Participation in Small Group Engineering Design Activities at the Middle School Level: An Investigation of Gender Differences

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Jeanna R. Wieselmann is a Ph.D. Candidate in Curriculum and Instruction and National Science Foundation Graduate Research Fellow at the University of Minnesota. Her research focuses on gender equity in STEM and maintaining elementary girls' interest in STEM through both in-school and out-of-school experiences. She is interested in integrated STEM curriculum development and teacher professional development to support gender-equitable teaching practices.

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Dr. Emily Dare is an Assistant Professor of Science Education at Florida International University. Previously, she taught at Michigan Technological University from 2015-2018, where she is still an affiliated faculty member in the Department of Cognitive and Learning Sciences. Dr. Dare’s research interests are focused on K-12 STEM education. In particular, she is interested in supporting science teachers’ reform-based instruction while simultaneously understanding their beliefs. As science classrooms shift to more integrated STEM approaches, this is especially critical. Additionally, Dr. Dare has a passion for working with K-12 students to understand how changes in classroom instruction impacts their attitudes towards and beliefs about STEM fields. In particular, she is looking at methods that positively impact girls, which may increase the number of women pursuing careers in STEM-related fields where they are currently underrepresented.

Dr. Gillian Roehrig, University of Minnesota

Dr. Roehrig is a professor of STEM Education at the University of Minnesota. Her research explores issues of professional development for K-12 science teachers, with a focus on beginning teachers and implementation of integrated STEM learning environments. She has received over $30 million in federal and state grants and published over 80 peer-reviewed journal articles and book chapters. She is a former board member of the National Association of Research in Science Teaching and past president of the Association for Science Teacher Education.

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Introduction

As demand for expertise in science, technology, engineering, and mathematics (STEM) continues to increase, STEM education is of growing concern in the United States and around the world. With ongoing calls for improvements to K-12 STEM education [1], [2], pre-college engineering experiences are becoming increasingly common. The Framework for K-12 Science Education [2] and Next Generation Science Standards [3] include engineering practices within the scope of science, indicating that teachers responsible for addressing science standards are also likely to be responsible for teaching engineering.

As efforts to improve the quality of K-12 STEM education continue, so too do efforts to increase the representation of women in STEM fields. Although women and men receive undergraduate degrees at about the same rate, women account for only 30% of all STEM degree holders and have particularly low representation in engineering [4], holding just 12% of engineering jobs [5]. STEM integration seeks to merge the disciplines and is promoted as a means of increasing the number of students who are interested in and prepared to pursue STEM careers [6], [7]. As STEM integration becomes more common at the middle school level, it is important to consider key components of integrated STEM that are particularly supportive of young girls’ interest in and continued study of STEM.

While a variety of theoretical and practical conceptions of STEM exist [8] – [15], there is an emerging sense of agreement around the importance of teamwork in integrated STEM instruction [9], [16] – [19]. Teamwork and collaboration are emphasized in educational reforms, including the Common Core State Standards and NGSS [1] – [3], [20] as well as the vision statement of The National Academy of Engineering [21]. Within middle school classrooms, teamwork is often implemented through small group activities. Small group learning is particularly effective when the learning task is open-ended and has multiple solution paths [22], which is often the case in engineering design tasks.

Despite the centrality of teamwork to integrated STEM and the high potential of engineering design activities within small groups, little is known about how students at the middle school level participate in small group engineering activities [23], [24]. Investigations of small group interactions in engineering tend to focus on the undergraduate level [25], [26]. Schnittka and Schnittka [27] explored small group gender dynamics in a design-based afterschool program for middle school students; however, their work was in a rural, primarily White setting, included cooperative group roles within self-selected groups, and has not yet been extended to formal middle school classroom instruction of engineering-based integrated STEM. Compulsory coursework driven by a teacher’s need to address specific academic standards in science and associated with grades for students is likely to create a different environment for student interactions than elective, non-graded, informal experiences. In addition, existing studies often use quantitative analyses to investigate associations between motivation, context, and engagement [28]. With small group work ubiquitous with STEM, the affordances and limitations of small group activities must be considered.
This study addresses the gap in the literature to explore the following research questions:

1) What differences, if any, are seen in the engineering practices middle school girls and boys display during an engineering design challenge?

2) How, if at all, is group gender composition related to students’ participation in small group engineering design activities?

**Literature Review**

**Small group learning and girls’ STEM interest.**

Although a variety of factors, including stereotypes and biases, curriculum, and workplace environments contribute to the underrepresentation of women in STEM [5], many researchers point out low levels of STEM interest among girls as a particularly salient factor in influencing the career trajectories of young girls [29] – [35]. In a survey of 7,970 individuals, Maltese and Cooper [36] found that STEM interest was most often initiated prior to grade 6, and throughout the school years, STEM interest was fostered more through school experiences and coursework than out-of-school experiences. Positive school STEM experiences in the middle school grades are critical for developing students’ STEM interest [37], [38].

A variety of studies, including two meta-analyses [39], [40], have found that small group learning contributes to positive outcomes in achievement, motivation, persistence, attitudes, engagement, and problem-solving [22], [28], [41] – [46]. These benefits likely arise from the combination of hands-on activities and discussions that take place in small groups. Small group instruction is proposed as an effective strategy for engaging girls in STEM because of research that indicates that girls are more cooperative and less competitive than boys [47] – [51]. A variety of researchers have found that small group learning environments benefit girls [28], [48], [52] – [57]. Hands-on activities that emphasize applications of knowledge in real-world contexts can meet girls’ desire to know how their learning can be applied [55], [58], [59].

Despite a number of beneficial outcomes associated with small group learning strategies, well-documented problems with small group learning also exist. The social dynamics and organization of small groups can interfere with learning [60]. It is often assumed that placing students in small groups will result in their learning of collaborative skills and teamwork [61], but there is little research that supports this assumption [62]. Girls and boys working in mixed gender small groups often display different interaction patterns [63], with girls often participating to a lesser degree in the small group activities [64]. Participation of girls often focuses on passive assistance and note-taking [65], [66], building positive relationships [67], [68], and following directions [50]. Girls show higher rates of interaction with group members [69] and tend to focus on interactive, cooperative, and people-oriented interactions in their group work [70].

In contrast, boys are more likely to actively lead a group and manipulate the materials [65], [66], [71], focus on tasks rather than group processes [72], express competitiveness with other group members [50], and spend time off-task [73]. In mixed-gender groups of fourth- and fifth-graders, boys were seen to have better ideas and be team leaders [74], often dominating the small group activities and handling of equipment [75], [76]. In addition to boys’ control of the physical
materials in their small groups, researchers have found that middle school boys also dominated speech in terms of both frequency and volume [27]. This pattern continues into college, when men are more likely to interrupt the women in their small group than they are to interrupt other men [77]. These interactional styles can further perpetuate gender stereotypes related to engineering.

**Group gender composition.**
With a significant body of research highlighting gender differences in group interactions and issues associated with mixed-gender small groups, the significance of group gender composition must be considered. Some studies have found the presence of girls to beneficial to both boys and girls in the group. For example, Monereo, Castelló, & Martínez-Fernández [78] found that among high school students, female-majority groups were more adept than male-majority groups at breaking down task objectives, regulating progress toward reaching these objectives, interacting in a collaborative manner, fostering a positive group climate, providing support for one another, and remaining on task. Having a female-majority group was the most significant predictor of group success. However, additional research findings have been contradictory. Some studies [79] – [81] have found group gender composition to be unrelated to participation in group activities. Other studies have found that mixed-gender groups are associated with more positive outcomes than single-gender groups. For example, researchers [82] found that middle-school students participating in a design-based physics curriculum performed better on assessments of content and practices if they had worked in mixed-gender as opposed to single-gender groups. Schnittka and Schnittka [27] found mixed-gender groups to be beneficial in engineering education, with girls learning more in such mixed-gender groups.

Although research findings related to the influence of group gender composition are mixed, a number of studies [78], [83] – [85] have found group gender composition to be significantly related to students’ participation, with single-gender groups having more equitable participation patterns than mixed-gender groups. For example, in a systematic review of 94 studies of small group discussions, researchers found that single-gender groups had more purposeful functioning than mixed-gender groups [83]. Other studies have found that single-gender pairs of elementary students had more verbal interactions, were more task-focused, and were more likely to share materials [84]. In addition, students’ self-efficacy in engineering increased significantly if they participated in single-gender engineering programs but decreased significantly for those in mixed-gender programs [86].

Single-gender small groups may be particularly effective in fostering girls’ equitable engagement in STEM activities, with girls experiencing greater benefits of single-gender groups than males. Green and Cillessen [71] found that all-girl groups of six-year-olds had high rates of collaboration, while all-boy groups were more likely to have “onlookers” who did not help with the task. Cooperation between girls in single-gender groups is more balanced than either mixed-gender or all-male groups [87], [88]. Within all-girl engineering groups, students tend to focus on group-oriented interactions, using we/us language more often than referring to self or others [27]. In considering this difference as well as other differences in interaction patterns, Schnittka and Schnittka [27] asserted that girls may adjust their interactional style depending on the gender composition of their group: collaborative and focused on group solidarity in all-girl groups, and
competitive in mixed-gender groups. The same degree of interactional shifts was not seen for boys in all-boy and mixed-gender groups.

Girls’ collaboration and group-oriented focus can provide a safe environment for girls who are working with their same-gendered peers. Girls often prefer to work in single-gender groups because they seek to avoid the dominance of boys and have the support of their friends [89]. This preference for all-girl groups is consistent for students at a range of ages, including those in elementary school [90], middle school [91], and college [85].

Theoretical Framework

As engineering is integrated in science instruction, engineering design activities are becoming more common at the middle school level. Design-based learning centers on engineering design challenges as the context for learning [92]. Engineering design activities that focus on solving problems are emphasized as an effective means of promoting engineering skills and habits of mind in K-12 settings [1] while engaging students in practices that are authentic to engineering [2], [3]. While these activities have the potential to support student learning and achievement, they can also promote students’ interest in STEM [1]. For example, researchers found that students who were taught using an engineering design-based science curriculum showed more positive attitudes toward STEM following the unit of instruction [93].

This study is grounded in the work of Crismond and Adams [94], who developed the Informed Design Teaching and Learning Matrix based on a meta-literature review. The matrix includes nine design strategies that are fundamental to informed engineering design and include: understanding the challenge, building knowledge, generating ideas, representing ideas, weighing options and making decisions, conducting experiments, troubleshooting, revising or iterating, and reflecting on the process. In addition to identifying these strategies, the authors describe learning progressions to highlight the range of design behaviors that develop from beginning designers to informed designers.

The design strategies in the Informed Design Teaching and Learning Matrix are intended to be used as an instructional tool for teaching design and were based on key performance dimensions of design [94, Table 1]. In this study, the performance dimensions of design are used to explore middle school students’ participation in small group engineering activities as we seek to answer the research questions:

1) What differences, if any, are seen in the engineering practices middle school girls and boys display during an engineering design challenge?
2) How, if at all, is group gender composition related to students’ participation in small group engineering design activities?

Table 1. Performance dimensions of design

<table>
<thead>
<tr>
<th>Performance Dimension</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning while designing</td>
<td>Informed designers learn continually as they brainstorm, plan, prototype, trouble, and revise their designs. Metacognition and reflection are</td>
</tr>
</tbody>
</table>
Making and explaining knowledge-driven decisions
Informed designers apply their understanding of science and how things work to their designs.

Working creatively to generate design insights and solutions
Informed designers use creativity and take productive risks in defining problems, developing potential solutions, and improving their solutions.

Perceiving and taking perspectives intelligently
Informed designers consider multiple perspectives in defining the goals and priorities in their work.

Conducting sustained technological investigations
Informed designers intentionally collect and use evidence as they consider their design.

Using design strategies effectively
Informed designers use a variety of design practices in their work and can work effectively with others.

Integrating and reflecting on knowledge and skills
Informed designers use knowledge from multiple disciplines and reflect on their design activity.

Methods

Research design.
This study utilizes a multiple embedded case study methodology to explore the phenomenon of students’ experiences in small group, integrated STEM activities. This methodology was selected because it allows for an in-depth exploration of a social phenomenon [95]. Three small groups of students represent three cases, and the individual students within each group serve as units of analysis.

Context.
This study is situated within the context of a five-year, federally-funded research project focused on developing K-12 science teachers’ understanding of the engineering design process. The project was grounded in the STEM integration framework [18], which outlines six key tenets of high-quality integrated STEM curricula: 1) a motivating and engaging context; 2) an engineering design challenge; 3) opportunity to learn from failure through redesign; 4) inclusion of mathematics and/or science content; 5) student-centered pedagogies; and 6) an emphasis on teamwork and communication.

During the first three years of the project, participating teachers attended a three-week professional development (PD) summer institute, where they learned about approaches to teaching engineering and data analysis, integrating engineering in science lessons, and understanding how to create integrated STEM curricula. Teams of teachers wrote engineering design-based curricular units during the PD, piloted their units with summer camp students, made revisions to the units, and then implemented their units in their classrooms. They were supported by university faculty in STEM education and STEM fields during the PD and by STEM education graduate student coaches throughout the school year.
During the final two years of the project, graduate students in STEM education revised and polished curricula that had been developed in the grant’s initial three years to strengthen their STEM integration and ensure the activities were purposeful and necessary for the engineering design challenge. These units were selected for field-testing because they had strong links or potential links to the STEM Integration Framework [17]. Participating teachers attended a one-week summer PD focused on the unit they would be implementing, then field-tested the revised versions of the curricula in their classrooms throughout the school year. The first author served as the curriculum development and PD lead for the unit explored in this study.

This study focuses on students experiencing Laser Security System, one of the teacher-developed, engineering design-based curricular units. This curricular unit was written for middle school students in grades 6-8 and focused on science content related to properties of light, including reflection, refraction, absorption, transmission, the wave model of light, and the electromagnetic spectrum. The unit was designed to have students work in small groups to meet the needs of a client who was developing a laser security system to protect valuable assets in a museum exhibit. Students are tasked with using a single laser, mirrors, and lenses to design a system that reflects and refracts light so that a thief would have to cross the laser light at least three times in walking from the exhibit entrance to the artifacts on display. The unit includes a planning phase, during which students apply their knowledge of properties of light to the design of their laser security system. During the testing phase, students identify problems or ways to improve their initial designs, and they have opportunities to make these improvements during the redesign phase. Evidence-based reasoning is emphasized throughout the curricular unit to ensure that students apply their content knowledge rather than “tinkering” with the materials when creating their designs.

This curricular unit was selected for this study via purposive, criterion-based sampling [96] due to its high-quality STEM integration based on the STEM Integration Curriculum Assessment [97]. The unit consisted of eight lessons, each of which was intended to take at least one 50-minute class period. In practice, this unit was implemented during 20 class periods, 10 of which focused on engineering.

Participants.
Participants were 11 students in grade 6 (aged 11-12 years) at a suburban middle school in the Midwestern U.S. The students’ science class had a total of 27 students (nine girls and 18 boys), and their science teacher had received PD related to both STEM integration and the unit itself. Their teacher had participated in the grant project for three years, and she assigned the participants to either a single-gender or mixed-gender small group for the duration of the Laser Security System unit. Within the class, there were two all-girl groups, three all-boy groups, and three mixed-gender groups. One group of each gender composition was selected for this study based on the group members’ consent to participate and their comfort levels with the video camera and audio recorder. These three groups serve as the cases and are the primary focus of this study. Within these three target groups, three girls participated in the all-girl group, four boys participated in the all-boy group, and two girls and two boys participated in the mixed-gender group. While the range of gender identities are associated with a range of complex issues
in STEM education, this study is limited in focus to the binary categories of female and male, which aligns with the literature cited throughout.

Participants’ pseudonyms and demographics are shown in Table 2. These students were representative of the school district in which they were enrolled. All 11 participants in this study were native English speakers. Brian, a student in the all-boy group, received special education services.

Table 2. Participant demographics

<table>
<thead>
<tr>
<th>Group Gender Composition</th>
<th>Pseudonym</th>
<th>Gender</th>
<th>Ethnicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-Girl</td>
<td>Elsa</td>
<td>Female</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td>Kiera</td>
<td>Female</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td>Kelly</td>
<td>Female</td>
<td>White</td>
</tr>
<tr>
<td>All-Boy</td>
<td>Charlie</td>
<td>Male</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td>Adam</td>
<td>Male</td>
<td>Asian American</td>
</tr>
<tr>
<td></td>
<td>Brendan</td>
<td>Male</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td>Brian</td>
<td>Male</td>
<td>White</td>
</tr>
<tr>
<td>Mixed-Gender</td>
<td>Madison</td>
<td>Female</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td>Amanda</td>
<td>Female</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td>Umar</td>
<td>Male</td>
<td>African American</td>
</tr>
<tr>
<td></td>
<td>Alan</td>
<td>Male</td>
<td>Asian American</td>
</tr>
</tbody>
</table>

Data collection.
Data were collected throughout the 20 days of unit implementation, and this study focuses on the 10 days of engineering-focused instruction. A video camera and audio recorder were trained on each small group each time they worked together, resulting in seven hours and 57 minutes of small group video available for analysis. All of the small group audio was transcribed, and additional data sources included the first author’s daily field notes from the unit implementation and researcher viewing memos (described in more detail below).

Data analysis.
During the first phase of data analysis, each researcher focused on one student in each small group throughout the duration of the unit to better understand individual patterns of participation. While viewing the videos, researchers wrote detailed memos about their target students. In addition, researchers used a coding protocol based on Jovanovic and King’s [65] protocol that examined student participation in small group science activities. The science-focused protocol was modified and expanded upon to include performance enactments of integrated STEM and engineering activities [98]. The final coding protocol consisted of 33 performance enactments, including both verbal and non-verbal means of participation (see Appendix A).

Once interrater reliability was established, this coding protocol was applied to each three-minute segment of small group engineering activity throughout the unit to generate frequency counts of the performance enactments for each student. The 33 performance enactments were coded using
a binary system: 1 indicated the presence of a performance enactment and 0 indicated its absence in a three-minute segment. As this phase of data analysis was completed for each group, the researchers met and discussed both the code frequencies and their researcher memos to capture details about the participation patterns, overall interactions, and cohesiveness of each group.

During the next phase of data analysis, researchers focused on cross-case analysis [95] to identify similarities and differences across the three small groups in the study. Constant comparative analysis strategies [99] were used to look across data sources (coding protocol, researcher memos, and field notes) and across groups and explore how group gender composition was related to students’ participation.

Findings

As students participated in the engineering activities of the Laser Security System unit, they displayed differing patterns of performance enactments. These patterns varied both by gender and by group gender composition. In the following sections, individual case summaries are shared to describe each group’s interactions. These findings focus on overall group cohesion and interactions based on data from both researcher memos and the coding protocol. Table 3 provides frequency counts by individual, by gender, and by group of the most salient codes from the coding protocol. These data are discussed in more detail throughout the findings. Following the individual case descriptions, cross-case analysis findings focus on the seven performance dimension of design [94].

Table 3. Performance enactment frequency counts by student, gender, and group

<table>
<thead>
<tr>
<th>Group</th>
<th>Student</th>
<th>Student Gender</th>
<th>Agreeing</th>
<th>Directing</th>
<th>Elaborating</th>
<th>Frustration: Person</th>
<th>Frustration: Task</th>
<th>Judging: Person</th>
<th>Manipulating</th>
<th>Metacognition</th>
<th>Off-Task</th>
<th>Peer Checking</th>
<th>Reasoning</th>
<th>Record Keeping</th>
<th>Referring to Earlier Material</th>
<th>Suggesting Idea</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-girl</td>
<td>Kiera</td>
<td>F</td>
<td>13</td>
<td>12</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>34</td>
<td>1</td>
<td>19</td>
<td>11</td>
<td>6</td>
<td>28</td>
<td>2</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Kelly</td>
<td>F</td>
<td>14</td>
<td>16</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>28</td>
<td>3</td>
<td>9</td>
<td>7</td>
<td>7</td>
<td>20</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Elsa</td>
<td>F</td>
<td>31</td>
<td>34</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>39</td>
<td>3</td>
<td>33</td>
<td>17</td>
<td>7</td>
<td>27</td>
<td>4</td>
<td>34</td>
</tr>
<tr>
<td>SUM - Group</td>
<td></td>
<td></td>
<td>58</td>
<td>62</td>
<td>12</td>
<td>3</td>
<td>6</td>
<td>0</td>
<td>101</td>
<td>7</td>
<td>61</td>
<td>35</td>
<td>20</td>
<td>75</td>
<td>7</td>
<td>89</td>
</tr>
<tr>
<td>Mixed-Gender</td>
<td>Madison</td>
<td>F</td>
<td>6</td>
<td>28</td>
<td>3</td>
<td>14</td>
<td>11</td>
<td>6</td>
<td>39</td>
<td>0</td>
<td>22</td>
<td>3</td>
<td>11</td>
<td>19</td>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Amanda</td>
<td>F</td>
<td>12</td>
<td>8</td>
<td>0</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>23</td>
<td>0</td>
<td>2</td>
<td>11</td>
<td>6</td>
<td>7</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Umar</td>
<td>M</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>33</td>
<td>0</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Alan</td>
<td>M</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>6</td>
<td>4</td>
<td>5</td>
<td>14</td>
<td>0</td>
<td>39</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>SUM - Girls</td>
<td></td>
<td></td>
<td>18</td>
<td>36</td>
<td>3</td>
<td>22</td>
<td>15</td>
<td>10</td>
<td>62</td>
<td>0</td>
<td>24</td>
<td>14</td>
<td>17</td>
<td>26</td>
<td>3</td>
<td>37</td>
</tr>
</tbody>
</table>
Case summaries.

All-girl group.
Overall, the all-girl group had highly cohesive group dynamics. Leadership responsibilities in the all-girl group were somewhat fluid, with different students taking primary leadership at different points in the design activities. Although Elsa was seen as the primary group leader, directing on 34 occasions, the leadership responsibilities were distributed across the group members. Kiera and Kelly both gave verbal directions to their teammates (12 and 16 occasions, respectively) at points in the lesson when they adopted temporary leadership responsibility. The cohesiveness of the all-girl group is also evidenced by the distribution of responsibilities (such as manipulating and record keeping), frequent peer checking and elaborating, and low occurrences of frustration and judging. Students in the all-girl group expressed frustration with their peers on only three occasions and frustration with the task on six occasions. They did not express judgement about a person on any occasion.

Girls in this group appeared familiar with the more structured aspects of engineering design, such as record keeping and developing initial plans guided by a worksheet. However, the open-ended design activities seemed to cause them to struggle to stay focused when they did not have a worksheet to use as a tool for moving forward. As a result, they resorted to tinkering to make adjustments to their design, not explicitly drawing upon their scientific knowledge, and they had multiple successful designs that they did not record. Although the students in the all-girl group did not apply scientific understanding to their engineering design as the unit intended, they were able to work in a supportive environment free from conflict with their same-gendered peers.

Mixed-gender group.
In general, girls in the mixed-gender group dominated the activities. Madison took primary responsibility as the group leader. These leadership responsibilities can be seen in the frequency with which the students gave verbal directions to their peers; Madison directed her teammates on 28 occasions, compared to the next most frequent eight directions by Amanda and only 10 total directions by both boys combined. In addition to directing, the girls in this group were more active than their male peers in almost all performance enactments related to their participation in the activities: agreeing, elaborating, manipulating, peer checking, reasoning, record keeping, and referring to earlier material. The single performance enactment where boys in the mixed-gender

<table>
<thead>
<tr>
<th>Case summaries.</th>
</tr>
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<tbody>
<tr>
<td>All-girl group.</td>
</tr>
<tr>
<td>Overall, the all-girl group had highly cohesive group dynamics. Leadership responsibilities in the all-girl group were somewhat fluid, with different students taking primary leadership at different points in the design activities. Although Elsa was seen as the primary group leader, directing on 34 occasions, the leadership responsibilities were distributed across the group members. Kiera and Kelly both gave verbal directions to their teammates (12 and 16 occasions, respectively) at points in the lesson when they adopted temporary leadership responsibility. The cohesiveness of the all-girl group is also evidenced by the distribution of responsibilities (such as manipulating and record keeping), frequent peer checking and elaborating, and low occurrences of frustration and judging. Students in the all-girl group expressed frustration with their peers on only three occasions and frustration with the task on six occasions. They did not express judgement about a person on any occasion.</td>
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<tr>
<td>Mixed-gender group.</td>
</tr>
<tr>
<td>In general, girls in the mixed-gender group dominated the activities. Madison took primary responsibility as the group leader. These leadership responsibilities can be seen in the frequency with which the students gave verbal directions to their peers; Madison directed her teammates on 28 occasions, compared to the next most frequent eight directions by Amanda and only 10 total directions by both boys combined. In addition to directing, the girls in this group were more active than their male peers in almost all performance enactments related to their participation in the activities: agreeing, elaborating, manipulating, peer checking, reasoning, record keeping, and referring to earlier material. The single performance enactment where boys in the mixed-gender</td>
</tr>
</tbody>
</table>

| SUM - Boys | 2 | 10 | 1 | 12 | 6 | 5 | 47 | 0 | 60 | 1 | 4 | 14 | 1 | 35 |
| SUM - Group | 20 | 46 | 4 | 34 | 21 | 15 | 109 | 0 | 84 | 15 | 21 | 40 | 4 | 72 |
| All-Boy | Charlie | M | 9 | 31 | 4 | 14 | 4 | 4 | 35 | 0 | 2 | 0 | 17 | 15 | 3 | 18 |
| Adam | 2 | 5 | 1 | 2 | 3 | 9 | 11 | 0 | 29 | 3 | 5 | 9 | 1 | 16 |
| Brendan | 5 | 3 | 0 | 1 | 0 | 4 | 16 | 0 | 27 | 0 | 0 | 5 | 0 | 17 |
| Brian | 6 | 0 | 2 | 11 | 3 | 1 | 5 | 2 | 38 | 0 | 4 | 2 | 0 | 5 |
| SUM - Group | 22 | 39 | 7 | 28 | 10 | 18 | 67 | 2 | 96 | 3 | 26 | 31 | 4 | 56 |
The boys’ off-task performance was especially prevalent in the initial design planning activities structured by worksheets.

When the activities shifted to less structured engineering activities that were not guided by worksheets, the boys attempted to become more involved. They suggested ideas and were interested in using the physical materials to design their laser security system. However, given the boys’ past lack of participation in the more structured activities, the girls were reluctant to shift any responsibility for the design to the boys, and this became a source of frustration and conflict within the group. Students in this group expressed frustration with their peers on 34 occasions. This type of frustration was more common among girls (22 occasions) than boys (12 occasions). As the students dealt with conflicting ideas about who should be involved and in what manner, they also expressed judgment about their peers. Judgment was more commonly expressed by girls (10 occasions) than boys (5 occasions). Together with judgment and frustration directed toward peers, students in this group expressed frustration related to the task on 21 occasions. Again, as they took primary responsibility for the group tasks, girls in the mixed-gender group expressed frustration with the task more frequently than their male teammates (15 versus 6 occasions, respectively). Throughout the less structured design activities, the laser pointer became a tool for wielding power in the group, with students attempting to control the laser pointer as a way to ensure their ideas were acknowledged. The mixed-gender composition of the group was associated with conflict and tension.

All-boy group.
Within the all-boy group, students’ levels of participation varied widely. Charlie was the clear group leader and took responsibility for the bulk of the design activities. Charlie directed his team on 31 occasions, compared to the next most frequent 5 directions by Adam. Charlie also dominated manipulating, reasoning, and record keeping within the group. He was off-task on only two occasions, while the rest of his teammates were off-task for at least 27 occasions each. The other boys in the group were generally less involved throughout the unit, although they occasionally became interested in the design activities, both manipulating the materials and suggesting ideas.

Although Charlie was able to produce an effective design for his group, he also experienced frustration. Students in the all-boy group expressed frustration with their peers 28 times, and Charlie accounted for 14 of these instances, often growing frustrated in attempts to manage his teammates’ participation and behavior. Brian, who was receiving special education services and was frequently marginalized by his peers, expressed frustration on 11 occasions. Together, Charlie and Brian accounted for 25 of the 28 total instances of frustration in the all-boy group. Frustration with the task was more evenly distributed across the group, with 10 total occasions and no single student accounting for more than four occasions. The students in the all-boy group expressed judgment of each other on 18 occasions. Many of these judgments were directed at Brian. While the all-boy group was ultimately successful in the engineering design activities, they did not equitably share in the responsibility or have cohesive group dynamics. The single-gender composition of this group was associated with one boy taking the lead on completing the group activities while his teammates were non-participatory.

Cross-case analysis based on the performance dimensions of design.
Learning while designing.
Learning while designing is a key performance dimension of informed design, and students displayed evidence of learning throughout the design process to different degrees across groups. Metacognition is indicative of learning while designing, and the all-girl group was the only group to have a metacognitive discussion throughout the unit. This conversation was unprompted by the teacher, and the girls talked about which decisions were more difficult for them to make and why. In the all-boy group, Brian made two metacognitive comments, but his teammates did not engage in conversation with him.

Although learning while designing is not observable in all instances, students’ record keeping offers one means of observing this learning, as they recorded details of their design ideas and tracked their revisions to these designs. Record keeping was most common in the all-girl group (75 occasions) and least common in the all-boy group (31 occasions). Students in the mixed-gender group engaged in record keeping on 40 occasions, with girls doing so more frequently than boys (26 versus 14 occasions, respectively). It is also important to note that in addition to keeping records throughout the design process most consistently, the all-girl group also showed the most even distribution in adopting this responsibility, with each student record keeping on at least 20 occasions. Although a formal measure of student learning was not included as part of this study, students in the all-girl group displayed performance enactments indicative of learning while designing more consistently than the other groups.

Making and explaining knowledge-driven decisions.
As students sought to design their laser security systems, many opportunities for data- and knowledge-driven decisions existed, although they were not emphasized by the teacher. Students’ use of knowledge-driven decisions is most clearly evidenced by the reasoning code, which requires students to explain the reasoning behind their decisions. Although reasoning was evenly distributed across girls in the all-girl group (6-7 occasions of reasoning per student), their overall frequency of reasoning (20 occasions) was lowest. Students in the mixed-gender group provided reasoning on 21 occasions, while those in the all-boy group provided reasoning on 26 occasions. The distribution of these reasoning performance enactments is also important to note. Within the all-boy group, Charlie accounted for 17 of the 26 instances of reasoning, largely dominating this performance enactment in his group. While students in other groups relied on “tinkering” to make adjustments to their designs, Charlie explicitly used his knowledge of the law of reflection to inform his design decisions. In the mixed-gender group, Madison and Amanda accounted for 17 of the 21 instances of reasoning, with their male peers showing evidence of reasoning on only four occasions.

Working creatively to generate design insights and solutions.
Informed design relies on creative design solutions, and students in this study displayed their creativity when suggesting ideas for their laser security system design. Students suggested ideas most often in the all-girl group (89 occasions) and least often in the all-boy group (56 occasions). No single student within a group clearly dominated the suggestion of ideas, but some interesting patterns were evident. In the all-boy group, Brian only suggested ideas on 5 occasions, markedly fewer than the other students on his team. Among students in the mixed-gender group, ideas were suggested in almost equal numbers between girls (37 suggestions) and boys (35
suggestions). In general, boys in this group were less involved than their female teammates in the engineering activities, as evidenced by their lower frequencies of agreeing, elaborating, manipulating, peer checking, reasoning, record keeping, and referring to earlier material. Given their general low level of participation in the group’s activities, it is interesting to note that the boys in the mixed-gender group actively suggested design ideas.

Perceiving and taking perspectives intelligently.
As informed designers work to create innovative designs, they consider a number of perspectives: those of other designers as well as the end users of the product. Evidence of considering others’ perspectives was most apparent in the all-girl group. Students in this group expressed agreement with their peers most often (58 occasions in the all-girl group versus 22 occasions in the all-boy group and 20 occasions in the mixed-gender group). In fact, each student in the all-girl group expressed agreement at least 13 times (and up to 31), which was greater than the maximum number of agreements in either the mixed-gender or all-boy groups. Participants in the all-girl group also elaborated on their teammates’ ideas most often (12 occasions in the all-girl group versus seven occasions in the all-boy group and four occasions in the mixed-gender group). In addition, they verbally compared ideas and answers before deciding on a response (peer checking) more often than students in other groups (35 occasions in the all-girl group versus 15 occasions in the mixed-gender group and three occasions in the all-boy group).

While the mixed-gender group did not show evidence of agreeing, elaborating, or peer checking on as many occasions as the all-girl group, girls in the mixed-gender group displayed these performance enactments more frequently than their male teammates. Girls expressed agreement on 18 occasions (versus two for boys), elaborated on three occasions (versus one for boys), and checked with their peers on 14 occasions (versus one for boys).

Conducting sustained technological investigations.
Sustained technological investigation is a key performance dimension of informed design, and students in this study displayed varying levels of sustained investigation. All groups investigated the properties of light that could be beneficial in their laser security system designs, and they frequently engaged with the materials available for use in their designs. Manipulating the materials was particularly frequent in the mixed-gender (109 occasions) and all-girl (101 occasions) groups. Within these groups, all students had opportunities to manipulate the materials, although the all-girl group displayed the most even distribution of this responsibility. In contrast, students in the all-boy group manipulated the materials on only 67 occasions, and Charlie accounted 35 of these instances.

Focused, on-task engagement is also important to consider in relation to sustained investigations. The all-girl group was off-task least often (61 occasions), and these occasions often occurred when the girls clearly felt confident they would have time to complete the necessary tasks. Off-task performance enactments were more common in the mixed gender group (84 occasions), and within this group, boys were off-task more frequently than girls (60 versus 24 occasions). The all-boy group was off-task most frequently (96 occasions). Within this group, Charlie was only off-task on two occasions, while the other three students were off-task more frequently (27-38 occasions each).
Using design strategies effectively.
Throughout the engineering design activities, all of the groups developed effective design solutions to the laser security system challenge. The way they went about reaching these solutions differed, however. Within the all-girl and mixed-gender groups, after developing an initial plan on paper, the students eventually relied on “tinkering” to make adjustments to their design. In contrast, the all-boy group, led by Charlie, consistently used measurement and application of scientific knowledge to develop their design; for example, in making adjustments to the group’s design, Charlie stated known angles based on the law of reflection and used a protractor to make precise adjustments to the design. The all-boy group also switched between design strategies more seamlessly than the other groups, transitioning between hands-on design activities and paper-based planning.

Integrating and reflecting on knowledge and skills.
Informed designers use knowledge from multiple disciplines and reflect on their design activities. In this unit, students planned, tested, and redesigned their laser security systems after learning science content that would support informed design decisions. They had access to their previous learning related to the design challenge and had opportunities to refer back to that material to integrate their science learning into their designs, although this was not explicitly encouraged by the teacher. As previously mentioned, Charlie led the all-boy group to apply the law of reflection to their group’s design. However, Charlie was largely silent in integrating this knowledge. He explicitly referred to earlier material on only three occasions throughout the design process, and his team referred to earlier material on a total of four occasions. The mixed-gender group also referred to earlier material on four occasions (three occasions for girls and one for boys). The all-girl group referred to earlier material slightly more frequently, on seven occasions, and they also incorporated metacognitive discussions that included reflection on their activities.

Discussion

Gender and small group participation.
With much of the literature around students’ small group interactions dating back to the early 2000s, the present study provides important information about how students navigate engineering and integrated STEM activities. This study confirmed previous research findings that girls and boys tend to participate in small group activities in unique ways, with boys spending more time off-task [73] and focusing more on tasks rather than group processes [72]. However, the present study also offered new insights into middle school students’ participation in small group engineering activities. A number of prior studies found that boys tend to act as leaders, dominate the physical materials, and be more involved in small group activities [64] – [66], [71], [74] – [76], but that was not confirmed in the present study. In the mixed-gender group, girls were primarily responsible for leading their team, taking on additional responsibilities to drive their group forward.

Girls’ means of participation were more extensive in this study than in prior work. While the girls in the present study were still involved in note-taking [65], [66], interacting with group members [69], [70], and building positive relationships [67], [68] to a greater degree than boys, they also adopted performance enactments that previous researchers have found to be more
characteristic of boys, such as manipulating materials and leading their team. This finding is significant because it suggests that perhaps these patterns have changed, with girls’ means of participating in small group activities broadening since the early 2000s.

Despite girls’ overall greater involvement in the mixed-gender group activities, the boys in this group became distinctly more interested and involved when the activity shifted from worksheet-based planning to open-ended design that included materials. This pattern of increased involvement was also seen within the all-boy group, with those students who had previously been onlookers expressing new ideas and engaging with the materials. In contrast, students in the all-girl group became less focused and more frustrated in the open-ended design activities. Their rate of off-task behavior increased dramatically, and their work was less purposeful. With no teacher expectations related to how long the engineering tasks were expected to take and a seemingly unlimited amount of time available to work, the girls did not make efficient use of their time, as they had in prior activities.

**Group gender composition.**

In exploring student participation related to their group’s gender composition, several interesting patterns emerged. Consistent with prior research findings [83], both of the single-gender groups had more purposeful functioning than the mixed-gender group. However, problematic patterns of interaction were evident in the all-boy group. Similar to other studies [71], this group faced more challenges in equitably distributing tasks. Some boys were rarely involved in the activities, and there were particular problems surrounding Brian’s involvement. Brian, who was receiving special education support, was often marginalized by his teammates and limited in his participation. His teammates did not listen to his ideas and managed his behavior negatively, often telling him he was not allowed to do certain things without suggesting alternative activities.

Consistent with previous research [87], [88], the all-girl group was more cohesive than either the mixed-gender or all-boy groups. Students in this group developed positive relationships and worked together on the engineering activities. Each girl in the group acted as the leader at different points, demonstrating fluidity in leadership responsibilities that was not apparent in the mixed-gender or all-boy groups. The single-gender environment was supportive of girls’ participation in the engineering activities within a safe, judgment-free zone. Because the students established this supportive group environment, they were able to suggest many ideas related to their design without fearing judgment.

Students in the all-girl group expressed agreement and elaborated on one another’s ideas more often than students in the other groups. Interestingly, they provided reasoning for their design decisions less often than those in the mixed-gender or all-boy groups. Because of their high rates of agreement, girls in the single-gender group were met with less skepticism and questioning, which resulted in fewer situations where they had to defend their ideas. Although this resulted in low levels of conflict, these girls also had fewer opportunities to justify and explain their reasoning in the face of potential disagreement, which is known to be particularly effective in promoting conceptual understanding of STEM content [100].

While both of the single-gender groups faced unique challenges, the mixed-gender group was fraught with frustration and conflict throughout the activities. Interactions between girls and boys
in this group were competitive in nature, with students using the physical materials such as the laser pointer to maintain control of the group’s activities. The mixed-gender composition of this group was associated with challenges and direct conflicts not found in the all-girl group. The high rates of frustration among girls in the mixed-gender group is problematic when considering the goal of fostering ongoing interest and engagement in engineering among girls.

**Limitations**

In considering the findings of this study, it is important to recognize that this case study focused on three small groups of students experiencing one curricular unit. Thus, probabilistic or statistical generalization is not possible, given that the students cannot be assumed to represent the population of middle school students as a whole. However, despite the fact that these findings do not represent the experiences of all students, it is possible to make theoretical generalizations from qualitative inquiry [101]. That is, in understanding the general process of engineering education, findings from this study help to develop a refined understanding of the unique experiences some students will encounter as they participate in small group engineering activities.

This study also focused on the binary gender categories of female and male, when there is much more complexity related to students’ gender identities and the intersectionality of gender identity with other identities (e.g., identifying as both a female and a student of color). Thus, the students in this study do not represent the full range of students who are experiencing small group engineering activities. Diversity in students’ cultures, languages, socioeconomic status, and background experiences likely intersect with their gender in relation to their participation in small group engineering activities.

**Implications**

Investigating small group activities and the potential impact of group functionality on girls’ ongoing participation in engineering, this work fills a gap in the literature around small group engineering activities in formal middle school settings. As engineering becomes increasingly common in pre-college education, students will need additional practice and support in equitably engaging in open-ended engineering design challenges. Several key findings emerged from this study with implications for instructional strategies, curriculum development, and future research.

**Teacher role in facilitating small group engineering activities.**

The role of the teacher cannot be underestimated in supporting students’ meaningful and equitable engagement in engineering design activities. In this study, small groups received no guidance from the teacher and were left to determine how the tasks would be divided amongst group members. With no discussion of the division of labor or how to keep all teammates involved, participation was inequitable, particularly in the mixed-gender and all-boy group. In designing engineering activities for implementation at the middle school level, explicit instruction in how to engage in teamwork should be included. Group roles may offer a practical solution to helping all students engage in small group activities more equitably. These roles should be fluid, offering different students opportunities to experience different roles. In addition, they should be authentic to the engineering tasks, rather than general group roles often
seen in middle school teaching (e.g., materials manager, time keeper). With the support of the teacher, groups of students should have opportunities to break down tasks, identify action steps in completing the tasks, and divide those responsibilities among group members. Ongoing and explicit discussion of effective teamwork will help support students in equitable engagement in engineering design activities and be better prepared for ongoing collaboration in engineering contexts.

**Supporting productive student participation in engineering activities.**

Students also require additional support to ensure the engineering design process is moving forward productively. Clear expectations about how long activities should take and ongoing checkpoints would be helpful in ensuring that students are making the most productive use of their time. In this study, students were not given clear time guidelines, so they felt they had unlimited time to complete the engineering activities. In some cases, this resulted in boredom and off-task behavior, while in other cases, this resulted in students redesigning an already effective solution without purpose. In addition to check-ins related to timing, there is a need for increased teacher involvement in encouraging students to make evidence-based decisions and integrate knowledge from all of the unit’s lessons. Two of the groups (all-girl and mixed-gender) in this study largely relied on tinkering to improve their designs, despite having access to previously explored data that would have allowed them to make more intentional decisions. Additional teacher guidance to support students in applying previous learning to their design decisions.

**Preparing students for open-ended small group activities.**

While some students, particularly the girls, struggled with the open-ended nature of the engineering design activities, other students attempted to engage in the open activities to a greater degree than their previous participation would predict. The boys in the mixed-gender group and select boys in the all-boy group became markedly more interested and involved in the design activities when they had access to physical materials and could make design suggestions without being constrained by a worksheet. Despite their interest, however, they still faced challenges in shifting to more active participation in their teams, with the team leaders reluctant to listen to or grant new responsibilities to those who had been previously been less involved. While engineering activities may serve as an opportunity for students who are typically less engaged in group activities to take on new roles and responsibilities, additional teacher support is needed to help students, particularly girls, navigate these open activities without the structure of a worksheet and be open to the process of failing and redesigning.

**Conclusion**

Working in a mixed-gender group was a source of frustration for girls, who had difficulties managing their male peers’ involvement. While this study suggests that the most positive group dynamics and equitable participation were found in the all-girl group, there is a need for further research regarding group gender composition in middle school engineering activities. Future studies should explore strategies for supporting girls in open-ended engineering activities that are not guided by worksheets. Additional research would also be beneficial in determining whether the pattern of boys in mixed-gender groups becoming more engaged in the less structured
activities is consistent; if so, future work could address the challenges of supporting all students in meaningful engagement in both highly-structured and less-structured activities.
References


[49] P. D. Ferguson and B. J. Fraser, “Student gender, school size and changing perceptions of


[62] V. Sampson and D. Clark, “The impact of collaboration on the outcomes of scientific


boys tell me’: Exploring small group student interactions in an integrated STEM unit,” *Journal of Research in Science Teaching*, accepted.


<table>
<thead>
<tr>
<th>Code Category</th>
<th>Code</th>
<th>Code Description</th>
</tr>
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<tbody>
<tr>
<td>Verbal</td>
<td>Explaining Procedure</td>
<td>Explaining the task/activity procedure to another student</td>
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<tr>
<td></td>
<td>Explaining Content</td>
<td>Explaining the science or engineering content to another student</td>
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<td></td>
<td>Elaborating on Another Student’s Statement</td>
<td>Building on another student's response verbally</td>
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<td></td>
<td>Reasoning</td>
<td>Explaining the reason for a certain decision (i.e., evidence-based reasoning)</td>
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<td></td>
<td>Metacognitive Thinking</td>
<td>Describing thinking about the learning process and/or understanding of the task</td>
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<td></td>
<td>Directing</td>
<td>Verbally leading the group to move forward</td>
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<td></td>
<td>Suggesting Idea</td>
<td>Verbally raising a new idea for how to complete the task/activity</td>
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<td></td>
<td>Expressing Uncertainty: Task</td>
<td>Verbalizing uncertainty about how to conduct the activity/task, including spelling questions</td>
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<tr>
<td></td>
<td>Expressing Uncertainty: Content</td>
<td>Verbalizing uncertainty about the science or engineering content</td>
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<td></td>
<td>Requesting Explanation from Student</td>
<td>Verbally asking another student for an explanation of the task or content</td>
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<td></td>
<td>Encouraging</td>
<td>Encouraging another group member to participate or to have confidence in their participation</td>
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<td>Agreeing</td>
<td>Expressing agreement with something that another student has explicitly said</td>
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<td>Disagreeing</td>
<td>Expressing disagreement with something that another student has explicitly said</td>
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<td>Judging: Task</td>
<td>Expressing verbal judgment about something related to the task at hand (could be judging an idea)</td>
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<td>Judging: Person</td>
<td>Expressing verbal judgment about an individual (could be self or other)</td>
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<td>Peer Checking</td>
<td>Verbally comparing answers to confirm or verify response</td>
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<tr>
<td>Mixed</td>
<td>Reading Directions</td>
<td>Reading directions to others in the group or referring group members back to directions</td>
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<tr>
<td>Referring to Earlier Material</td>
<td>Looking back (in notebooks, classroom artifacts, etc.) to earlier material for use in the current task/activity</td>
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<tr>
<td>Expressing Frustration: Task</td>
<td>Showing signs of exasperation (verbal or physical) related to a task</td>
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<tr>
<td>Expressing Frustration: Person</td>
<td>Showing signs of exasperation (verbal or physical) related to another student</td>
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<tr>
<td>Distracting other Students</td>
<td>Actively distracting other students by talking to them about off-task subjects or physically interfering with their on-task participation</td>
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<tr>
<td>Off Task</td>
<td>Failing to do something they should be doing (do not code as off task if the students are between activities and waiting for the next step)</td>
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<tr>
<td>Avoiding</td>
<td>Refusing to participate (verbally or non-verbally)</td>
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<td>Requesting Help from Teacher</td>
<td>Asking the teacher for help related to task or content (verbal or through raised hand)</td>
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<tr>
<td>Non-Verbal</td>
<td>Manipulating</td>
<td>Handling the materials/equipment; MUST be part of hands-on activity (i.e., not just handling worksheet) for the purpose of completing the task, observing, or collecting data</td>
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<tr>
<td>Record Keeping</td>
<td></td>
<td>Taking notes or writing down results</td>
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<tr>
<td>Assisting</td>
<td></td>
<td>Helping a student who is directing the activity, unprompted by the student who is directing; MUST be a clear distinction in the type of participation between leader and other students</td>
</tr>
<tr>
<td>Following</td>
<td>Following another student's direction when explicitly prompted</td>
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<tr>
<td>Observing</td>
<td>Passively observing the activity</td>
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<td>Initiating: Non-Verbal</td>
<td>Using materials to move the group forward</td>
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<tr>
<td>Managing Materials</td>
<td>Using materials in support of the task, but not while doing the actual task</td>
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<tr>
<td>Forcefully Controlling: Non-Verbal</td>
<td>Controlling the task through non-verbal means</td>
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<tr>
<td>Copying</td>
<td>Looking at another student's paper and copying what was written</td>
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