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Multimodal Communication in Engineering Discourse and Epistemologies: How Speech and Gesture Shape Expressions of Engineering Conceptualizations

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Michael is an artist and musician masquerading as an academic, honored with the opportunity to research and design educational technologies that engage the body and the mind to make learning fun.

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Engineering Students' Multimodal Discourse: How Speech and Gesture Reveal Emerging Epistemologies When Reasoning About Mechanics of Materials

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Abstract:

This full paper considers how collaborative discourse can reveal ways upper-class engineering students mechanically reason about engineering concepts. Argumentation and negotiation during collaborative, multimodal discourse using speech and gestures helps establish common ground between learners and fosters reflection on their conceptual understandings. Gestures produced during speech can be either conceptually concordant (or redundant) with speech, suggesting a stable epistemology, or conceptually discordant (or complementary) with speech, suggesting an evolving epistemology. Epistemic Network Analysis (ENA) supports visualizing changes in students' connections between concepts, as revealed by their multimodal discourse, displaying their evolving epistemologies. To investigate changes in students' emerging epistemologies, we hypothesized (H1) students enrolled in a *Mechanics of Materials* course would initially describe their conceptualizations using course-specific, formalized speech, which would be correlated with their conceptually discordant gestures; once common ground was established, students' course-specific, formalized speech would become more strongly correlated with their conceptually concordant gestures, evidenced by a shift in students' epistemic networks. Results showed students initially displayed a weak correlation between course-specific speech and conceptually discordant gestures. They displayed a moderate correlation between course-specific speech and conceptually concordant gestures while establishing common ground. Once students established common ground, the correlation between course-specific speech and conceptually discordant gestures disappeared, while the correlation between course-specific speech and conceptually concordant gestures remained unchanged. These results show engineering students' emerging conceptualizations of a Mechanics of Materials concept as revealed by their shifting gestures during collaborative argumentation and negotiation, so they better align with the scientific epistemology. This is in contrast to information gleaned from traditional assessments that provide a static snapshot of students' knowledge (expressed almost exclusively in verbal and symbolic forms). Multimodal analyses and ENA offer alternatives to traditional assessment practices by revealing a richer, more detailed understanding of the cognitive processes students' thinking and

learning that can inform and complement current engineering teaching and assessment practices and advance theories of learning that guide engineering education.

Introduction:

Across engineering disciplines, *Mechanics of Materials* (*MoM*) is a core course. Concepts are typically taught through a Formalisms First (FF) approach [1] in which students first learn key scientific concepts (e.g., torsion) using *second-order experiences*, such as abstracted symbolic and or iconic representations (e.g., equations, graphs), absent of *first-order experiences*, such as practical applications in the real-world, with the expectation they will eventually recall and apply this information to sufficiently reason about some new physical phenomena. However, transfer of these second-order experiences [3] seldom succeeds in developing students' mechanical reasoning [2] to a degree that they are flexibly and adequately applied to authentic scenarios [1]. This is because introducing new concepts through abstract, second-order experiences does not adequately ground the concepts to their physical referent. Students can learn to generate and manipulate the formalisms in these ungrounded, formal representations, but they are not actually personally meaningful to students. Grounding [4] knowledge occurs when formalisms are clearly linked to real-world referents and students can relate them to first-order experiences [3], which enables students to better interpret these formalisms, and make fewer errors, as well as to transfer that knowledge to new contexts [1,3]. For example, physically observing the angular displacement of a sample under torsion (i.e., a first-order experience) undergirds one's understanding of the abstract symbols that represent the displacement which informs the application of the symbolic equations to calculate the angle of twist (i.e., a second-order experience). Formalisms are highly valuable in engineering for their concision and computational efficiencies, but they are most valuable to engineering students when they are meaningful; what's at stake is understanding when these formalisms remain ungrounded, there is a risk that they inhibit deeper levels of scientific reasoning and transfer to new tasks [5].

In engineering education especially, assessments reward rote memorization of formalisms as a means for applying procedural and declarative knowledge – the proverbial "plug and chug." This type of "mimicking" epistemology stems from the belief that new information can be acquired by repeating information presented by instructors and interpreted using symbolic equations as practical expressions of accumulated knowledge. Formalisms First learning disconnects students from personally meaningful experiences; it truncates their abilities to express their emerging knowledge—their personal epistemologies—in various communicative forms. Pedagogies that discourage students from pursuing their own epistemologies can leave engineering students feeling isolated from other students and contribute to attrition from academic programs [6].

Engineering instructors can help students embody their mechanical reasoning by leveraging body-based resources like perception and gestures to simulate experiences that ground students' understandings [7-8]. Investigating students' evolving epistemologies by attending to students' perceptions and gesture production could indicate deeper levels of scientific reasoning than revealed by speech and written symbols alone. Therefore, our primary objective is to explore the multimodal communication employed by engineering students en route to deeper levels of conceptual understanding and scientific reasoning.

Theoretical Background:

Grounded and Embodied Cognition [GEC; 1] proposes that progressive formalization (PF) is an effective pedagogical approach that leverages students' concrete, first-order perceptual experiences to ground meaningful reasoning and problem solving before progressing to more idealized and abstract second-order representations. For example, students learning Algebra via progressive formalization (PF) may be introduced to objects arranged on a physical pan balance and shown that removing identical objects simultaneously from both sides conserve equilibrium, a concrete representation that allows students to ground algebraic concepts through physical enaction (see Figure 1). Next, this process can then be represented as iconic depictions of objects "balanced" on a diagrammatic pan balance. Lastly, symbolical equations represent the abstractions of these concepts using letters and mathematical symbols (e.g., =) that formalize the relationships [9]. Fortunately, throughout this progression, gestures made by instructors are often copied by students as resources for encoding, decoding, and storing information about algebraic equilibrium; providing ways for students to physically represent their reasoning about algebraic concepts.

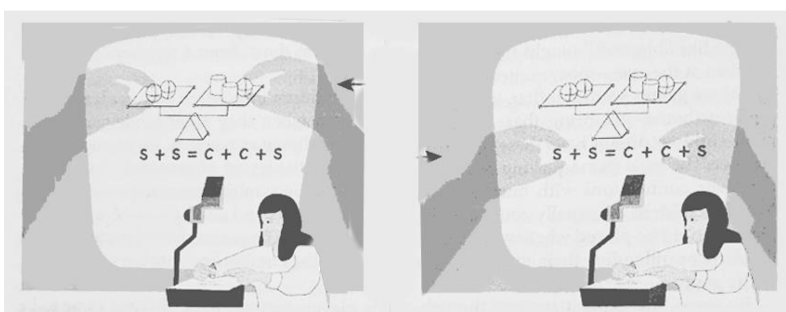


Figure 1. Connecting algebraic concepts using progressive formalization [PF; 10].

As spontaneous, co-speech and co-thought movements of one's hands and arms, gestures can convey a person's current and evolving knowledge state [11-12]. Separate from speech, gestures can be formidable communicative resources for teaching, learning, and grounding STEM principles [13-15]. In Figure 1, the pan balance allows the instructor to gesture with their hands, thereby enacting balance and communicating, through gesture, the concept of equilibrium (see Figure 2). These types of *gestures as simulated action* [GSA; 16] can also reveal a students' underlying reasoning processes as sensorimotor activity while engaged in problem solving as complements that enrich verbal descriptions [11].

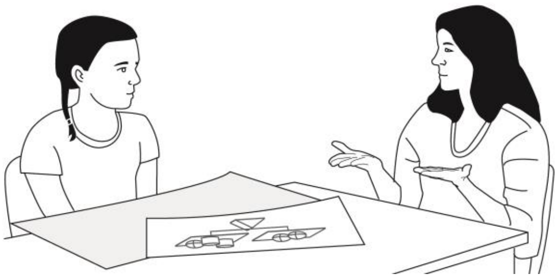


Figure 2: An instructor communicating the concept of equilibrium to a student learning *Algebra.* Notice the open-faced palms representing the pans of the balance apparatus. Often, gesture is accompanied by speech to redundantly communicate information to others [10].

In communication, the relationship between gestures and speech can vary: (1) they can be either conceptually concordant, (CC) i.e., there is a match between the meaning conveyed by a gesture and the contemporaneous speech, so their meanings are redundant; (2) they can be, conceptually discordant (CD), where gesture and speech mismatch and convey complementary information [17, 7]. Informatively, conceptually discordant events are instructionally valuable because they index a learner's "transitional state of knowledge;" when a student is on the cusp of learning a new concept, their reconceptualization is often first available through gestures until the ability to verbalize that new conceptualization catches up. For example, Church & Goldin-Meadow [18] investigated children's developing understandings of conservation of mass. Using Piaget's classic experiment, liquid was transferred from a tall-thin vessel into a wide-short vessel (while the actual volume was perfectly preserved) and children were asked to whether one vessel had more liquid. Some children made conceptually *discordant gestures:* they verbally expressed that the shorter vessel contained "less" liquid while gesturing that the vessel was wider (expressing their perception that the container changed in two dimensions that might compensate for the loss in height). Those students who expressed this dual awareness through their discordant gestures better learned the principle of conservation of mass than did students whose gestures were concordant with their speech. Qualitative analyses showed that although students were unconsciously aware that the greater width might compensate for the reduced height in preserving the volume, their ability to verbalize this awareness trailed. Those producing the discordant gestures showed that they were better poised to make this developmental progress in conceptual understanding than their concordant peers. Thus, students sensed attributes that grounded their understandings of the abstract concept through their body-based behaviors even before they may be explained through their own speech [19]. Thus, gestures can expose students' "leading edge" of conceptual development and complement their verbal expression of that emerging knowledge.

As another example, O'Hara [20] note that novice engineers frequently describe physical or mechanical systems using conventions established by the engineering community, even if they do not understand the formalisms. This can occur when knowledge and instruction are framed culturally for the "majority" students within STEM disciplines. Grondin and colleagues [8] found that students in collaborative settings who leveraged non-formalized speech (i.e., speech not derived from theory-based or lab course materials) were more consistently aligned in their conceptualizations than students attempting to mechanically reason through formalized speech (i.e., materials explicitly used in theory-based or lab courses). Danielak and colleagues [6] investigated engineering students' epistemologies and found that students' diverse ways of reasoning about mechanical phenomena were often overlooked by traditional engineering assessment practices. Inadequately assessing students can perpetuate prior conceptions of who belongs in engineering.

Since the primary purpose of producing gestures and speech is to communicate information to others, lab-based engineering courses can leverage their affordances from students' collaborative discussions while using professional engineering equipment. These grounded opportunities allow students to meaningfully co-construct knowledge through their discussions (i.e., collaborative learning [21]) in which they argue and negotiate to establish common ground [10]. This social mediation of their arguments is quite beneficial for highlighting students' views of a problem space from competing perspectives [22]. For example, a student might discuss the phenomenon of torsion as a transversely applied point load prior to their conceptualization being challenged by another group member that it is a force acting at a distance that causes rotation of the cross-section [8]. These competing views and explanatory adjustments foster the necessary reflections for the reconceptualization of students' knowledge considering comments from other students [23-24]. Traditional engineering lab environments that focus on lab protocols tasks, modeling, and analysis of physical phenomena limit the collaborative discussions that foster deeper-level, scientific reasoning "that support critical thinking, problem solving, and creativity in STEM" [5, pg. 28].

Traditional approaches to engineering education often privilege knowledge of formalism over a grounded understanding of the concepts to which these formalisms refer, To address this problem, we propose capturing students' emerging insights by expanding formative assessment practices to include multimodal discourse analysis of communications during collaborative discussions. Specifically, Alibali and colleagues [9, 13] found that explicit use of gesture among instructors influenced students' understandings and conceptualizations in mathematics learning. Moreover, Grondin and colleagues found preliminary evidence for students' conceptualizations of mechanics in the connections between engineering students' gestures [7] and their speech [8]. Nonetheless, research is needed to investigate how these multimodal forms of communication can be integrated into contemporary assessment practices.

Purpose:

In sum, the purpose of this study is to explore new pedagogical approaches to instruction and assessment that provide simulated, enactive learning of engineering phenomena in lab contexts by grounding students' understandings to grounded, embodied experiences. We pose the following research question: **What do students' gestures reveal about their emerging conceptualization of the mechanics of torsion that is not revealed in speech alone?** From prior research, Grondin and colleagues [7] found that engineering students collaboratively learning in a *MoM* lab-based course generated a variety of gestures including conceptually discordant gestures. Furthermore, when engineering students verbally expressed their conceptualizations of torsion, Grondin and colleagues [8] found that engineering students' discussion employed two different types of speech: (1) formalized speech (i.e., course-specific) that was explicitly from the *MoM* class and (2) speech independent of these formalisms (i.e., non-course-specific). Students' unique ways of perceiving a problem space while developing scientific reasoning [5] has been well-documented for contributing to collaborative argumentation and negotiation in the processes of establishing common ground [10]. Thus, we hypothesize (H1) that, initially, students' course-specific, formalized speech will be more correlated with conceptually discordant gestures. After establishing common ground, students' course-specific, formalized speech will become more correlated with conceptually concordant gestures.

Method:

Participants. Four white, male sophomore- and junior-level engineering students from various engineering disciplines (aged 20-23 years) and had previously passed or who were concurrently enrolled a *Mechanics of Materials* (*MoM*) were convenience sampled from a predominately White student body at a Midwestern university and assigned to two dyads (2 groups of 2 students). The research team received IRB approval and consent from the Department of Mechanical Engineering to conduct this study.

Setting. From a small summer course with eight students enrolled, we present data from four students that were able to complete participation as dyads (n=2; 4 students total). The remaining student's data was excluded based on the absence of gesture and or speech during mechanical reasoning (n=2) or their inability to participate in class that day (n=2). In general, the *MoM* lab offers a hands-on environment to observe and physically experience torsion, as well as the formal symbolic equations that model torsional loads.

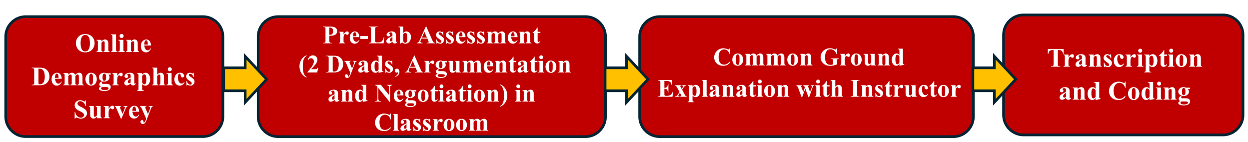


Figure 3. Schematic of experimental study design. The pre-lab assessment and instructional intervention each took approximately 15 minutes to complete.

Procedure. As shown in Figure 3 above, students first completed an online demographics survey (Age, Ethnicity, Identified Gender, Year in School, Engineering Coursework, etc.). In the classroom, after completing the demographics survey and prior to the pre-lab assessment, the instructor prompted students in each dyad to explain their responses to the pre-lab assessment questions. The instructor then left the two dyads for 15 minutes to discuss their responses to the question below without instructor present, followed by a pre-lab assessment in the lab room in which the students shared their common ground solutions with the lab instructor.

Prompt: You are curious to know which material will respond better under a torsional load. The samples are consistent in shape and size, only the material changes. The program for the test permits consistent angular displacements regardless of the material being tested.

1. What ways can you determine how the material responds to torsional loading? Describe any indicators in the experiment that can provide relevant information.

2. How was energy added to the specimen in the lab? How was energy released from the specimen? Describe these processes as clearly as you can.

3. Describe where the maximum shear stress occurs on the sample due to torsional loading. Why does maximum shear stress occur at this location? What information does this provide about the response of the material under torsional loading?

Data Collection. Participants' pre-lab assessment and torsional testing activities were video recorded and transcribed. Each dyad completed participation in separate areas of the engineering classroom and their responses were recorded separately.

Coding. Videos were transcribed and coding analysis was completed in two prior studies [7-8]. Speech was categorically coded as either MoM-specific or non-MoM-specific speech and gestures were analyzed and coded as either conceptually concordant or discordant. Conceptually concordant and discordant gestures rely on accurate coding of gesture and speech while students explain their conceptual understandings of torsion. Tables 2-3 provide the coding schemas and definitions applied to this body of data and Table 4 shows the key concepts in the pre-lab assessment and expression criteria for gesture and speech. To understand the underlying patterns during students' mechanical reasoning, gesture and speech codes were analyzed using epistemic network analysis [ENA; 25].

Table 2: Verbal reasoning coding schema and definitions [8].

Coding Schema	Code	Definitions	Examples
MoM-Specific Speech	**M**	Participant generates this description **within the bounds of theory-based terminology** in Mechanics of Materials.	And, and I guess then, yea it would either be rotational, or it would be energy [***M***] going into breaking the bonds through shear [***M***] and plastic deformation [***M***]. That is just the cross-section [***M***].

Non-MoM-Specific	**nM**	Participant generates this description **outside of theory-based terminology** in Mechanics of Materials.	Energy can be released [***nM***] by untwisting [***nM***] it back to its normal position or by twisting [***nM***] it so much that it breaks [***nM***]. Yea, the further out you go whatever rotates that arc length [***nM***] gets bigger and bigger for the same theta.

Table 3: Conceptually concordant and discordant coding schema and definitions [7].

Gesture Type	Code	Explanation
Conceptually Concordant	**CC**	Depicted gestures **represent** concepts in **verbal descriptions**.
Conceptually Discordant	**CD**	Depicted gestures **do not represent** concepts in **verbal descriptions** or, **Verbal descriptions** of concepts are **not representative** of the **gesture** produced during reasoning or, Depicted **gesture and verbal descriptions** are **misaligned** from the concepts being inquired.

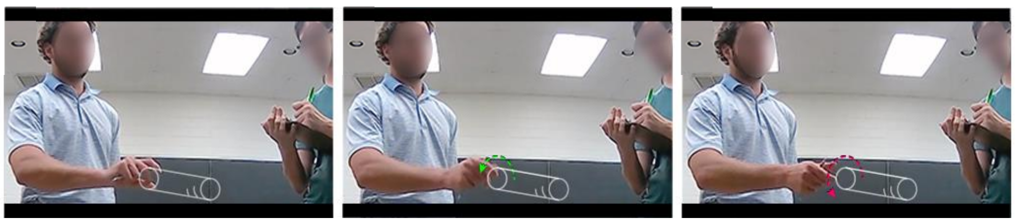
Table 4: Criteria for accurately coding conceptually concordant and discordant gestures.

Key Concepts	Concordant Expressions in Gesture	Concordant Expressions in Speech
Features of the Material	Depictions of the material shape and length	Descriptions of material's shape and length
Response During Testing	Depictions of angular changes and rotation of the material	Descriptions of the angular displacement of the material and material properties
Energy Addition	Depictions of rotation of the material	Descriptions of how energy is added and can include discussions of mechanical work through torque
Energy Release	Depictions of rotation of the material and fracture mechanisms	Descriptions of how energy is released and can include fracture mechanisms, heat, sound, removal of torque load, and material relaxation
Maximum Shear Stress	Depictions of the outer radius and location of neutral axis	Descriptions of the location of maximum torsional shear stress, angular displacement, distance from neutral axis, and torque

Applying the criteria for conceptually concordant and discordant gestures, Grondin and colleagues [7] presented a few examples shown in Figures 4 and 5.

"Maximum shear stress occurs on the outer radius."

Figure 4: Depicts a student using a concordant *geometrical shape* gesture while describing the location of maximum shear stress [7].



"…depending on the material you can physically see… a… a… a… is that a transverse shear?"

Figure 5: Depicts a student's discordant *rotational (loading)* gesture while describing transverse shear [7].

Data Analysis. Using the transcript and gestural codes, our primary analysis uses Epistemic network analysis [25]. *Epistemic network analysis* (ENA) assists in: (1) identifying and visualizing conceptual connections in collaborative discourse using the gesture and speech codes (Tables 2-3), (2) quantifying these connections using a proxy measure for the strength of association between codes based on the frequency of interconnections, and (3) indicating changes in the frequency of these codes in the processes of argumentation and negotiation that establish common ground. As for the unit of analysis, ENA models the multimodal communication (i.e., gesture and speech) using transcript segments from each dyad. ENA can be used to determine how codes that apply to each transcript segment are connected to other codes as they co-occur within recent temporal proximity [25].

ENA generates graphic representations of a *weighted network graph* as analytic outputs where nodes correspond to codes and line thickness reflects the relative frequency of co-occurrences between any two codes; these graphs are also termed *primary* and *secondary plots* that represent different educational environments. For example, in our data, if the code 'MoM-Specific Speech' (from Table 2) and code 'Conceptually Discordant' (from Table 3) co-occurred more frequently during argumentation and negotiation than common ground responses, then the argumentation and negotiation weighted network graph (or the primary plot) would depict the strength of association between the two codes as a thicker line weight (i.e., stronger) compared to the associations in the common ground responses plot.

Once weighted network graphs are generated for argumentation and negation as well as common ground, ENA computes a second analysis, a *difference graph* or *comparison plot*, which subtracts the weights of each connection from the primary and secondary plots. This plot visualizes which connections are strongest and weakest by depicting the remaining association – thus, if the relationship between two nodes was stronger for the primary plot, then only the amount difference is plotted. The mean subtracted network reveals which epistemic elements (i.e., associations between nodes) from gesture and speech are relatively central to the discourse of each engineering concept. In the current analysis, primary and secondary plots of students' responses (see codes in Tables 2-3) as well as a comparison plot allow us to visualize, identify, and interpret the epistemic changes in students mechanical reasoning over the procession from argumentation to negotiation to establishing common ground.

Provided that this investigation is solely qualitative, there exists a third ENA representation, the *plotted point*, that represents students' responses during argumentation and negotiation and common ground in two-dimensional space. Plotted points have associated numeric values making computation using a Student's t-test viable in examining statistically significant differences in students' discourse [25]. While the plotted point provides statistical analyses on the differences between nodes and associations on plots (i.e., argumentation & negotiation compared to common ground responses), the small sample size in this investigation precludes any such analysis.

In order to perform ENA, transcripts (see Figure 6) must be segmented by speakers and include: (1) the location in which students responded to the questions where responses took place (i.e., the classroom or lab room), (2) group identification, (3) assessment item content or question number, (4) student participant identification, (5) the time stamp in which the segment occurred, (6) utterances, (7) corresponding codes, (coded as Boolean variables 1/0) and (8) appropriate window size (i.e., how many utterances get included in a block of analysis). For the purposes of this study, segmentation was based on turn of talk between students in each dyad or when there was a pause of greater than two seconds indicating a shift in discourse. For this analysis, the window size chosen was four segments; thus, each ENA moves through the transcript one segment at a time (e.g., (9) in Figure 8) to view and interpret connections for three separate models—including primary, secondary, and comparison plots for dyadic communication. Before discussing the results of the study, it is valuable to demark the magnitudes of strength of relationships between individual code from these epistemic network analyses. According to Akoglu [26] and applying Dancey & Reidy's [27] criteria for strengths of relationships in psychology: perfect ($r=\pm1$), strong ($r=\pm0.7$-0.9), moderate ($r=\pm0.4$-0.6), weak ($r=\pm0.1$-0.3), and zero.

Location	Group	Q's	Student	Time Stamp	Utterance	Conceptually Discordant	Conceptually Concordant	Dynamic Depictive	Static Depictive	MoM-Specific Function	MoM-Specific Structure	Non-MoM-Specific Function	Non-MoM-Specific Structure
Class	2	Q1	P3	4:51	Alright. How can we determine how the material responds under torsional loading? How can you tell? What indicators might exist to inform you?	0	0	0	0	0	0	0	0
Class	2	Q1	P4	5:02	The first thing that comes to mind is whether or not material is brittle, depending on whether it.. if it is a brittle material than it will fracture...	1	1	1	0	1	1	0	0
Class	2	Q1	P3	5:13	Right.	0	0	0	0	0	0	0	0
Class	2	Q1	P4	5:15	...and there, there'll be a very like parallel fracture point. Whereas like a more ductile material sort of bends.	1	1	1	0	0	1	0	1
Class	2	Q1	P3	5:24	Right.	0	0	0	0	0	0	0	0
Class	2	Q1	P3	5:27	Alright..	0	0	0	0	0	0	0	0
Class	2	Q1	P4	6:09	Yea. The utility determines whether it'll have a brittle fracture or...	1	0	1	1	0	1	0	0
Class	2	Q1	P3	6:16	Or it'll, it won't fracture or bend torsionally	0	1	1	0	1	0	0	0
Class	2	Q2	P4	6:22	How is energy added to the material under torsional loading? How might energy be released? What indicators might exist to inform you?	0	0	0	0	0	0	0	0
Class	2	Q2	P3	6:30	How would energy, How's energy added to the material under torsional loading? So torisonal loading is applying torque to the...	0	1	1	0	1	0	0	0
Class	2	Q2	P4	6:37	Yup.	0	0	0	0	0	0	0	0
Class	2	Q2	P3	6:38	Let's say it's like a one of the steel specimens we've had and where like they [inaudible] for example.	0	1	1	0	1	1	0	0
Class	2	Q2	P4	6:45	One of the easy, like, example questions you might see in 306 just involve, like, umm shaft...	0	1	0	1	0	1	0	0
Class	2	Q2	P3	6:52	Right.	0	0	0	0	0	0	0	0
Class	2	Q2	P4	6:52	...connected to an immovable and then it's like on a gear...	0	1	0	1	0	1	1	0

Figure 6: Example image of the data for epistemic network analysis. (1) is the location of the participants while they answered the conceptual questions in either the classroom or lab spaces. (2) is the group ID indicating the individual dyads the participants were randomly assigned to. (3) is the conceptual question ID for each of the three questions posed to the students. (4) is the participant ID for each of the participants in the study. (5) is the time stamp indicating the temporal flow of discourse during student responses. (6) are students' verbal responses to the conceptual questions, split based on turn of talk or pauses greater than 2 seconds in their speech. (7) are the codes applied to the utterances. 1 indicates the code was applied to the utterance in the row while 0 is the absence of the code in the transcript. (8) is the temporal window selected for the analysis. The window size used for the epistemic network was a size of 4. (9) is the moving window while maintaining the same window size of 4. Notice a one row shift downwards encompasses three utterance rows from the initial window plus an additional new utterance row that represents temporal proximity.

Results:

ENA Results for the First Research Question. The research question (RQ1) investigated the conceptual gestures employed by students while they expressed their collaborative understandings using course-specific speech. With conceptual gestures either concordant (i.e., conceptually aligned with verbal explanations) or discordant (i.e., conceptual misalignment of speech, gesture, or both) [7], we hypothesized (H1) that initially, students' course-specific, formalized speech would be strongly correlated with conceptually discordant gestures while establishing ground and once common ground was established, students' course-specific, formalized speech would become strongly correlated with conceptually concordant gestures. ENA network models were generated from students' multimodal discourse in the classroom, including explanations they provided of their solutions once they had established a common ground as a dyad in the lab room. To examine differences between argumentation, negotiation, and establishing common ground, epistemic networks were generated for each dyad using ENA [25].

Panel A of Figure 7 shows the ENA graph of the baseline strength of interconnections among codes representative of students' argumentation and negotiation in the classroom. Observations of epistemic relationships during argumentation and negotiation (red connections) show a weak CD-M correlation ($r=0.16$) and moderate CC-M correlation ($r=0.49$). This suggests that during argumentation and negotiation, students produced less gestures that were misaligned with course-specific speech compared to gestures conceptually aligned with course-specific speech. This differs from H1's prediction that there would be a stronger correlation between students conceptually misaligned gestures and course-specific speech.

Interconnections among codes of students' common ground responses in the lab room are shown in Panel C of Figure 7 (blue connections). During students' common ground responses, there was a near-zero CD-M correlation ($r=0.04$) and a moderate CC-M correlation ($r=0.49$). This suggests that while expressing their common ground responses, students produced less gestures that were conceptually misaligned with course-specific speech and higher associations between gestures conceptually aligned with course-specific speech. This result is in partial alignment with the H1 in that, once common ground was established, student responses were more strongly correlated with conceptually concordant gestures and course-specific speech.

The comparison plot (Panel B in Figure 7) indicates *changes* in students' collaborative epistemologies between argumentation and negotiation in the classroom and common ground responses in the lab room. This ENA displays the differences between the weights of connections from the argumentation and negotiation plot (Panel A) and common ground plot (Panel C) epistemic networks. There was a decrease in the frequency of CD-M relationships ($r=-0.12$) and no change in the frequency of CC-M relationships ($r=0$) once students established a common ground. This suggests that after argumentation and negotiation, students were less likely to produce conceptually discordant gestures while using course-specific speech, but they were consistent in making conceptually concordant gestures alongside course-specific speech. These results partially support H1 that the correlation between conceptually discordant gestures while using course-specific speech would decrease with common ground, after argumentation and negotiation.

Between the CD-nM and CC-nM correlations, during argumentation and negotiation in the classroom (Panel A), there was a near zero CD-nM correlation (*r=0.08*) and moderate CC-nM correlation (*r=0.47*). However, during common ground responses in the lab room (Panel C) there was a near-zero CD-nM correlation (*r=0.04*) and moderate CC-nM correlation (*r=0.48*). The comparison plot (Panel B) shows a small decrease in strength of the CD-nM correlation (*r=-0.04*) and small increase in the CC-nM correlation (*r=0.01*).

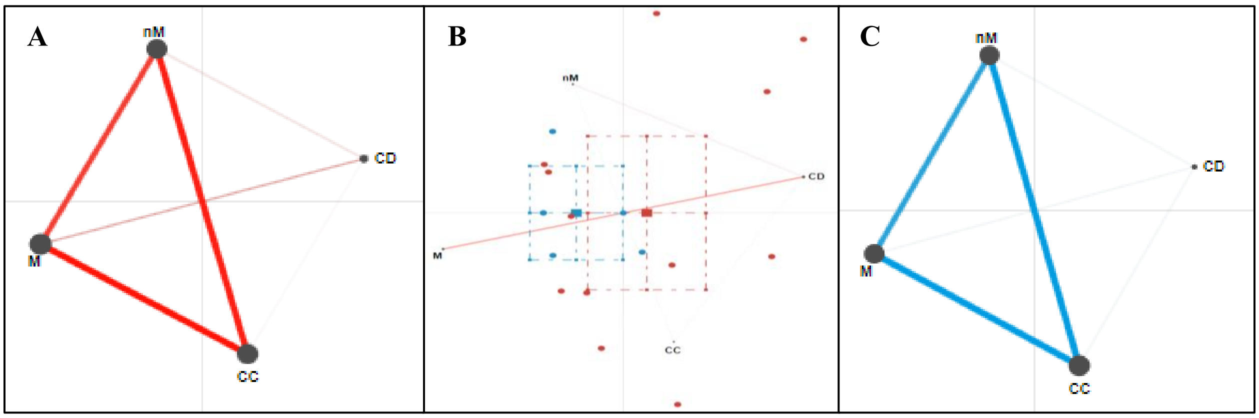


Figure 7: Displays ENA graphs for conceptual gestures and course- and non-course-specific speech codes. The first network is the argumentation and negotiation graph from the classroom (red connections of Panel A), the second is their common ground responses graph from the lab room (blue connections of Panel C), and the third is the mean subtracted network (Panel B). Codes include Conceptually Concordant (CC), Conceptually Discordant (CD), course-specific speech (M), and Non-Course-Specific speech (nM).

Discussion:

Often, the various ways students choose to learn (i.e., their epistemologies) and communicate their emerging knowledge multimodally (i.e., through gesture and speech) to engineering instructors and professionals is underrepresented. This exploratory study in an engineering lab-based course investigated (RQ1) what gestures reveal about students' collaborative understandings using course-specific speech not revealed in speech alone. Assessment of knowledge in the engineering disciplines is frequently based on written exams that predominantly evaluate one's formal knowledge of the properties of mechanical systems. Findings from Epistemic Network Analyses [ENA; 25] based on a small sample of undergraduate engineering students in a *Mechanics of Materials* (*MoM*) lab course, suggest that a collaborative, embodied learning activity was beneficial in re-aligning formalized, conceptual understandings of torsion.

When initially reasoning during argumentation and negotiation, students less frequently produced conceptually discordant gestures while describing torsion phenomena through course-specific speech compared to more frequently producing conceptually concordant gestures with descriptions using course-specific speech; a finding that is counter to our hypothesis. During students' common ground, the frequency of conceptually discordant gestures while using course-specific speech decreased while the frequency of conceptually concordant gestures while using course-specific speech was maintained. These findings suggest that a collaborative, embodied learning activity that invoked argumentation and negotiation to establish a common ground among students reduced the frequency of students producing conceptually discordant gestures aligned with course-specific speech; developing their understanding of the formalisms taught in their *Mechanics of Materials* course. Thus, there is reason to suspect that collaborative interactions between students are beneficial when mechanically reasoning in developing students' scientific reasoning. In this discussion, we look to broaden the perspective of our findings by offering practical implications for improving engineering education learning and assessment practices.

Although beyond the scope of our initial research question, the moderate correlations of CC to nM during both argumentation and negotiation as well as with common ground suggests that: (1) students less frequently produced conceptually misaligned gestures when reasoning through non-course-speech ($r=0.08$) compared using course-specific speech ($r=0.16$) during argumentation and negotiation and (2) there was a maintaining of conceptually concordant gestures while reasoning through non-course-specific speech that had nearly an identical relationship to conceptually concordant gestures while reasoning course-specific speech in both argumentation and negotiation in the classroom and common ground responses in the lab room. Future work should explore the reasoning behind why students less frequently produced conceptually discordant gestures when reasoning through non-course-specific speech compared to course-specific speech, as well as the similar relationships between conceptually concordant gesture production and course- and non-course-specific speech.

For this small sample of undergraduate engineering students, these results support earlier findings. During argumentation and negotiation in the classroom there was an increased frequency in conceptually discordant gestures when using course-specific speech; frequency of conceptually discordant gestures when using course-specific speech reduced to a near-zero correlation. Conceptually discordant gestures occur when speech and gesture are out of alignment or when there is no alignment between speech and gesture regarding a concept [7]. Church & Goldin-Meadow [18] noted discordant learning behavior occurs when speech and gesture are competing against each other, and Goldin-Meadow and colleagues [19] claimed that a brief lesson was more likely to benefit students who more frequently produced discordant gestures. Grondin and colleagues [8] noted that students were frequently describing their mechanical reasoning using formal or course-specific speech. Furthermore, students in the current study maintained their generation of conceptually concordant gestures when using course-specific, indicating no detriment in students reasoning during the simulated, enactive embodied learning activity. Therefore, attending to students conceptually discordant gestures, especially when students are incorporating professional vernacular, can assist students in reconceptualizing prior ways of knowing through a re-alignment of gesture and speech during mechanical reasoning [2].

Limitations and Future Work:

Although this study reports identifiable patterns in discourse that emerge in students' speech and gesture as they mechanically reason in engineering lab spaces, there are various limitations to address. First, additional findings from the ENA correlations remain unaddressed. Although the frequency of conceptually discordant gestures aligned with non-course-specific speech was small, their low incidence rate warrants further consideration and investigation. It may be that students who are developing their engineering conceptualizations have a higher affinity to use speech that is more familiar compared to unfamiliar speech they are attempting to learn. Second, the small sample in this study may not be representative of the larger population of undergraduate engineering students. While ENA is robust enough to calculate associations between conceptual nodes in semantic networks, these connections are not statistically reliable and generalizable beyond these case study interactions. Third, this study focused on one concept (i.e., torsion) from *Mechanics of Materials* and did not consider students' speech and gesture used in discourse for other concepts, such as axial loading, bending stresses, combined loading, or energy. It is possible that the results discussed here may apply to other engineering concepts, even those outside of *Mechanics of Materials*, but more evidence would be needed for empirical validation. Fourth, this study did not integrate instructor discursive techniques which are fundamental to teachers facilitating classroom discourse, and relevant in the context of researching instruction and learning in engineering education. Fortunately, we are currently processing data from an *in-situ* intervention with 15 sections (N=189 students) of an engineering lab on torsion. This dataset will have the needed statistical power for quantitative analysis using ENA. Further, the larger data set more closely aligns with the demographics of the broader engineering student population. Additionally, this larger dataset may help to assess collaborative gesture production in engineering discourse. Thus, the current study is meant to guide engineering educational researchers to future projects with hopes of reaching educators, their classrooms, and their students.

Conclusion:

Assessment of emerging engineering knowledge requires understanding how students are applying information relayed by their instructors and other professionals. The current findings suggest that engineering undergraduate students perpetuate prior conceptions while explicitly using terminology from their *Mechanics of Materials* course. Using an embodied learning activity that invokes simulated, enactive experiences could help decrease prior conceptions. Mechanical reasoning from undergraduate engineering students is more than application, and misapplication of vernacular used by educators. Mechanical reasoning, including the interactions between students and instructors, across multiple modes of speech and gestures, construct and re-construct students' conceptual understandings of engineering phenomena and higher order concepts [10]. In the development scientific reasoning [5], we must address concerns regarding instruction and assessment practices in engineering education: Instructors need to provide moments for their students to actively engage in socially mediated discourse pertaining to engineering phenomena and careful consideration must be given to student speech and gesture production to understand how students' experiences undergird their abilities to answer conceptual questions. Speech and gestures that do not align with the professional engineering community do not necessarily indicate perpetuation of prior conceptions—rather, there may be alternative communicative modes to express emerging knowledge grounded and embodied by students. Educators must draw from the rich sources of student knowledge to improve instruction and learning in engineering education as a means for promoting diversity, equity, and inclusion. It is imperative that engineering education recognizes the value of all students' lived experiences [The RISE principles; 28] and allows prior and personal experiences to help construct knowledge about new concepts in ways that are meaningful.

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