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# Moving Apart and Coming Together: Discourse, Engagement, and Deep Learning

**Andrea S. Gomoll[1*], Cindy E. Hmelo-Silver[1], Erin Tolar[1], Selma Šabanović[2] and Matthew Francisco[2]**

[1]School of Education, Indiana University, Bloomington, IN, USA // [2]School of Informatics and Computing, Indiana University, Bloomington, IN, USA // agomoll@indiana.edu // chmelosi@indiana.edu // etolar@iu.edu // selmas@indiana.edu // francm@indiana.edu

[*]Corresponding author

**ABSTRACT**

An important part of "doing" science is engaging in collaborative science practices. To better understand how to support these practices, we need to consider how students collaboratively construct and represent shared understanding in complex, problem-oriented, and authentic learning environments. This research presents a case study centered on the work of four students in a human-centered robotics curriculum enactment. We explore how discursive features including embodied gesture and positioning of material artifacts contributed to the problem-solving process and helped students move towards deeper learning — showing how nonverbal and verbal discourses were used to construct agreement and disagreement, parallel interaction, and accountability. Each of these discursive actions informed how the group moved forward or was halted in their complex collaborative work. We found that early stages of constructing a joint problem-solving space (JPSS) in this classroom environment required extended engagement, student ownership, and negotiation of shared activity. By exploring how select students worked toward the co-construction of joint problem-solving spaces, we reimagine what deep engagement and learning in STEM learning environments can look like, and we inform better design for the creation of these spaces.

**Keywords**

Human-centered robotics, Joint problem solving, Collaborative learning, Discourse analysis

## Introduction

As learners construct knowledge in social and interactive contexts, they negotiate power dynamics and disagreement, establish group norms, and navigate what it means to come to a consensus (Barron, 2000). In this article, we focus on these complex collaborative learning practices as a central piece of deep STEM engagement and learning. Collaborative learning practices are essential to STEM interest, engagement, and learning. These collaborative practices are also important for students' ability to see themselves as capable of "doing" science and engineering (Tan et al., 2013). Collaboration is essential for STEM careers, which require practitioners to navigate jointly what cannot be solved alone, obtain and evaluate evidence, design solutions, and communicate pertinent information. In the Next Generation Science Standards (NGSS), Engineering Practices 7 and 8 pertain to the ability to obtain and evaluate evidence, construct explanations, and design solutions (NGSS Lead States, 2013). Engaging students in the work of collaborative learning practices is therefore intertwined with authentic STEM engagement in classroom contexts and beyond. We conjecture that supporting students as they engage in these collaborative practices promotes deep learning. Although there is no single definition that we have found to categorize "deep learning," we view it as learning that leads to robust understanding of disciplinary practices, disciplinary concepts, and how these are interconnected (Sawyer, 2008). To better understand how to support deep collaborative learning, we need to consider how students navigate the challenging task of constructing shared knowledge (Barron, 2000; Roschelle, 1992).

The research presented here reveals the process of constructing joint problem-solving spaces (JPSS) in the discourse of one small group of middle school students. JPSS are shared "conceptual spaces" where students are able to develop their understanding together (Teasley & Roschelle, 1993, p. 69). These spaces, where students negotiate using shared language and activity, can be an important springboard for long-term STEM engagement and deep learning. As students collaboratively construct knowledge, they use verbal and nonverbal discourse to create a shared language for problem solving. This negotiation spurs students to engage deeply with disciplinary content and practices (Engle & Conant, 2002). The interactional data presented here comes from a larger research project that aims to engage students with engineering design practices through the use of a socially-oriented robotics curriculum. Prior studies of JPSS have taken place predominantly in lab settings or with advanced student populations (Hmelo, Nagarajan, & Day, 2000; Roschelle, 1992). Studying JPSS in a complex classroom setting advances our understanding of how students jointly progress toward deeper learning in naturalistic environments.

The human-centered robotics (HCR) curriculum described here is an inquiry-based curriculum of robotics experiences centered on a human-centered problem ("How can we create a robot that serves a need in our local context and connects students with remote peers?"). We designed and studied an HCR curriculum that helps learners develop technical skills along with an understanding of the relationship between technology, nature, and society. A key goal of this curriculum was to engage non-dominant populations (e.g., females and ethnic and racial minority populations) in STEM via a social robotics experience. Hands-on robotics and participatory design activities are an effective way to engage diverse groups of students in STEM (DiSalvo et al., 2008). HCR attends to "societal context" and "human needs" and has led to increased motivation in STEM, particularly for underrepresented female populations (Pajares, 2005). In this robotics unit, students in Indiana collaboratively personalized and programmed robots to both meet a local need and to communicate telepresently (i.e., via remotely controlled robot) with students from Alaska (Gomoll, Hmelo-Silver, Šabanović & Francisco, 2016). This connection was framed as an opportunity to interact with students and physical environments they might not be able to visit otherwise.

As students worked together to build a telepresence robot, they negotiated how to organize the problem-solving process. This negotiation within a real-world context involves active and creative problem solving, and is thus an ideal context for deep learning (Wang, Kirschner, & Bridges, 2016). In this study, deep learning occurs as students move beyond the ability to connect basic robotic components to recognizing how they work together as a designed socio-technical system. It also means that students come to appreciate the potential of collaborative roles and iterative design within the robotics project. Thus, our present analysis aims to understand how and where students make these connections, as well as when they fail to do so. Joint problem-solving spaces (JPSS) are constructed through interaction as group members set goals, define and redefine problems, and propose actions to solve them (Barron, 2000). This negotiation is akin to the kind of problem solving process that STEM practitioners and designers navigate (Silva, 2008). By pinpointing where JPSS are and are not occurring, as well as how the success and failure of JPSS are mapped to discourse, we can better understand how this curriculum supported deep engagement on the way to deep learning. In doing so, we also inform the literature on how to design curricula that support deep STEM learning experiences. This research expands upon earlier work around JPSS as well as research that has been conducted on knowledge convergence — exploring how these collaborative spaces are constructed in the face-to-face learning environment of an HCR experience over an extended period of time, and how they act as a precursor to collaboratively constructed understanding (Jeong & Chi, 2007; Roschelle, 1992). We focus in particular on the nonverbal and embodied contributions and collaborative practices that shaped one small group's work.

This paper addresses three research questions:

- How do individual students engage with collaborative work within this curriculum?
- How and where do we see JPSS in the collaborative work of one group in a middle school robotics curriculum?
- What discursive practices support and impede the creation of JPSS in this human-centered robotics context?

In the sections that follow, we provide an overview of joint problem solving and engagement, describe our qualitative analysis methods, and present episodes of small group interaction to reveal the dynamic nature of problem solving in one small group's experience of our HCR curriculum.

**Joint problem-solving spaces and discursive practices**

In early stages of collaboration, learners have different knowledge about the concepts they are working to master, challenging them to construct shared conceptual understanding through creation of a joint problem-solving space. When this joint construction of a space for problem solving is achieved, learners are able to move towards knowledge convergence (Roschelle, 1992). When knowledge convergence occurs, increasingly similar representations and socially shared meaning are produced by group members (Jeong & Chi, 2007; Weinberger, Stegmann, & Fischer, 2007). Jeong and Chi (2007) found that collaboration experiences led to knowledge convergence. However, these authors highlighted that examining conversation alone was not enough to paint a full picture of knowledge convergence as a collaborative process. We must also attend to social norms, nuanced contributions, and indicators of divergence. Before knowledge convergence can occur, students must create a JPSS where new understanding can be built. Within a JPSS, students establish common ground and coordinate their interactions to achieve a shared goal (Barron, 2000). We aim to better understand the work of constructing a JPSS by exploring the interaction of one small group.

As students work together to build a telepresence robot, they make decisions about how to organize the problem-solving process. Working cooperatively, students often take up individual roles and piece their work together to create a final product (Damon & Phelps, 1989). This group structure makes it difficult to construct a shared problem space, as one group member's ideas may dominate the problem-solving process. Alternatively, groups working collaboratively tackle problems together, offer peer feedback, and build on each other's ideas (Jordan & McDaniel, 2014). JPSS, and the interactions that construct them, serve as indicators of effective collaboration. If participants do not develop a shared problem space, they may not converge upon a shared understanding, and thus deep learning for all of the participants is unlikely. As demonstrated in Barron's work (2000), middle school groups engaged in complex problem solving often struggle to agree upon their goals, negotiate joint solutions, and achieve shared understanding. The barriers to engagement in complex problem solving and coordination included focusing on individual outcomes, treating personal workbooks as territory (i.e., only recording your own ideas), and failing to acknowledge peer contributions. High coordination in Barron's (2000) contrasting case study was marked by consistent turn-taking, shared workbook navigation, productive conflicts, and uptake of peer ideas. These activities all constitute discursive practices — doing something to shape an interactional event in situ (Potter & Wetherell, 1987; Potter & Hepburn, 2008). Barron and Roschelle (2009) argued that instances of disagreement and repair are necessary for the achievement of shared cognition. As groups uncover discrepancies, they must repair them in order to achieve shared understanding. This repair acts as a catalyst for knowledge convergence.

As we work to design a curriculum that supports knowledge convergence and deep STEM engagement, it is important to create spaces where discrepancies are expected and encouraged, and where organic JPSS can emerge. Our work unpacks one group's patterns of interaction — considering how verbal and nonverbal discourses are connected to a group's engagement and their eventual trajectory toward the construction of a JPSS and shared understanding.

**JPSS, engagement, and deep learning**

In past research, behavioral engagement (e.g., on-task behavior and participation), cognitive engagement (e.g., willingness to persevere to solve a problem), and emotional engagement (e.g., student attitudes and interests) have been privileged as evidence of students' interest and learning (Fredricks, Blumenfeld, & Paris, 2004). These forms of engagement are often studied in isolation, when they should be considered as dimensions of the complex and contextually determined concept of engagement (Fredricks et al., 2004). Furthermore, these defined forms of engagement are difficult to measure and interpret in meaningful ways (Fredricks & McColskey, 2012).

Throughout this paper, we consider engagement as context dependent and continually in flux. Across diverse definitions of engagement, there is agreement that it is a multidimensional construct. Engagement is nuanced and involves emotional, behavioral, and cognitive dimensions — including multifaceted forms of participation (Appleton, Christenson, & Furlong, 2008; Fredericks et al., 2004; Sinha et al., 2015). As such, this research examines how engagement unfolds in an HCR learning environment over time and across groups.

Exploring engagement and its connection to the construction of JPSS, we look for evidence of co-construction of understanding as students participate in diverse ways. We attend to the ways that students use verbal and nonverbal discourse to structure their interaction — including the use of gesture and the orientation to physical materials at the group's table. Such materials can be considered "boundary objects," artifacts that make the negotiation of group norms and understanding possible (Engeström, Engeström, & Kärkkäinen, 1995). Nonverbal discourse and embodied gesture are important aspects of communication and cognition (Alibali & Nathan, 2012). Human interaction depends on the use of a large toolkit of semiotic resources — from the sequence of talk to the positioning of the body, to aspects of the surrounding environment made relevant through gesture (e.g., pointing; Goodwin, 2000). Researchers have increasingly attended to embodiment (e.g., pointing, gaze, posture) as a significant interactional feature that can be used to perform discursive action such as collaborative knowledge construction and participation (Nevile, 2015). We conjecture JPSS and the nuanced verbal and nonverbal engagement that occurs within them not only to be an indicator of effective collaboration, but also as a precursor to deep learning.

## Methods

### Participants

Participants in this study were students in a five-week HCR unit in a seventh and eighth grade Applied Science class in a rural, U.S. public school in Indiana. Of the 30 students in the class, the instructor selected eight as focus group participants. One focus group of four was selected for analysis because of more appropriate and respectful group dynamics that the research team viewed as a condition for examining the deep engagement needed for constructing a JPSS. This group included two female eighth grade students and two male seventh grade students. All students were Caucasian. The rural demographic and female population of this middle school class was categorized as a non-dominant population in STEM (Avery, 2013; Tan et al., 2013).

### Instructional context

Over the course of the unit, students collaboratively personalized and programmed robots to meet both a need in their local environment and to engage telepresently with students from Alaska (see Gomoll et al., 2016). Telepresence connections allowed students to drive a robot remotely. For example, a student in Indiana would drive a robot in Alaska — engaging with remote peers using a video feed and sensors embedded in the telepresence robot's design. Students worked collaboratively in groups of four with support from a facilitator as they tackled ill-structured problems. Students also identified a need in their classroom that could be solved by a robot, and adapted their robot to solve this problem. This dual focus between solving a local problem and communicating with distant peers helped students consider how robots could both affect their local environment and be used to connect to a remote context.

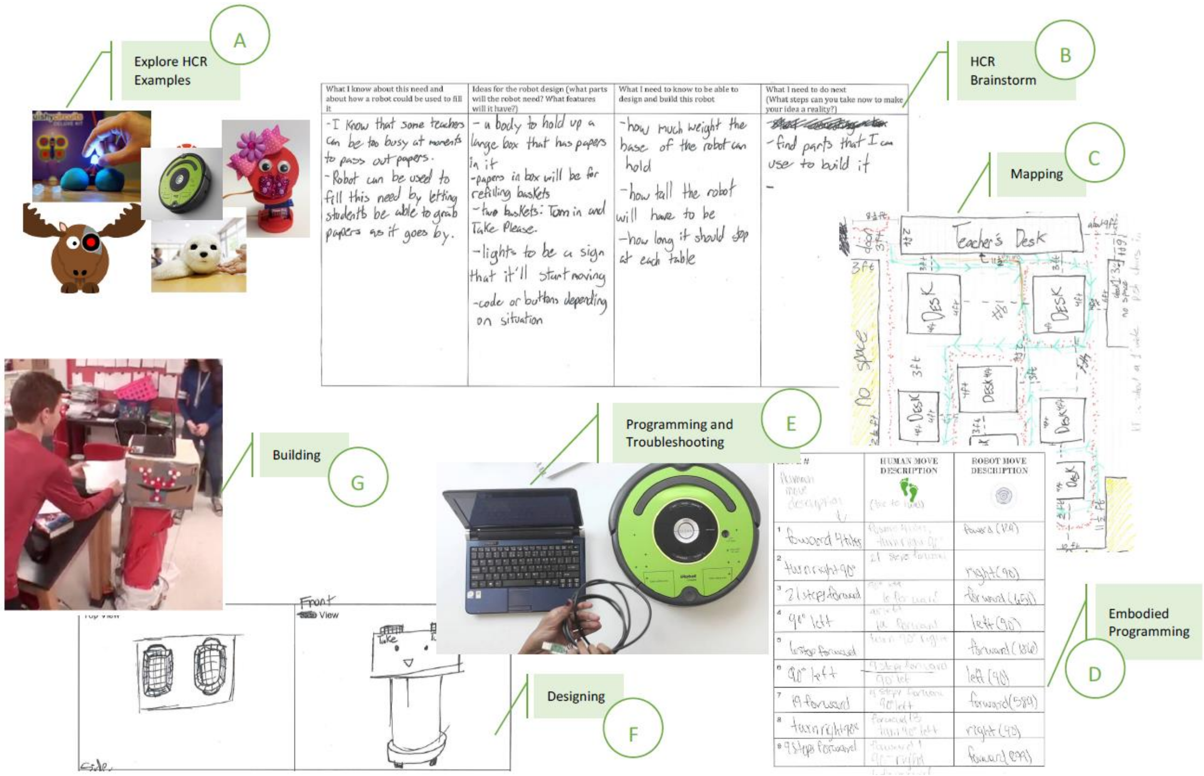



*Figure 1.* Overview of HCR unit trajectory

Figure 1 shows an overview of the HCR unit. During the unit introduction, students experienced several activities that introduced HCR and basic engineering practices. In groups of four, they moved between tables where different HCR interactive experiences were set (Figure 1A). The design challenge was then presented: Design a robot that serves a local need in your community and allows remote students to explore your space telepresently. Students brainstormed ways that robots could be used to address local needs (1B). Students then created maps of their classroom as aids for telepresent exploration and to better understand how a robot would move in their local environment (1C). This was followed by an embodied programming activity where students discovered the need for clear, specific instructions (1D). Here, they took on the role of the robot and translated directions into basic code. Students then practiced programming and troubleshooting as they drove the iRobot Create (1E). In the design portion of the unit, students designed prototypes of robots for their schools (1F). Each group agreed upon a unified design and was challenged to build and program a working human-centered robot, building up from an iRobot Create platform (1G). Throughout the unit, an engineering design cycle (see Figure 2) was used as a resource to help students to organize and reflect upon their problem-solving process. Students were encouraged to reflect on which part(s) of this cycle they were enacting as they designed and built their robots. In final presentations of their robot designs, groups used the engineering design cycle as a framework for explaining their group's process. Students provided examples of questions asked, information collected, challenges faced in the process of testing solutions, and refinements made based on these challenges.

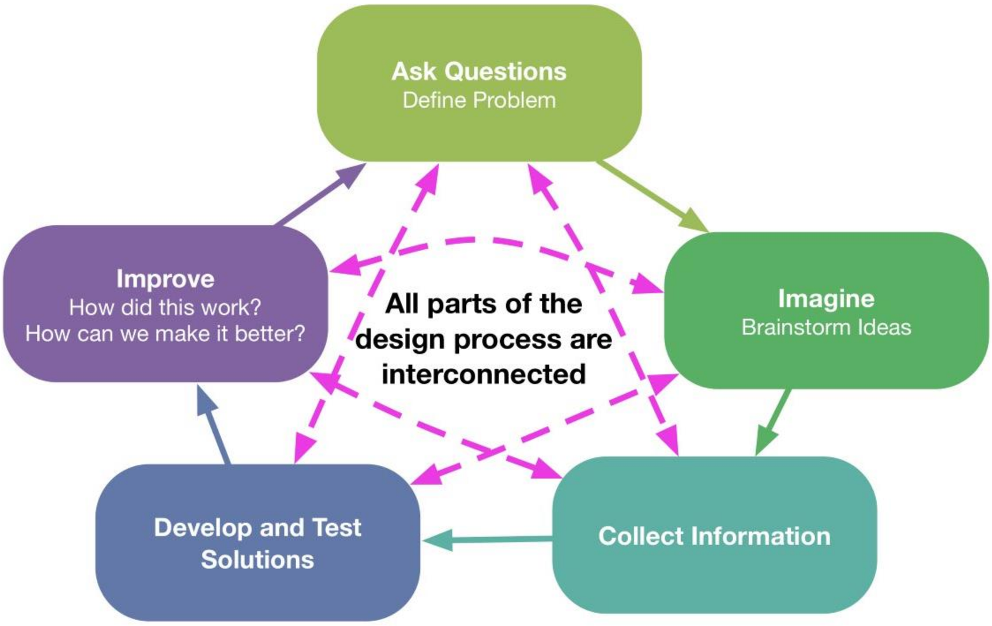



*Figure 2.* Engineering design cycle adapted from Resnick (2007)

**Data sources and selection**

Video of the focus group was recorded for every class session, with data from four class periods selected for this analysis. The selected videos involved group reasoning and joint activity directly related to our research question about the nature of collaborative work in this setting. In these clips, the students were engaged in tasks that could not be completed alone, including embodied programming, troubleshooting, and user testing. We were interested in the construction of JPSS in collaborative tasks, and we therefore selected inherently collaborative tasks to provide the best chance of "seeing" a JPSS emerge.

The first author developed initial analytic memos for each video. These memos noted the actions performed in small group discourse (e.g., disagreement) and features that related to the group's problem solving. Seven 2- to 7-minute video clips were selected for further exploration. These clips included group problem-solving experiences where a variety of verbal and nonverbal discourse features were highlighted in memos. These moments were flagged as potential JPSS.

## Analysis

We investigated our research questions using tenets of discourse analysis. Discourse analysis considers talk as a social action, and can be used to identify discursive patterns and norms that both shape and are shaped by participants (Gee & Green, 1998; Potter & Wetherell, 1987). We used discourse analysis to consider how this group's nuanced engagement shaped their collaborative inquiry and knowledge construction. We were interested in (a) the role of both nonverbal and verbal discourse in an interaction, and (b) how norms and practices such as turn-taking, agreement, disagreement, and decision-making, evolved at individual and group levels (Edwards & Potter, 1992).

The seven case-study clips were transcribed and analyzed in four data sessions. Participants in the data sessions noted interesting features of each interaction and converged around three themes related to the creation of JPSS: discrepancy, accountability and ownership, and parallel play. These themes were adapted into emergent codes and further memos were then applied to transcripts. Early codes were tags that noted features and functions of talk related to collaborative inquiry (e.g., disagreement, accountability, facilitation, questioning, blame). For each of these early codes, we explored sub codes that spoke to the mechanisms that made these actions possible — thinking about how students and facilitators were actively constructing disagreement, accountability, facilitation, etc.

Iterative review across data sessions allowed us to refine our research questions to focus on the nature of engagement in this context — drawing attention to nonverbal discourse in particular. This led to the reformatting of transcripts to privilege nonverbal action. Orienting to embodied interaction, we added layers of codes related to nonverbal features that appeared to be shaping the interaction. These codes fit into three categories (movement of artifacts, gesture, and gaze). Three episodes were selected that best represented each of these categories in action. Choosing such moments in which nonverbal engagement is well represented is particularly important for investigating how nuanced collaboration contributes to knowledge convergence and to deep learning. The findings will present examples of each of these discursive features and the nuanced functions they performed. These episodes speak to the nature of this small group's collaborative work and the nonverbal actions used to move towards the construction of a JPSS.

## Findings

We present three episodes that highlight discursive themes that emerged in our qualitative analysis: discrepancies, accountability and ownership, and parallel interaction. Each of the episodes highlights a theme that speaks to the construction of a JPSS and illuminates the nonverbal aspects of the small group's collaborative work. As we trace these discourses, we map them to the group's activity — working to understand how and when this group achieved a shared problem space. These findings provide a developing framework for discursive features that shape the construction of JPSS in our HCR curriculum.

### Episode 1

As students called attention to and negotiated discrepancies throughout the HCR unit, a potential space was created for knowledge convergence. In the movement of artifacts across the table and verbal uptake and rejection of group members' ideas, students performed accountability and ownership. This performance shed light on how the group was negotiating discrepancies, but it also illuminated norms around what it meant to "do STEM" in this space. As students coordinated their activity, the words they used and the movement of materials in the workspace shaped what they achieved. We conjecture that the interaction analyzed in the following two episodes can be labeled a JPSS, though it may not be one that was productive for knowledge convergence. This episode demonstrates that not all convergence is necessarily productive.

During the session in which the first episode takes place, students used maps they created of their classroom to consider a route that a robot could take in order to allow remote students to see the most important elements of the room. Each group in the class experimented with a "human robot" to develop specific directions they could translate into coded language to be used on a programming platform developed for this unit (http://robotmoose.com). As groups tested their human robot directions (e.g., "walk forward 10 steps"), they found ways to refine their directions to be increasingly specific for a wide audience (e.g., using units like "floor tiles," "feet," and "degrees"). Though the group put forth several ideas for units (tiles on the floor, the metric unit of a "foot") they did not all use the same units in their individual written work. Thus, they were engaged in a parallel interaction where each individual was pursuing his or her own solutions (Barron, 2000). In this first episode, the discrepancies in the four students' individual work come to the fore. In the activity that follows (Figure 3), the group's productive negotiation of these spaces was impeded. This highlights unsuccessful JPSS as a precursor to this group's successful construction of a JPSS. The episode began with student Karen's attempt to check the work that she has been doing independently. Her groupmates (Chad, Rayna, and Evan) filled in their own individual robot direction worksheets (see Appendix A for transcript conventions). All student names have been changed.

| Line | Name | Verbal transcript | Nonverbal transcript |
|---|---|---|---|
| 1 | Karen (K) | So 1 is forward 4 tiles, right? | *Gazes at Evan as she speaks.* |
| 2 | Chad (C) | This is (.) this is yours. That's yours | *Shuffles papers and holds one paper out to Rayna* |
| 3 | Rayna (R) | Well not really, 'cause everybody wrote on it, so I mean. | *As she speaks, Chad puts the paper back down on the table, between himself and Rayna.* |
| 4 | C | Oh yeah. Well I wrote on it. | |
| 5 | C | Wait is this right? | *Glances across papers on the table* |
| 6 | E | [Mine is right | *Evan gazes at his paper, moves it closer to Chad who sits beside him.* |
| 7 | C | Which- yours is right. This, this one (.) isn't right. Yours is right] | *Continues to shuffle through the group's papers. C & E gaze at Evan'paper.* |
| 8 | C | Four tiles. | *C& E gaze at E's paper. K & R work alone.* |

*Figure 3.* Episode 1

In this episode, ownership and authority were performed in the positioning of artifacts. As Chad distributed worksheets (line 2), he foregrounded the separation of solutions — positioning each set of directions as belonging to one individual (Rayna). When Rayna rejected the paper that Chad handed her (line 3), she rejected personal ownership, as "everybody wrote on it." This statement highlighted Rayna's attention to the group as a community. At this point, Evan was positioned as an authority (line 1 and 6), likely because he was the student to physically walk the paces while measuring the number of tiles for each move. His peers oriented to him and his work. The movement of artifacts across the table provided a visible representation of their negotiation of authority as they worked to develop a solution. In lines 6-8, the artifact movement across the table served as an emerging boundary object — passed between two participants, but not yet achieving its potential as a conduit for joint problem solving. All students continued to write on their own individual worksheets, deferring to the perceived group authority (Evan) as they copied his responses. We view this as a failed JPSS. In the episodes that follow, we explore more successful collaborative problem-solving experiences and what made them possible.

**Episode 2**

Episode 2 demonstrates how the group's coordination of ownership and display of engagement continued across multiple levels. This extract occurred early in a class period when students were preparing to present their group's robot design to the whole class. In the days leading up to this, students proposed individual robot designs and agreed upon a shared design for the group. This design was then submitted to be 3D printed as a small prototype by the research team. In these lines of interaction, we see how students negotiated authority in the group and discrepancies about one feature of the 3D-printed design. Throughout this interaction, students engaged in the developing and testing of solutions and improving phases of the design cycle. In this episode, nonverbal transcription sheds light on the role that nonverbal discourses played within the interaction (see Figure 4).

In line 1, Chad used gesture to reference the group's design drawing on the table as he asserted that the group's 3D printed model did not reflect what they represented in their sketch. Here, he called attention to the discrepancy between drawn fingers on their hand-like robot and the 3D printed rendering. This subtle gesture demonstrated Chad's engagement with the group's process and shared design history, indicating that he was working within a JPSS organized around that history. The movement functioned to orient the group to what they had already done (the design drawing) and where to go next (articulating their idea to the whole class). Rayna took up this orientation and contributed to the group's coordination in line 2 — articulating what the design was "supposed to be like." This statement of "supposed to be" asserted knowledge about the design. However, Rayna's unfinished sentence and hand gesture complicated this action and created a space for refinement of the collective understanding (a possible JPSS). As she constructed her argument for facilitators positioned at the table, Rayna extended her own hand, using her body as a representation of what the robot hand should look like. She then abandoned this gesture, moving her hand to cover her eye (line 2). This movement functioned as a cue for others to jump in and participate. Rayna's embodied gesture and her verbal reasoning both halted in line 2. The remainder of her sentence waited to be filled.

In line 3, Karen responded to this bid for participation from others by leaning back from the table and fixing her gaze on Rayna. This movement away from the design drawing shifted the responsibility back to Rayna. Rather than referencing the group's designs or responding verbally, Karen leaned back and thus established herself as a listener. This positioning further established Rayna's ideas as representative of the collective group. In this moment, the potential JPSS seemed to narrow and disintegrate — centering again on one individual as responsible for problem solving. Here, we see how these students are moving apart and coming together as they use discourse and material objects to negotiate problem solving.

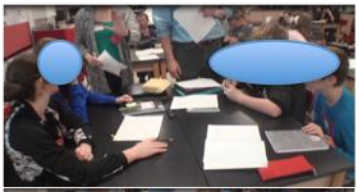
| Line | Name | Verbal transcript | Nonverbal transcript | Image |
|---|---|---|---|---|
| 1 | C | See the design had fingers but the new one didn't. | *Gestures towards design drawing with right hand. This hand also holds a piece of the 3D printed model.* | |
| 2 | R | I mean like (.) it was supposed to be like-- | *Rayna extends her right hand in front of her chest and then moves over her eyes* |  |
| 3 | K | | *Leans back from table to sit upright, gaze directed at Rayna.* | |
| 4 | Facilitator 2 (F2) | | *Facilitator 2 arrives at the table.* | |
| 5 | Facilitator 1 (F1) | Like a hand like this?= | *Facilitator 1 holds up her hand up with palm facing the table, mirroring the beginning of Rayna's gesture.* |  |
| 6 | C | :=I know but you told me to do it like that | *Moves left forearm across table with palm facing himself towards the design drawing that sits in front of Rayna and Karen, then back to rest on the table in front of him* |  |
| 7 | R | Okay, I told him to do it like that= | *Raises right forearm from table, moves right hand in a flipping motion with palm moving away from her body* |  |
| 8 | F2 | =You don't like the square ones like that? | *Facilitator 2 points to drawing* | |
| 9 | E | | *Leans in towards drawing in front of Chad as facilitator begins speaking* | |

*Figure 4.* Episode 2

In line 5, a facilitator mirrored the beginning of Rayna's gesture. This movement functioned as a piece of the facilitator's role — ending Rayna's sentence via embodied movement and guiding the group's work with a question: "Like this?"

Lines 6-7 include examples of gestures that speak to accountability and ownership in this small group. In line 6, Chad gestured toward the group's design drawing as he verbally placed blame for the state of the group's design ("you told me to"). This gesture drew attention to the shared artifact and evidence at the table — contributing to Chad's construction of accountability as the group negotiated a discrepancy. Rayna used her own gesture to dismiss in the following line — flipping her wrist outward as she declared: "Okay, I told him to do it like that."

Facilitator 2 then referenced the drawing as he mediated the group's interaction. This embodied discourse from an authority figure validated Chad's move to make the artifact relevant as evidence in the argument.

Finally, in line 9, we see the action of leaning made relevant for the second time in this exchange. Evan, who had not yet spoken, leaned forward in his chair — craning his neck towards the design drawing. This subtle gesture demonstrated his peripheral engagement in a JPSS. Throughout this extract, we see how gesture was used to make shared artifacts relevant in group reasoning and how body positioning (e.g., leaning) can be linked to attention and peripheral participation (line 9) and division of labor (line 3). We also see how gesture was used as a facilitation strategy — reorienting the group to their shared design. This re-orientation might be leveraged as a way to help groups recognize and reflect upon their JPSS in real time.

Throughout this episode, a JPSS was created through nuanced performances of accountability and ownership. These discursive performances served to construct a shared space for problem solving. While we do not see deep learning and knowledge convergence at this stage, this demonstration of a JPSS acts as a precursor. In the episode that follows, we move beyond the construction of accountability and ownership to see how discrepancy was negotiated by this small group and the class as a whole.

**Episode 3**

Throughout the process of creating and coding nonverbal transcripts for the analysis featured here, pointing emerged as a significant feature of group interaction. In preliminary coding, we identified three functions of pointing: accountability (e.g., directing another student to respond), attribution of blame (e.g., pointing that highlights a discrepancy), and evidence (e.g., pointing to artifacts that support a claim). Episode 3, presented below, gives an example of pointing that provided evidence for deep engagement with design reasoning (Figure 5). Prior to the beginning of this episode, a classroom facilitator (Facilitator 2) discussed the 3D printing process for a prototype of the robot that the group had drawn. He went on to describe some of the decisions he had to make when he translated the group's drawing into 3D form. The group noticed aspects they intended did not come through clearly in the 3D model. They used pointing as a means of coordinating discussion around these features, attempting to create a shared understanding of the problem.

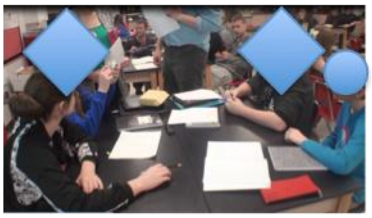
| Line | Name | Verbal transcript | Nonverbal transcript | |
|---|---|---|---|---|
| 1 | F1 | So what's this one? | *Pointing to a feature of the design* |  |
| 2 | E | | *Gaze directed at design drawing and 3D model* | |
| 3 | F2 | take it home can.] | *Facilitator is finishing the sentence "anyone who wants to take it home can"—overlapping from interaction immediately preceding this episode.* | |
| 4 | R | Oh that's a cup holder | *Picks up the 3D model and points to a feature* |  |
| 5 | K, C, E | | *Gaze directed at Rayna* | |
| 6 | R | It's supposed to have like a bottom on it. | | |

*Figure 5.* Episode 3

In lines 1 and 4 of this interaction, pointing directed attention to features of the group's 3D modeled design. Facilitator 1's pointing called attention to a specific feature of the group's 3D printed design model (line 1). Evan directed his gaze to this feature — orienting to the move made by the facilitator to achieve joint attention (line 2). Rayna physically handled the 3D model and pointed to the highlighted feature (line 4). She explained that it was intended as a cup holder. Here, Rayna gave voice to the collective ideas of the group. With this move, she used the physical model at the table and the gesture of pointing to support her explanation. As she gestured and explained, the other three members of the group oriented to her, as demonstrated by their gaze (line 5).

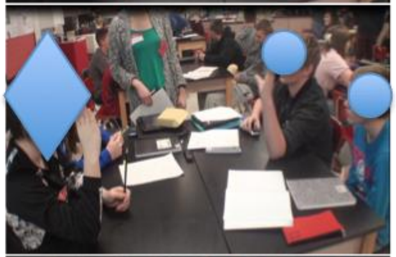
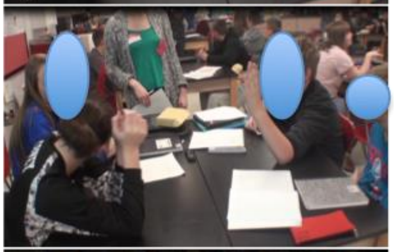
| Line | Name | Verbal transcript | Nonverbal transcript | Image |
|---|---|---|---|---|
| 7 | C | (.) [Rayna], you said you can't pick up a cup without fingers. | *Taps table with left hand on design drawing. E,R,K gaze directed at C's hand. C extends left fingers out from palm, moves hand up from table and then down as he says "fingers."* |  |
| 8 | K | It did have fingers on it. And it was the side view. | *Holds her hand vertical in front of her with left elbow on the table* |  |
| 9 | C | It had this on front, side, and top. | *C mirrors K's hand motion. K lowers her head between her elbows on the table, directs gaze at R.* |  |
| 10 | C | I mean it had (.) that's all it was. | *C moves the design drawing on the girls' side of the table closer to his spot at the table.* |  |
| 11 | K | Okay, it doesn't matter. | | |

*Figure 6.* Episode 3 continued

Following this interaction, the physical model of the group's robot was passed between group members as they further explained their intended design. Here, students participated in a shared activity structure that made use of tools (the robot model and design drawings at the table) to communicate their collective robot design goals. This tool use helped the group to address issues that were not immediately visible in their prior drawing, and it also appeared to support students' developing understanding of the need to iterate using physical prototypes within a design cycle. In this case, the physical robot prototype served as a boundary object for the group. In the following interaction, a later portion of episode 3, the students addressed discrepancies in their design ideas using pointing and physical artifacts (see Figure 6).

Throughout this connected episode, Chad worked to re-orient his group members to their design drawing and to come to consensus about their robot's appearance. Again, the group refined their design ideas. As he pointed to the design drawing in line 7 and enacted robot movement, Chad argued for the inclusion of fingers in their final robot design. He also referenced Rayna's idea — prompting the group to remember their shared decisions. This orientation to a shared design space and history served to construct a JPSS. In line 8, Karen used her hand to contribute. Here, she used physical gesture to show Chad what she and Rayna were depicting in their design drawing — a flat hand with touching fingers. Chad mirrored this gesture in line 9. As Chad and Karen mimicked one another, they appeared to be constructing a shared and embodied means of representing their robot design. Chad further supported the construction of this shared understanding by bringing the original design drawing back into the conversation (line 10). In this interaction, the students experienced real issues in designing robots that will complete specific tasks (e.g., grasping). This authentic experience helped them to recognize the limits of static images in the iterative brainstorming phase of the design cycle.

For the purposes of this analysis, we claim that pointing is a meaningful feature of engagement and a site for co-construction of understanding. We provide one example of how pointing functioned to direct attention and provide evidence in this small group's work with human-centered robotics. We conjecture that this particular gesture is important for groups' communication of design and construction ideas, to command joint attention, negotiate discrepancies, and to make connections — thus serving to build toward a JPSS.

## Discussion

In examining these episodes in a middle school HCR context, our analysis oriented to the functions of discrepancy, ownership and accountability, and parallel interaction in one group's discourse. First, we showed how the performance of ownership and accountability can both support and impede joint problem solving. Across these episodes, we showed how the HCR context provided opportunities to create JPSS (even when not realized). The curriculum provided physical materials and a designed problem that allowed students to negotiate iteratively designed artifacts, the ownership of which could change over time. These curricular aspects, which support the creation of JPSS, can be leveraged further to deepen collaborative engagement with the engineering design cycle and the socio-technical systems that are critical aspects of HCR. Building upon the productive use of physical robot prototypes and shared written artifacts as boundary objects, we might integrate more opportunities for students to physically move ideas across the table. Tools and activities such as collage boards for design ideas and collaborative word documents can promote embodied argumentation and scaffold the creation of a shared space for meaning making. Students might be encouraged to use movement and gesture to explain — modeling ways that embodied and verbal actions can contribute to the construction of shared understanding. Furthermore, video reflection might be used with instructors to scaffold active noticing of embodied engagement. Attending to joint interaction and gesture can serve as an indicator of group engagement.

Throughout our analysis, we were particularly interested in how group collaboration and problem-solving occurred. As students engaged with their HCR projects, they moved apart and came together. Students were not always in a JPSS, but over time, the ability to imagine the others' perspective became richer so that even in parallel work it was possible to attend to the perspective of the group. In the work presented here, we are interested in the social tensions and triumphs of small group work, considering how group dynamics and engagement are constructed and constructive in problem solving as well as how we can design for them. As students moved towards the construction of a JPSS, they came together more than they moved apart. We were able to see this coming together as we tracked verbal and nonverbal collaborative contributions. This analysis sets the stage for future work exploring JPSS, collaboration, and deep learning.

## Conclusion

This research made a case for the importance of nonverbal engagement in collaborative interaction and presented a preliminary framework of four specific features that were significant in one small group's collaborative interaction in a human-centered robotics curriculum. This framework includes embodied actions of leaning, the movement of artifacts, pointing, and gaze. These embodied elements functioned to position authority and accountability, direct attention, and provide support for verbal reasoning. These embodied actions are highlighted as aspects of deep engagement, and they contribute to existing literature on engagement and what it looks like in collaborative learning environments (e.g., Barron, 2000; Sinha et al., 2015). Tracing embodied actions throughout a series of episodes, we've demonstrated how they help us to "see" JPSS taking shape. Though these spaces are difficult to pin down and represent, we have highlighted how nonverbal actions taken by group members serve to create a shared mental and physical environment for meaning making.

This research has also shown that not all convergence was productive for group work. As students leaned and directed gaze, they communicated their participation and expectations about participatory patterns in group work. As they moved artifacts and pointed, they used material objects as artifacts to think with (Papert, 1980). These actions played out over time to weave the group's collaborative fabric as they wrestled with the challenge of engineering design practices. Embodied action supported students' brainstorming and iterative design. As they displayed and negotiated ownership and accountability in the problem-solving process highlighted here, students engaged with authentic STEM practices — perhaps beginning to see themselves as STEM learners in a new light. An open question remains as to whether engaging in these more robust practices leads learners to appreciate them over time, suggesting that we need to continue to consider the relationship between deep engagement and deep learning.

This research demonstrated how collaboration in verbal and non-verbal dimensions was an important part of students' design process, and thus that embodiment was central to students' understanding of robotics design. As students engaged in embodied ways, they made connections and developed more robust collaborative learning practices. In this sense, they were engaging deeply. From our sociocultural perspective, this kind of deep engagement and participation is deep learning. Opportunities like these for deep STEM engagement are important for the development of STEM interest and collaborative practices. For non-dominant populations in STEM who often find it difficult to identify themselves in STEM activities and careers, experiences that prompt exploration of diverse embodied and verbal discourses may help to re-define what STEM can and should look like.

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# Appendix A. Transcript conventions (adapted from Jefferson, 2004)

**Transcript conventions**

| | |
|---|---|
| [ | A single left bracket notes the beginning of overlapping talk |
| ] | A single right bracket notes the end of overlapping talk |
| = | An equal sign notes latching talk (no gap between turns) |
| (1) | Numbers in parentheses note pauses. (1) notes a pause of ~ 1 second |
| (.) | A period in parentheses notes a small pause between utterances |
| _____ | Underlined speech notes an emphasis on the underlined word(s) |
| *Italics* | Italicized words inside of double parentheses notes nonverbal behavior |

**Student pseudonyms and table positions**

| | |
|---|---|
| Rayna | Chad |
| Karen | Evan |

Front of classroom/bottom of transcript images