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Epistemological Changes: How Structure and Function Shape Mechanical Reasoning About Torsion in Speech and Gesture

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Epistemological Changes: How Structure and Function Shape Mechanical Reasoning About Torsion in Speech and Gesture

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Abstract

This full length, empirical research paper investigates undergraduate engineering students' emerging conceptualizations of torsion-related concepts for the relations between the functions and behaviors of materials to their structures, both observable and unobservable. While cognitive processes are unavailable for direct inspection, advances in the Learning Sciences show that learning in collaborative contexts creates favorable conditions for communicative displays of students' reasoning and knowledge in transition via speech and co-speech gestures. Analytic tools such as Epistemic Network Analysis (ENA) provide visualizations of these conceptual transitions and calculate the degrees to which these changes show statistically reliable evidence of learning. Moreover, ENA can elucidate ways in which traditional engineering assessments often are insufficient- namely, that they: (1) rely primarily on single snapshots of students' knowledge at a single point in time, thereby neglecting the developmental nature of students' emerging conceptual understandings; (2) over-emphasize the importance of verbalizable and symbolic ways of expressing knowledge. In effect, this can exclude the nonverbal and embodied ways students express emerging knowledge of complex, dynamic phenomena.

The current study explores the potential of this approach by considering how gestures and speech during collaborative discourse can reveal transitions in mechanical engineering students' understanding of structure-function relationships governing torsion. Qualitative and quantitative analyses focused on four students (two dyads) from a Mechanics of Materials lab course that offered a hands-on environment to observe, physically experience, and mathematically model torsional loads. Data was obtained from videos during a pre-lab assessment as well as a collaborative torsional testing lab activity.

Within a grounded and embodied cognition framework, we applied ENA to students' collaborative, multimodal discourse about the mechanics of torsion. We hypothesized (H1) that analysis of students' collaborative discourse will reveal frequent use of gesture alongside speech that describes the underlying structures that give rise to functions and behaviors during torsion. We also hypothesized (H2) that in collaboration, students' reasonings will shift from expressing the underlying structure towards functions and behaviors, evidenced by their gesture and speech.

ENA results from coded transcripts showed changes in students' conceptualizations, emphasizing the importance of including both gesture and speech as a means for accurately assessing students' emerging understandings. In support of H1 (argumentation and negotiation) and H2 (common ground), student reasoning initially depicted and described the structure (i.e., static) of torsional loads, and after establishing common ground, students' reasoning demonstrably shifted towards a focus on functionality (i.e., dynamic), revealing a shift in their epistemology.

This pilot study offers a theoretically operationalized approach for improving formative assessment practices in engineering education. Together, ENA's use as a formative assessment of

students’ multimodal expressions of their understandings during collaboration provides a more comprehensive evaluation of students’ reasoning and learning than traditional forms of assessment. We identify initial limitations, future work, and provide promising guidelines for improving formative assessments of students’ emerging conceptual understanding of complex engineering phenomena.

Introduction

Across numerous engineering disciplines, *Mechanics of Materials* is a core course where students apply formal knowledge from *Statics* while learning new concepts of normal stresses, shear stresses, their combinations, and their relation to energy. Torsion is a fundamental topic in mechanics that explains the development of stress as a material rotates about its central axis. In engineering education, concepts are typically taught through a *formalisms first* (FF) approach [1]. Students learn to memorize and procedurally apply *formalisms*, such as mathematical equations and conventional visuals that quantify and represent physical phenomena prior to opportunities for meaningful application. In academic engineering contexts, (e.g., classrooms, discussions, design, labs, and case studies), students are expected to interpret these formalisms in preparation for their application in professional practice. Nathan [1] showed empirically that FF is misaligned with how concepts develop in STEM disciplines and fosters a formalisms-only mindset among instructors and students that dismisses other non-formal representations (i.e., personally meaningful or invented) and reasoning.

Mechanical reasoning [2] learned via formalisms may result in student's inabilities to master deeper understandings. Unfortunately, assessment in engineering education frequently tests students' memorization of formalisms with little consideration for the diverse ways by which students learn and understand complex engineering phenomena. While the formalized ways of quantifying, inferring, representing, and equating stress offer valuable tools for visualizing, modeling, and analyzing stresses, they are often devoid of personally meaningful experiences. Learning complex concepts in engineering includes not only the utility of formalisms but requires deeper understanding of their applications for designing and determining solutions to problems.

For teaching, instructors can leverage body-based resources such as *gestures* and *speech* to simulate experiences that embody learners' understandings. However, when students pursue additional epistemologies, such as *Embodied cognition*, a theoretical framework that contends human cognition arises from manipulation—physical, virtual, or simulated—of objects situated in our environment and filtered through our body's perceptual systems [3-5]. *Grounded cognition* [6] posits that cognition does not merely arise from computations of abstract representations such as symbols, graphics, or other formalisms that are independent of perception, action, and introspection. Contrarily, Barsalou [6] contended that cognition stems directly from perception, action, and introspections that are situated with affordances from one's physical environment.

For example, in *Mechanics of Materials* labs students often witness materials being deformed. These experiences can be internally simulated (or recalled) when reasoning about new concepts or problem-solving. For example, in *Mechanics of Materials* labs, students use the ADMET machine to deform materials often leading to a test sample's fracturing. Embodied experiences of torsion not only allow learners to observe the orientation of slip planes but feel the change in temperature and hear the material fracturing. In effect, the physical manipulation of the tested sample grounds learners' understandings about deformation, energy, and fracture. Nathan [1] proposes *progressive formalization* (PF) as an effective pedagogical implementation of *Grounded and Embodied Cognition* (GEC) that leverages students' sensorial experiences to engage in meaningful reasoning and problem solving prior to progressing to more idealized and abstract experiences. For example, students' introduction to the concept of torsion via progressive formalization (PF) may watch a videorecording of torsional testing in which an initial straight-line drawn down the gauge length of the sample spirals around the sample indicating angular deformation. Such a concretized representation grounds the concept of torsion and in collaborative discussion, students may gesture to simulate the deformation process during torsion. Then, they can plot the angular deformation graphically prior to the incorporation of mathematical formulae to calculate its quantity. Reliably, students make gestures throughout this progression, and they serve as physical resources for encoding, decoding and storing information about angular deformation and other *Mechanics of Materials* concepts.

Gestures are spontaneous, co-speech movements of the body that convey a person's state of knowledge [7-8]. Gestures can be formidable communicative, embodied resources for grounding principles in STEM. Discussing torsion, a student may enact angular deformation by gesturally communicating their emerging understanding to peers (see Figure 1). Gestures can indicate a students' reasoning processes as sensorimotor activity is engaged in problem solving and analysis [7; see Figure 1]. In engineering, students and instructors often produce gestures while reasoning about physical and mathematical phenomena [9] and carry nonverbal information that complements verbal reasonings [10].

Grondin and colleagues [10] catalogued the gestures engineering students produced in an engineering lab as they mechanically reasoned about the concept of torsion. These gestures often depicted the geometric shape of the sample, how materials were loaded and unloaded, magnitude of stress, and the cross-sectional area. These gestures were coded into two superordinate categories as either: (1) static depictive or (2) dynamic depictive [11]. *Static depictive* (SD) gestures occur when a learner depicts an object, like the shape of a metallic rod as in Figure 1. *Dynamic depictive* (DD) gestures occur when a learner depicts the transformation of an object (e.g., displacing the metallic rod to represent deformation as seen in Figure 1). Gestures during engineering activities can non-verbally convey an engineers' practical knowledge complementary to their verbal description [10].

In previous research, Grondin and colleagues [12] noted that in collaborative settings students' gesture production also leveraged various forms of speech, not only including *formalized speech* (i.e., speech explicitly used in theory-based or lab courses) but also *non-formalized speech*. Among these formalized and non-formalized components of speech, Grondin and colleagues [12] identified instances of engineering students' speech as referring to either the *structure* (S) or *function* (F) of engineering objects. Structure refers to the static nature of an engineering object (e.g., the metallic rod or the geometry of the sample) whereas function refers to the dynamic or time-dependent nature of an engineering object being acted upon (e.g., deformation due to torsion).

Mechanical reasoning tasks elicit both static and dynamic depictive gestures and structural and functional speech. These insights provide evidence of conceptual understanding regarding engineering phenomena. Kang & Tversky [13] discussed the role of gesture production when reasoning about dynamic systems—specifically, the workings of a four-stroke engine. Fifty-nine participants, individual participants were randomly selected for one of two conditions: (1) a structure gesture condition (i.e. static depictive) in which verbal explanation was accompanied by gestures showing forms of the parts and their spatial relationships, or (2) an action gesture condition (i.e., dynamic depictive) in which the same verbal explanation was accompanied by gestures representing the action experienced by the structures. Participants in the dynamic depictive gesture condition exhibited a deeper understanding of the dynamic system in their speech, gesture, and performance questions. Although these results lend credence to the efficacy of gesture production in promoting deeper understanding, it is unclear whether these results would hold in collaborative discourse. Although novice students tend to struggle with conceptualizing *dynamic systems* (i.e., systems that consist of one or more structures that are affected by a sequence of actions) [14-15], may benefit from collaborating with peers that have a range of knowledge.

Gestures can convey information that novices may not yet be able to vocalize, such as emerging conceptual knowledge [16], including procedural and spatial information [7].

Engineering lab-based courses afford not only collaborative opportunities for discussions about concepts but also group interactions with assistive technologies. By providing opportunities for students to meaningfully co-construct their knowledge in discourse (i.e., collaborative learning [17] students may engage in argumentation to negotiate their positions to establish common ground [18]. For example, a student might discuss the phenomena of torsion as a transversely applied point load to which a peer may counter that it is a force acting at a distance that causes rotation of the cross-section (i.e., argumentation) [12]. Competing views foster reflection and correction of students' knowledge (i.e., negotiation) [19-20] until a mutual understanding is achieved (i.e., common ground). Establishing common ground requires that students overtly monitor their communication to express themselves clearly to their collaborators [21].

Traditional engineering lab environments, in which the main goal is to experiment, model, and analyze dynamic systems can limit the collaborative discussions that foster deeper scientific reasoning, critical thinking, problem solving, and creativity, especially in STEM [22]. Students focused on completing lab protocol tasks can miss the benefits of discussing their emerging conceptualizations with their peers. Thus, the primary objective in this study was to investigate how embodied activities influenced students' communications (i.e., gesture and speech) during their collaborative reasoning about torsion (i.e., a dynamic system) in the processes of argumentation and negotiation to establish a common ground.

Research Questions

This empirical study serves as a pilot for a larger study that investigates the following research questions: (RQ1) How do engineering students in collaborative discourse initially depict and describe their emerging understandings of the functions and behaviors and underlying structures of torsion? (RQ2) How do structural-functional relationships in students' discourse change from argumentation to negotiation to establish common ground? For geometric reasoning, Walkington et al. (2014) found that static depictive gestures communicated ideas about mathematical objects whereas dynamic gestures communicated correct intuitions, insights and valid proofs. For mechanical reasoning, Grondin and colleagues [10] found that gestures produced while reasoning about torsion often depicted geometric shape, loading and unloading of the material, magnitude of stresses, and cross-sections. In follow-up, Grondin and colleagues [12] explored students' speech during mechanical reasoning and found descriptive explanations of the structure and or function of engineering objects.

Understanding the relationships between gestural depictions and verbal descriptions of structures and functions in a collaborative engineering context needs to be explored further. Collaborative learning promotes the processes of argumentation and negation that help develop understandings [18] by providing students with moments to reflect on their individual understanding and thinking critically about dynamic systems [13]. We therefore hypothesize (H1) that analysis of students' collaborative speech will reveal frequent use of gestures that complement verbal descriptions of the underlying structures that undergird the functions and behaviors during torsion. We also hypothesize (H2a) that collaborative argumentation and negotiation about torsion will more frequently rely on depictions and descriptions of structures than functions and behaviors; (H2b) However, once common ground is established, will shift towards more frequent use of depictions and descriptions of the functions and behaviors of torsion.

Methods

Participants. A convenience sample of engineering students (N=4, 2 dyads, all male) who previously passed or were concurrently enrolled in a *Mechanics of Materials* (MoM) course from various disciplines, grade levels, and coursework experiences from a predominately White student body at a large Midwestern university (see Appendix A Table 1).

Setting. Participants were enrolled for a small summer course in the School of Engineering. In general, the Mechanics of Materials lab space offered a hands-on environment to observe and physically experience the concept of torsion, as well as the formal symbolic equations that model torsional loads.

Procedure & Materials.
<u>Demographic Survey</u>. Prior to the classroom, students completed a demographics survey (Age, Ethnicity, Identified Gender, Year in School, Engineering Coursework, etc.).
<u>Pre-Lab Assessment</u>. In the classroom, the instructor prompted student dyads to complete a pre-lab assessment by answering a series of questions about torsion and to explain their responses (for prompts and conceptual questions, see Appendix A). The instructor then left the dyads for 15 minutes to discuss their responses without instructor influence.
<u>Lab Activity</u>. Led by the lab instructor, student dyads tested samples of various metallic rods (aka, a dog-bone sample) using an ADMET material testing system (Figure 3.a; see Appendix C). Students drew a straight line (green) along the gauge length of an undeformed A36 steel specimen–a ductile material (Figure 3.b); material testing concluded at failure (Figure 3.c).

Data Collection. Participants' pre-lab assessment and torsional testing activities were video recorded and transcribed. Each dyad was placed in separate areas of the engineering classroom and their responses were recorded separately. Students were asked to state their common ground solutions to the lab instructor and completed a torsional lab testing activity. Common ground was determined by the natural conclusion of discussing a conceptual question, writing their solutions on a sheet of paper without further discussion of the conceptual questions, or discussing non-related topics during the allotted pre-lab assessment time. Transitions between questions were naturally occurring in students' discourse, unprovoked by the instructor, often using statements like, "I think we've answered this question." or "Are we ready to move on?". Of the 15 minutes allotted, the average duration to reach common ground was 9 minutes and 11 seconds with a standard deviation of 30 seconds.

Coding. Aligned with embodied theories of learning [18], transcript analysis implemented *sociocultural discourse analysis* [23] focused on co-construction of knowledge from the pre-lab questions within institutional (i.e., the classroom, lab room) and sociocultural (i.e., engineering education) contexts. Gesture codes were adapted from Walkington and colleagues [11] to include engineering objects. From students' speech, researchers developed structural and functional speech codes. Tables 2 and 3 (see Appendix A) provide the coding schemas and definitions applied to this corpus of data. Figure 4 (see Appendix C) provides examples of a student's mechanical reasoning producing static and dynamic depictive gestures. Coded data was imputed into epistemic network analysis (see next section) to elucidate the underlying patterns in students' gesture and speech during their mechanical reasoning (Figure 5 in Appendix C)

Data Analysis. Primary analysis used *epistemic network analysis* (ENA) [24]. ENA visualizes relationships between theoretical constructs and quantifies the strength of associations between them based on frequencies to determine their interconnectedness in a multi-dimensional space as a nodal network. The size of a node increases with its frequency and ENA calculates the centroid (i.e., Euclidean mean) of each network. As for the unit of analysis, ENA models segments of coded transcripts (i.e., multimodal communications like gesture and speech; see Tables 2 and 3 in Appendix A) within each dyad and quantify the connections between them as they co-occur within recent temporal proximity (see Appendix C for example). ENA also provides comparison plots (i.e., of networks) to indicate changes between phases (i.e., from argumentation and negotiation and establishing common ground).

For the purposes of this study, discourse was segmented by *turn of talk* between students or when there was a pause of greater than two seconds indicating a shift in mechanical reasoning. For ENA, each segment of a transcript (see Figure 5) includes: (1) utterances that have been segmented, (2) the location (i.e., the classroom or lab room), (2) group identification (i.e., which dyad), (3) assessment item or question number, (4) student participant identification (i.e., who is speaking), (5) time stamp in which the segment occurred, (7) the code that applies, and (8) appropriate window size. The window size (i.e., per iterative analysis, how many utterances are included in a sequence of discussion between group members) was selected to be four segments and the analysis moves through the transcript one segment at a time (e.g., (9) in Figure 5).

ENA's produces *weighted network plots*, in which nodes correspond to codes, and line thickness between nodes depict the relative frequency (i.e., weight) of co-occurrences between two codes. ENA can generate plots that differentiate by various factors. In the current data, these *primary* and *secondary plots* represent different educational environments at different times (i.e., pre-lab in the classroom vs. activities in the lab space). For example, the strength (i.e., line thickness) between the nodes for 'Structural Speech' (from Table 2) and 'Static Depictive' (from Table 3) is greater (i.e., co-occurred more frequently) during argumentation and negotiation than during common ground discourse. We use these calculations as a proxy measure for the strength of relationship between codes.

ENA also generates a *difference graph* or *comparison plot*, that subtracts the weights between nodes from the primary and secondary plots. This allows researchers to visualize and quantify the direction of change (i.e., is the magnitude net positive or negative; did strength of associations increase or decrease from one phase to the other). The mean subtracted network of a comparison plot not only identifies the change is a network's centroid, but also which epistemic elements of gesture and speech are significantly related to the progression of discourse as students mechanical reasoning and conceptualizations develop.

If (H2) is supported, the pre-lab assessment (arguing and negotiating) will exhibit a stronger interconnection for static depictive gesture and structural speech compared to dynamic depictive gestures and functional speech, and after establishing common ground, the strength of the interconnection will weaken for static depictive gestures and structural speech while the interconnection for dynamic depictive gestures and functional speech will increase. If there is no support for (H2), ENA results will show a stronger association between dynamic depictive gestures and functional speech compared to the strength of connection between static depictive gestures and structural speech.

Results

Using a grounded and embodied framework to investigate students' multimodal communication patterns while reasoning about torsion, we revisit our research questions: (RQ1) How do engineering students initially depict and describe their emerging understandings of the functions and behaviors and underlying structures of torsion in collaborative discourse? (RQ2) How do structural-functional relationships in students' discourse change between argumentation and negotiation to an established common ground? We hypothesized: (H1) that analysis of students' collaborative speech from collected transcripts will reveal frequent use of gesture in addition to speech that, together, describes and depict the underlying structures that give rise to functions and behaviors during torsion, and (H2) that during preliminary arguing and negotiating about torsion, students will rely more frequently on depictions and descriptions of structures compared to functions and behaviors and once common ground is established, the instances of gesture and speech will shift towards more frequent use of depictions and descriptions of the functions and behaviors of torsion compared to structures. To investigate these research questions, we employed sociocultural discourse analysis and epistemic network analysis to code and model the structural-functional relationships evident in students' gestures and speech during their collaborative discourse.

Regarding the first research question (RQ1), students initially produced numerous static and dynamic depictive gestures when reasoning about concepts of torsion. The transcript in Appendix D and Figure 6 in Appendix C provide detailed descriptions and depictions of students' discourse when reasoning about the first conceptual question (i.e., how a material responds to torsion). In support of the first hypothesis (H1) that students' discourse would initially depict and describe structure and functions of torsion, students frequently produced static and dynamic depictive gestures accompanying their structural and functional speech. For example, the transcript includes a moment or argumentation and negotiation in which students depicted and described the type of shear stress and material response experienced for the first conceptual question (see Appendix B). Participant 3 inquired about whether the stress developed during testing to which Participant 4 asked for clarification on the question. Participant 4 then followed their question with discussion of necking behavior as a possible mode of deformation indicative of the sample shearing. Participant 3 responded by claiming that necking behavior was observed during tension. After reflecting on their answer, Participant 4 agreed with Participant 3. Participant 3 produced both static and dynamic depictive gestures (see Figure 6 in Appendix C) while describing the material (a structure) and its transverse shear (a dynamic or functional behavior). Further, the transcript in Appendix D includes many static and dynamic depictive gestures, especially while reasoning about the deformation experienced by the material under torsion. For example, Participant 3 discusses how envisioned cubes on the surface of material deform into parallelogram-like or diamond-like shapes during torsion. In the process of their explanation, Participant 3's explanation produced multiple static gestures to represent the shapes their speech described before and during the material's deformation. Participant 3 asked Participant 4 finally reached common ground when the discussion shifted to non-relevant banter about where each was from, and Participant 4 made no attempt to revisit their collaborative conceptualization to answer the questions.

To investigate this second research question (RQ2), epistemic networks based on the transcripts of the dyads' argumentation and negotiation in the classroom (i.e., pre-lab), and explanations of their common ground responses (i.e., during lab activity). To examine differences between argumentation and negotiation and compare it to discourse with established common ground, we constructed mean epistemic networks for each dyad using ENA. In support of the second hypothesis (H2), that students' discourse would go from more frequent use of static depictive gestures and structural speech to more frequent use of dynamic depictive gestures and functional speech, there was a significant shift towards dynamic gestures and functional speech was observed in the comparison of epistemic networks.

Panel A of Figure 7 in Appendix C shows the epistemic network for the baseline strength of interconnections among gesture and speech codes from students' argumentation and negation. Observations of epistemic relationships (Figure 7; red connections) show a weak correlation for the interconnection between static depictive gestures and structural speech (SD-S; $r=0.33$) and weak correlation for the interconnection between dynamic depictive gestures and functional speech (DD-F; $r=0.29$). This suggests that while arguing and negotiating to establish a common ground, students more frequently produced gestures that represented the structure of torsion-related objects while they described these structural features than gestures that represented dynamic behavior and descriptions of the functional behavior. These results align with the hypothesis (H1) that there would be more frequent use of static depictive gestures and structural speech compared to dynamic depictive gestures and functional speech indicated by the strength of relationship, even though differences in structural-functional relationships were small.

Interconnections between nodes during students' common ground responses in the lab room are shown in Panel B (Figure 7; blue connections). There was a weak correlation for the interconnection between static depictive gestures and structural speech (SD-S; $r=0.18$) and a moderate correlation for between dynamic depictive gestures and functional speech (DD-F; $r=0.49$). The relative magnitude of changes (indicated by changes in line weight) in students' collaborative epistemologies between argumentation and negotiation (Panel A; Figure 7) and common ground (Panel B; Figure 7) responses are subtracted from each other in the comparison plot (Panel C; Figure 7), showing a relatively large decline in the correlation between static depictive gestures and structural speech (SD-S; $r=-0.25$) and a relatively large increase in the correlation for the interconnection between dynamic depictive gestures and functional speech (DD-F; $r=0.23$) with common ground established. These results suggest that once students established common ground, they produced more dynamic depictive gestures with functional speech and produced less static depictive gestures with structural speech in alignment with the second hypothesis (H2).

Figure 8 (see Appendix C) displays the changes in students' use of depictive gestures and speech once the dyad established common ground for first conceptual question (see Appendix B). This example counters the previous examples for the first research question. We see Participant 4 depicted and described how the material responded to torsion using a rubber-band metaphor to simplify Participant 3's reasoning about the deformation of cubes resulting in parallelograms or diamonds indicative of stress development. Participant 4's common ground response produced dynamic depictive gestures along with functional speech to describe and depict loading and deformation and less static depictive gestures with structural speech to discuss the material.

Beyond our research questions, this analysis yielded an interesting result between dynamic depictive gestures and structural speech. During argumentation and negotiation in the classroom (Panel A; Figure 7) there was a moderate DD-S correlation ($r=0.47$) and during common ground responses in the lab room (Panel C; Figure 7) there was a lower DD-S correlation ($r=0.30$). The comparison plot (Panel B; Figure 7) shows a decrease in strength of the DD-S correlation ($r=-0.17$). We discuss this finding further in the discussion.

Discussion

As an exploratory study in an engineering lab-based course, we investigated (RQ1) how students expressed the structural-functional relationships in gesture and speech regarding a dynamic system (i.e., torsion) and (RQ2) the shifts in students' expression of torsion between argumentation and negotiation and common ground responses. Our Epistemic Network Analyses (ENA) [24], even though it is based on a small sample of undergraduate engineering students (N=4) in a *Mechanics of Materials* lab course, suggest that collaborative, embodied learning activities were beneficial in shifting students' epistemologies. The expressions of their understandings in their descriptions and depictions of the structure of a dynamic system shifted towards descriptions and depictions of the functional behavior of a sample under torsion.

In alignment with Walkington and colleagues [11] findings that spontaneously produced dynamic gestures provide affordances to ground learners' conceptualizations, our results indicate that, for a small sample of undergraduate engineering students, dynamic gestures can assist in grounding their mechanical reasoning. Furthermore, prior mathematics research on language constructs, including verbs, was shown to predict dynamic depictive gestures with a significantly large effect ($d=1.60$, $p=0.0011$) [25]. Our results provide similar evidence that when students generate dynamic depictive gestures, they frequently accompanied functional speech that described transformations of an engineering object under torsion.

Finally, our additional finding of the reduction in the strength of interconnection between dynamic depictive gestures and structural speech (DD-S) from argumentation and negotiation to common ground suggests that students more frequently discussed the structure of an engineering problem while representing the dynamic behavior. The current study suggests that grounding collaborative learning in embodied activities affords students opportunities to enact their understandings of the structure of an engineering object as a conduit for deeper level scientific reasoning [22] shown in dynamic depictive gestures and described through functional speech.

Limitations and Future Work

Although this study reports identifiable patterns in students' collaborative discourse that emerge in structural-functional relationships in gesture and speech as they mechanically reason in engineering lab spaces, we must address some of the study's limitations. Firstly, there were the additional findings from the ENA correlations that require further understanding. Initially, during argumentation and negotiation, students more frequently described the structure of the engineering object alongside dynamic depictive gestures. Future work should explore the relationship of this epistemic connection to understand the initial reliance of structural speech and representations of the dynamic behavior, and why there was a decline in the frequency of the DD-S connection after establishing common ground. It may be that descriptions of the structure of an engineering object do not always require depictions. Rather, students may need to offload transformations of the engineering object that may be more difficult to conceptualize or verbally describe. Secondly, a larger sample size is required. Ostensibly, these connections lack statistical power to generalize beyond reported interactions. Moreover, revisiting this study using a controlled experimental design would allow research to establish causality between the factors identified in the network analyses. Thirdly, within the breadth of the entire *Mechanics of Materials* course it is imperative to look for corroborating evidence of students' multimodal expressions across multiple concepts. We speculate that the results discussed here will be replicated for other engineering concepts.

Lastly, this study did not address the contributions of instructor discourse that scaffolds students' learning.

Conclusion

Assessment of knowledge in the engineering disciplines is predominantly based on formalisms-first [1] approaches that use written exams to test one's formal knowledge of the properties of dynamic systems. Adequately assessing emerging engineering knowledge requires understanding how students are applying information relayed by their instructors and other professionals. Our findings suggest that engineering undergraduate students misalign conceptions of engineering concepts. Initially, students described the structure of an engineering object while depicting their understandings using static depictive gestures; this relationship flipped during their common ground responses in which they more frequently described the functional behavior and produced dynamic depictive gestures. In the current study, students' multimodal communications provided insights into their acquisition of knowledge through gesture and speech not only to their peers, but also to engineering instructors and professionals. These results suggest that students' epistemologies shifted from superficial, structural understandings to deeper, functional understandings in their reasoning. Thus, we contend that collaborative interactions between students are beneficial for developing students' scientific reasoning by permitting exploration of the structural-functional relationships related to engineering concepts.

Mechanical reasoning from undergraduate engineering students is more than the use of disciplinary formalisms used by educators; it must also include the professional applications for which engineering educators prepare their students. A progressively formalized curriculum grounded in embodied activities provides students with experiences upon which engineering principles are based. Moreover, by bringing speech and gesture into formative assessment practices, students can construct or re-construct their conceptual understandings of engineering phenomena to facilitate their understanding of higher order concepts [18]. The uniqueness of students' lived experiences diversify the contributions of prior and personal experiences to construct knowledge about new concepts [26]. Acknowledging these alternative epistemologies that draw from this rich source of students' communicative expressions helps students whose competencies may not yet include the formalisms typically indicative of mastery.

References

[1] M. J. Nathan, “Rethinking formalisms in formal education,” *Educational Psychologist*, vol. 47, no. 2, pp. 125–148, 2012.

[2] M. Hegarty, “Mechanical reasoning by mental simulation,” *Trends in Cognitive Sciences*, vol. 8, no. 6, pp. 280–285, 2004.

[3] W.M. Roth & Y.J. Lee, “Contradictions in theorizing and implementing communities in Education,” *Educational Research Review*, vol. 1, no. 1, pp. 27–40, 2006.

[4] M. Wilson, “Six views of embodied cognition,” *Psychonomic Bulletin & Review*, vol. 9, no. 4, pp. 625–636, 2002.

[5] F. J. Varela, E. Thompson, & E. Rosch, *The embodied mind: Cognitive science and human experience*. Cambridge, MA: MIT Press, 1991.

[6] L. W. Barsalou, “Grounded cognition,” *Annual Review of Psychology*, vol. 59, no. 1, pp. 617–645, 2008.

[7] S. Goldin-Meadow, *Hearing Gesture: How Our Hands Help Us Think*. Cambridge Mass.: The Belknap Press of Harvard University Press, 2005.

[8] D. McNeill, *Gesture and Thought*. Chicago, IL: University of Chicago Press, 2005.

[9] M. J. Nathan, R. Srisurichan, C. Walkington, M. Wolfgram, C. Williams, & M. W. Alibali, “Building cohesion across representations: A mechanism for STEM integration,” *Journal of Engineering Education*, vol. 102, no. 1, pp. 77-116. 2013.

[10] M. M. Grondin, M. I. Swart, F. Xia, & M. J. Nathan, “Assessing Engineering Students’ Embodied Knowledge of Torsional Loading Through Gesture,” presented at the 2022 ASEE Annual Conference & Exposition, Minneapolis, MN, June 26-29, 2022.

[11] C. Walkington, R. Boncoddo, C. Williams, M. J. Nathan, M. W. Alibali, E. Simon, & E. Pier, “Being mathematical relations: Dynamic gestures support mathematical reasoning”, *International Society of the Learning Sciences*, 2013. https://repository.isls.org//handle/1/1153.

[12] M. M. Grondin, M. I. Swart, A. R. Pandey, K. Fu, & M. J. Nathan, “How does students' use of speech ground and embody their mechanical reasoning during engineering discourse?” presented at the 2023 ASEE Annual Conference & Exposition, Baltimore, MD, June 25-28, 2023.

[13] S. Kang &B. Tversky, (2012). “From hands to minds: gestures promote action understanding,” *Cognitive Research: Principles and Implications* vol. 1, pp. 1-15, 2012.

[14] C. E. Hmelo-Silver & M. G. Pfeffer, “Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions,” *Cognitive Science*, vol. 1, pp. 127–138, 2004.

[15] B. Tversky, J. Heiser, & J. Morrison, "Space, time, and story," In *The psychology of learning and motivation*, B. H. Ross, Ed. Oxford: Elsevier, 2013, pp. 47 –76.

[16] R. B. Church & S. Goldin-Meadow, "The mismatch between gesture and speech as an index of transitional knowledge," *Cognition*, vol. 23, no. 1, pp. 43–71, 1986. doi:10.1016/0010-0277(86)90053-3

[17] P. E. Dillenbourg, *Collaborative Learning: Cognitive and Computational Approaches*. Elsevier Science, Inc., 1999.

[18] M. J. Nathan, *Foundations of Embodied Learning: A Paradigm for Education*. New York, NY: Routledge, 2022.

[19] D. W. Johnson, "Student-student interaction: The neglected variable in Education," *Educational Researcher*, vol. 10, no. 1, pp. 5–10, Jan. 1981. doi:10.3102/0013189x010001005

[20] M. J. Baker, "Collaboration in collaborative learning," *Coordination, Collaboration and Cooperation*, vol. 16, no. 3, pp. 451–473, Dec. 2015. doi:10.1075/is.16.3.05bak

[21] D. L. Schwartz, "The emergence of abstract representations in dyad problem solving," *The Journal of the Learning Sciences*, vol. 4, no. 3, pp. 321-354, 1995.

[22] K. Koenig, K. E. Wood, L. J. Bortner, & L. Bao, "Modifying traditional labs to target scientific reasoning," *Journal of College Science Teaching*, vol. 48, no. 5, pp. 28–35, May 2019. doi:10.1080/0047231x.2019.12290473

[23] M. Johnson and N. Mercer, "Using sociocultural discourse analysis to analyze professional discourse," *Learning, Culture and Social Interaction*, vol. 21, pp. 267–277, 2019.

[24] D. W. Shaffer, *Quantitative Ethnography*. Cathcart Press, 2017.

[25] K. Schenk, "Mathematical knowledge is embodied: Synergistic contributions of gesture and speech during geometry proof production," in *Proceedings of the American Education Research Association Annual Meeting, AERA 2020*. https://doi.org/10.3102/1574898

[26] N. S. Nasir, C. D. Lee, R. Pea, and M. McKinney de Royston, "Rethinking learning: What the interdisciplinary science tells us," *Educational Researcher*, vol. 50, no. 8, pp. 557–565, Oct. 2021. doi:10.3102/0013189x211047251

Appendix A: Tables

Table 1: Participant dyad assignment, demographics, and engineering coursework history

Participant	Dyad ID	Gender	Age	Race/Ethnicity	Engineering Discipline	Grade Level
P1	Group 1	Male	20	White/Caucasian	Mechanical	Junior
P2	Group 1	Male	20	White/Caucasian	Mechanical	Junior
P3	Group 2	Male	20	White/Caucasian	Civil and Environmental	Junior
P4	Group 2	Male	23	White/Caucasian	Engineering Mechanics	Sophomore

Table 2: Depictive gesture coding schema and definitions (Walkington et al., 2014); see Figure 4 (Appendix C) for examples.

Coding Schema	**Abbreviation**	**Definitions**
Static Depictive	**SD**	Gestures that **represent** an **engineering object** or its **features** that are not **being acted upon or interacting** with other engineering objects.
Dynamic Depictive	**DD**	Gestures that **represent transformations** of an **engineering object** or its **features**.

Table 3: Verbal reasoning coding schema and definitions (Au).

Coding Schema	**Abbreviation**	**Definitions**	**Examples**
Structure	**S**	Used to describe the **function** (i.e., dynamic or time-dependent) nature of an engineering object within the problem space.	That is just the cross-section [***S***].
Function	**F**	Used to describe the **structural** (i.e., static or non-temporal) nature of an engineering object within the problem space.	And, and I guess then, yea it would either be rotational, or it would be energy [***F***] going into breaking the bonds through shear [***F***] and plastic deformation [***F***].

Appendix B: Assessment Prompt and Conceptual Questions

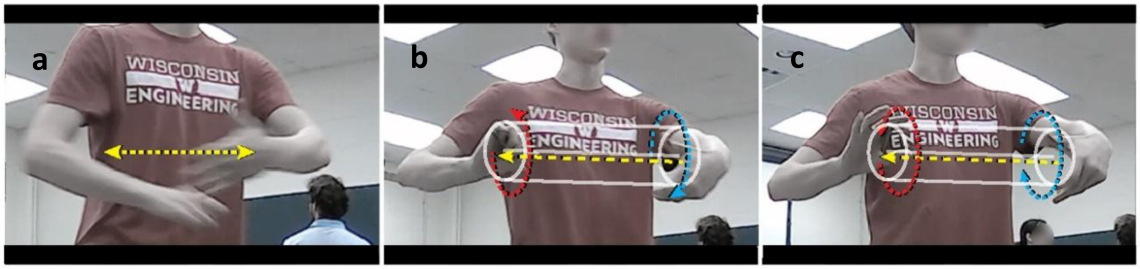
Prompt: You are curious to know which material will respond better under a torsional load. The samples are consistent in shape and size, only the material changes. The program for the test permits consistent angular displacements regardless of the material being tested.

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?

Appendix C: Figures



"Well, if the material's in its elastic state, then if you twist it…"

Figure 1: Depicts a student using a gesture sequence while describing energy addition and release during torsional loading. (a) the student spatially constructs a metallic rod depicting geometrical shape. (b-c) the student depicts rotational loading of the sample while describing angular deformation.

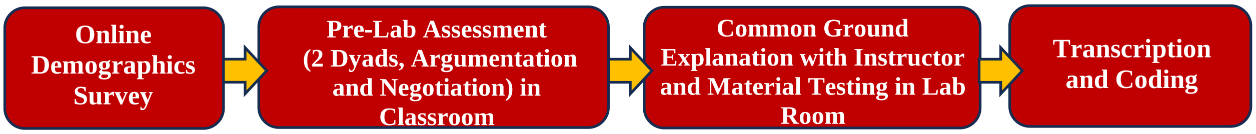


Figure 2: Schematic of experimental study design. The pre-lab assessment and instructional intervention each took approximately 15 minutes to complete.

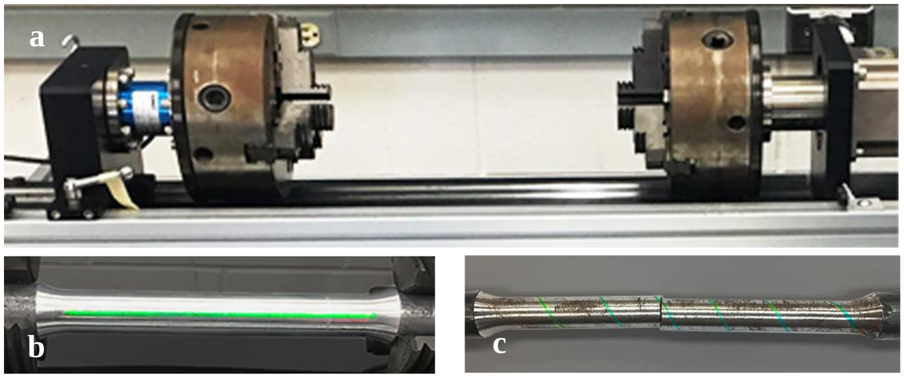
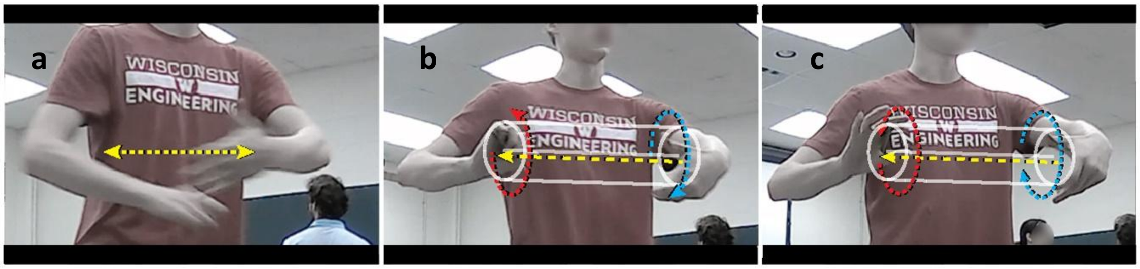
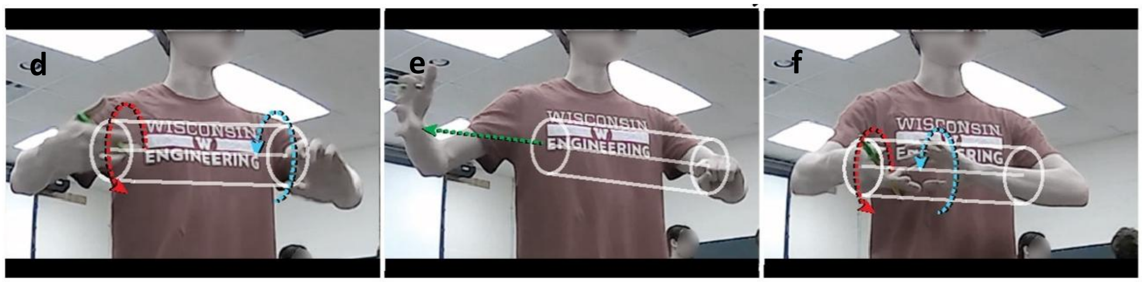


Figure 3: Torsion **e**quipment and testing. (a) Displays the ADMET testing system. (b) shows an undeformed sample; the green line allows a visual representation of deformation. (c) a deformed sample on which the green line providing represents the deformation at fracture.



"Well, if the material's [***Static Depictive***] in its elastic state, this if you twist [***Dynamic Depictive***] it and then…"



"…you release [***Dynamic Depictive***] it's going to twist back really fast [***Dynamic Depictive***]. That's a release of energy right there."

Figure 4: Depicts a student using a gesture sequence while describing energy addition and release during torsional loading. (a) the student spatially constructs a testing sample depicting geometrical shape with a *static depictive gesture*. (b-d) the student depicts rotation loading of the sample with a *dynamic depictive gesture* while describing deformation. (e) the student depicts releasing the torsional load with a *dynamic depictive gesture*. (f) the student uses a rotational unloading with a dynamic depictive gesture while describing how the material responds to the removal of the torsional load and energy release.

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 5: 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.

"…depending on the material [***Static Depictive, Structural Speech***] you can physically see… a uhh… is that a transverse shear [***Dynamic Depictive, Functional Speech***]?"

Figure 6: Participant 3 produces a gesture sequence that includes a static and subsequent dynamic depictive gesture while describing transverse shear during argumentation and negotiation. The student used a static depictive gesture to represent the sample followed by a dynamic depictive gesture to represent movement of the material.

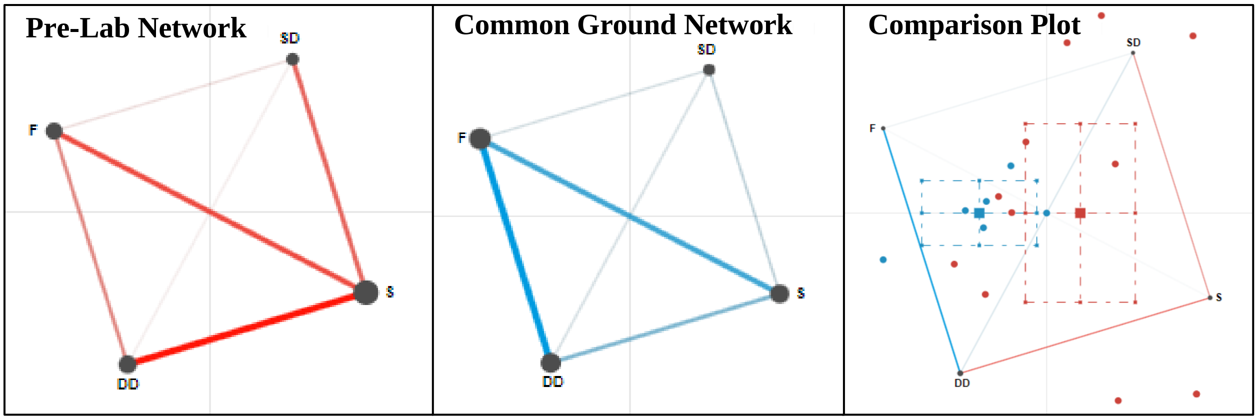


Figure 7: Displays epistemic networks for static and dynamic depictive gestures and structural and functional speech codes. The first network is the argumentation and negotiation graph from the classroom (red connections of Panel A), the second is their common ground responses graph from the lab room (blue connections of Panel B), and the third is the mean subtracted network (Panel C). Codes include Static Depictive (SD), Dynamic Depictive (DD), Structural speech (S), and Functional speech (F).

"You can see that the... **[Dynamic Depictive]**"

"…the material **[Static Depictive, Structural Speech]** of the rubber band **[Structural Speech]** is twisted up **[Dynamic Depictive, Functional Speech]**."

"…It's where you really see… **[Static Depictive]**"

"…you can tell that it returned **[Dynamic Depictive, Functional Speech]** to its original position **[Structural Speech]**."

Figure 8: Depicts a student's gestural sequence while describing, through a rubber band metaphor, how a material responds during torsional loading. (a-c) the student uses a concordant *rotational (loading)* gesture to depict angular displacement. (d-f) the student using a concordant *rotational (loading)* gesture to depict the twisting potion observed during torsional loading. (g-i) the student uses a concordant *geometrical shape* gesture to spatially represent the material. (j-l) the student discordantly using a *rotational (loading)* gesture while describing the material returning to its original configuration.

Appendix D: Transcript from First Conceptual Question

Participant 3 [10:52]
Umm... you can also respond to the material [*Structural Speech*], you can see how the material responds [*Functional Speech*] depending on the material [*Structural Speech*] you can physically see. A..

Participant 4 [11:02]
Right.

Participant 3 [11:03]
..a uhh... [*Static Depictive*] a.. is that a transverse shear [*Dynamic Depictive, Functional Speech*]? Is that technically what it is?

Participant 4 [11:11]
Sorry?

Participant 3 [11:12]
No. Umm...

Participant 4 [11:14]
Are you referring to like the way that it looks as you are applying [*Dynamic Depictive*] the torsion [*Functional Speech*]?

Participant 3 [11:18]
Yeah.

Participant 4 [11:20]
Ummm... Well, we can see that like, if it starts necking [*Functional Speech*], then that's a good uhh.. that will tell you right away that it's not going to shear [*Dynamic Depictive, Functional Speech*] immediately.

Participant 3 [11:33]
Would it, would it be necking [*Functional Speech*] then? From torsion [*Functional Speech*]?

Participant 4 [11:35]
Uhhhh...

Participant 3 [11:38]
Isn't necking [*Functional Speech*] from tension [*Functional Speech*].

Participant 4 [11:39]
Actually, no you're right. Necking [*Functional Speech*] does't really occur in torsion [*Functional Speech*].

Participant 3 [11:43]
It could just be if like... depending on the uhh... depending on the specimen [*Static Depictive, Structural Speech*], you could [*Dynamic Depictive*] technically see.. you would see the.. let's say, like, it was uhh.. like all cubes [*Static Depictive, Structural Speech*], you would see the [*Dynamic Depictive*] angles [*Structural Speech*] within the cubes [*Structural Speech*], oh sorry not the cubes [*Structural Speech*].. Angles [Structural Speech] within the, like, squares [Structural Speech]. If you were, like, [*Static Depictive*] on a cylinder [*Structural Speech*] ro.. even squares [*Structural Speech*] everywhere.

Participant 4 [11:11]

Yea.

Participant 3 [11:12]
You can see the uhh...

Participant 4 [12:12]
Actually, the first indicator...

Participant 3 [12:12]
You can see the angles [*Structural Speech*]. They would, they would turn [*Dynamic Depictive*, *Functi*onal *Speech*] into like trapezoids [*Structural Speech*]...

Participant 4 [12:16]
Yea.

Participant 3 [12:16]
...not trapezoids [*Structural Speech*]...

Participant 4 [12:18]
Umm.. Like diamonds [*Structural Speech*].

Participant 3 [12:19]
...like parallelograms [*Structural Speech*] or diamonds [*Structural Speech*]. Yea.

Participant 4 [12:20]
The first indicator would be what the material [*Structural Speech*] is. Because if it's not metal [*Structural Speech*], it's not going to be ductile [*Structural Speech*], right? Or.. if it's not.. uhh well that's not true, plastics [*Structural Speech*] that could deform [*Functional Speech*].

Participant 3 [12:35]
I mean, anything [*Static Depictive*] can be under torsion [*Functional Speech*]. Like [*Dynamic Depictive*] just being like this is under torsion [*Functional Speech*].

Participant 4 [12:40]
Yea. You can actually sort of see it's different towards [*Dynamic Depictive*]....

Participant 3 [12:43]
Yea. Yea, if I was strong enough.

Participant 4 [12:47]
I wouldn't want to do it anyways. Breaking a real pen.

Participant 3 [12:53]
Where are you from?

Participant 4 [12:54]
I'm from El Paso, Texas.