategies that more actively engage students and dynamically represent physical situations (such as interactive models and videos). While it is unknown exactly how various delivery methods impact student learning, Cognitive Load Theory [28] suggests that traditional lecture methods may increase cognitive load on students, resulting in less working memory available to be used for understanding and learning key fluids concepts. Future work will focus on expanding the sample size of instructors and courses to better understand the ways different instructors approach the explanation of these concepts. Additionally, we plan to conduct student interviews to better understand how these instructional strategies are connected to student understanding of spatialized course content and how delivery methods impact student cognitive load and learning.

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