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Productive Thinking and Science Learning in Design Teams

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Abstract

Recent reforms in science education have supported the inclusion of engineering in K-12 curricula. To this end, many science classrooms have incorporated engineering units that include design tasks. Design is an integral part of engineering and helps students think in creative and interdisciplinary ways. In this study, we examined middle-school students' naturally occurring design conversations in small design teams and their learning of science as a result of engaging in an engineering and science unit. We found that the proportion of different thought processes used by boys and girls was quite similar. Both girls and boys produced a higher percentage of ideas or thoughts associated with divergent thinking, but a lower proportion in convergent thinking, evaluative thinking, and cognitive memory. In addition, gender composition of design teams influenced thought processes expressed by girls and boys. Interestingly, in mixed teams, both girls and boys expressed less divergent thinking than those in single-sex teams. With regard to science content learning, both girls and boys showed statistically significant learning gains. There were no significant gender differences in the pre- and post-test scores. These results suggest that participating in an engineering design task in small design teams provided students opportunities to engage in productive thinking and enhance their learning of the targeted science concept—ecosystems.

Keywords Engineering design · Engineering integration · Productive thinking · Science learning

Over the past decade, the national reform efforts in improving K-12 science education have focused on integrating engineering practices and thinking into science classrooms. Recent reform documents, such as the *Next Generation Science Standards* ((NGSS),

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NGSS Lead States, 2013), recognize engineering design and practices as important elements in a new vision for science education. A growing body of research suggests that meaningful and purposeful integration of engineering into the science instruction contributes to student learning in science (English, 2017; Guzey et al., 2016; Guzey et al., 2019; Lachapelle, Oh, & Cunningham, 2017; Park et al. 2018; Wendell & Rogers, 2013). Another important aspect of engineering is the decision-making process in which students engage to solve a given engineering challenge. The act of design is creative and complex and requires students to make evidence-based decisions for successful design solutions. In design conversations, students articulate their decision-making and thought processes (Adams, 2015; Llyod, Lawson, & Scott, 1995). However, there is limited research exploring design conversations of K-12 students (Guzey & Aranda, 2017; Wendell, Wright, & Paugh, 2017).

In this paper, we focus on design conversations to explore productive thought processes of K-12 students with respect to the gender composition of design teams. Because engineering design problems are ill-defined and complex, solutions require students to use “creative and critical-analytic dimensions of reasoning” which are elements of productive thinking (Gallagher & Achner, 1963, p. 185). More specifically, in the context of engineering design, productive thinking involves using and organizing information about the engineering problem and engaging in design synthesis that allows to make judgments and to develop solutions. Yet, despite the acknowledged importance of productive thinking in the design process in professional practices, it appears that little is known about young learners’ or novice designers’ use of productive thinking processes.

In this article, we argue for the importance of studying productive thinking in mixed and single-sex design teams participating in an engineering design activity. Engineering education research at the undergraduate level has demonstrated the influences of group dynamics and interactions on female students’ participation and performance (Laeser, Moskal, Knecht, & Lasich, 2003; Stump, Hilpert, Husman, Chung, & Kim, 2011). Furthermore, recent research into gender differences in science learning has extensively examined the gender differences in achievement, science-related attitudes, and interest (e.g. Desy, Peterson, & Brockman, 2011; Tan & Calabrese Barton, 2018); factors impacting girls’ participation in science (Greenfield, 1997; Ryu, 2015); identity development in science (Calabrese Barton, Birmingham, Takumi, Tan, & Calabrese, 2013); and teachers’ gendered practices and curriculum materials (Nyström, 2009). However, a paucity of science education research exists that examines gender in the context of learning science through engineering design (Scantlebury, 2014).

We focused this study on the gender composition of the design teams. More specifically, we were interested in investigating 6th grade students’ naturally occurring design conversations and their science learning in an engineering and science unit with a specific focus on gender. The research questions guiding this study included the following:

- Are there any differences in the productive thought processes expressed by girls and boys when they engage in an engineering design task in mixed and single-sex teams?
- What is the effect of the gender composition of teams on students’ productive thought processes?

- Are there any differences between girls' and boys' science learning when they engage in an engineering design task?

Theoretical Framework

The theoretical framework for this study is comprised of research on gender in science and engineering education and Guilford's (1956) theory of productive thinking. We used gender as an analytical category to investigate girls' and boys' discourse in small design teams and the learning of science as a result of engaging in the curriculum unit and working in mixed and single-sex design teams. Students' discourses about science and engineering when working in mixed and single-sex teams document girls' and boys' engagement with science and engineering (Schnittka & Schnittka, 2016). The small group learning spaces allow students to voice their understandings and perspectives and to generate knowledge (Lou et al., 1996). We used Guilford's (1956) theory of productive thinking to examine ideas shared by boys and girls when they discuss science and engineering. In the following section, we first review research studies focusing on discourse, science, and engineering education in relation to gender. We later introduce the theory of productive thinking.

Gender in Science and Engineering Education

Using critical perspectives, science education researchers have studied how gender differences impact performance, learning, engagement, and interest; consequently, a number of strategies and models for promoting gender equity in the science classroom have been developed from this work (e.g. Calabrese Barton, Tan, & Rivet, 2008; Desy et al., 2011; Due, 2014; Jones, Howe, & Rua, 2000; Kim, Sinatra, & Seyranian, 2018). Brotman and Moore's (2009) review of the literature of gender and science education identified four areas of focus: equity and access, curriculum and pedagogical practices, culture of science, and identity.

The research in equity and access theme has documented inequality in between boys' and girls' science education. These studies reported the inequities in classroom learning environments and the gender disparities in science learning, attitudes, and participation (e.g. Greenfield, 1997; Jones et al., 2000). A number of researchers have offered approaches to address inequities and disparities in science classes. For example, Calabrese Barton et al. (2008) illustrated the importance of fostering learning environments that support girls in participation and learning in science. In their study, urban girls created hybrid spaces for engaging in science by making signature science artifacts, taking up science class identities that are different from their usual science class identities, and negotiating roles to participate in science. These practices enabled girls' inclusion of a range of science activities in class.

The second theme focused on curriculum and pedagogical practices that are gender-inclusive. Such curricular and pedagogical interventions draw upon both girls' and boys' interests and experiences, allow for active participation and engagement in science, emphasize collaboration and group work, and connect learning and science activities to students' cultures, everyday experiences, and funds of knowledge. While findings of gender-inclusive interventions are mixed (Murphy & Whitelegg, 2006; Whitelegg, Murphy, & Hart, 2007), it is critical for teachers to adopt practices to promote equity in science education for *all* students.

The nature and culture of science also has been examined in research on gender and science education. Researchers documented girls' perceptions of science—male-oriented, boring, and a challenging field (Scantlebury, 2014). Studies also addressed the impact of science instruction and classroom culture on students' ideas of science and positionings (Moje, 1995). The fact that scientific knowledge and learning largely occur in classrooms, teachers should address and critically examine how science is practiced, how scientific knowledge is formed, and how science influences society in science instruction.

The last theme focused on identity. Studies highlighted that students' experiences in science and their culture, ethnicity, language, and socioeconomic status shape their identities and influence their career pathways (Basu, Calabrese Barton, Clairmont, & Locke, 2009; Calabrese Barton et al., 2013; Carlone, Scott, & Lowder, 2014; Kim et al., 2018). A strong science identity can lead girls (and boys) toward a science or STEM-related career.

While K-12 engineering education is relatively a new area of scholarship (National Academies of Engineering (NAE) & National Research Council (NRC), 2009), recent studies documented that the abovementioned factors in gender literature also fundamentally influence girls' engagement in engineering and inform their identity development. For example, Godwin and Potvin (2016) reported a longitudinal study of a young woman, Sara, who considered dropping out high school, but then chose to become a geological engineer. Sara's positive experiences in a science project shaped her science and math identity during her senior year at high school; however, her experiences at college caused her to drop out of engineering in her second year at college. Sara simply did not find the math and engineering courses exciting, interesting, or relevant to everyday aspects of her life. In another study, Calabrese Barton, Tan, and Greenberg (2017) studied an after-school engineering program housed in a boys' and girls' club. Thirty-six middle-school students participated in the program and made community-based engineering design projects. The authors found that critical, connected, and collective engagement in makerspaces supported youth in learning and in becoming a part of the STEM community. Girls particularly engaged in activities that reflected their experiences or were related to their everyday life experiences. Similarly, Martin, Dixon, and Betser (2018) implemented an engineering program designed as a makerspace for high school age boys and girls. Through their iterative analysis and design work, the authors illustrated the importance of examining the power dynamics among boys, girls, and adults, and embracing students' repertoire of practices for more equitable engagement in the design and making space. These and similar studies (Ryoo, Kali, & Bevan, 2016; Sheridan et al., 2014) are critical for identifying pedagogical strategies and design elements of (engineering) programs for supporting success and engagement of students in STEM.

In addition to this line of studies of gender and equitable practices in science and engineering education, there are several examples of studies that have sought to examine gender differences in learning, participation, and interactions through examining students' discourse about science and engineering (Due, 2014; Guzey & Aranda, 2017; Tan & Calabrese Barton, 2018; Wendell et al., 2017). Small group discussions in science classes provides opportunities for students to engage in learning activities as they explain, discuss, and negotiate ideas (Rivard & Straw, 1999). Various studies have showed the effect of small group work on student achievement (Lou et al., 1996), engagement (Fredricks, Hofkens, Wang, Mortenson, & Scott, 2018), and learning science (Cohen, 1994). Discourse between students in small groups provide evidence of gender and social interaction, participation, positionings, and perspectives. For example, Due (2014) analyzed student discourse in physics to study social interaction and positionings in small group work. She found that girls were positioned as less competitive, showed low interest in physics, and less supported by their peers. Similar findings of gender differences in the context of engineering education reported in Clegg's (1999) study. Schnittka and Schnittka (2016) also examined group work in an engineering design space. Collaborative mixed and single-sex groups designed wind- and/or gravity-powered generators using motors, gears, and other materials in an informal engineering program. The authors documented the positive impact of group work on both girls' and boys' learning, yet they also illustrated the differences in group dynamics and interactions in groups—girls-only group displayed solidarity and collaboration, while boys were more competitive in boys-only group.

Taken together, studies of gender in science and engineering education highlight the importance of instruction and curriculum materials attentive to issues of gender. It is important to note that gender has been conceptualized or analyzed at different levels in the aforementioned studies and similar others in the literature. Researchers explored and framed gender issues in their studies at a structural level (e.g. influences of gender along with other social categories on student achievement), symbolic level (e.g. gender influences on teacher practices), or individual level (e.g. impact of student gender on learning and attitudes) (Scantlebury, 2014). Depending on the gender theories used or analysis conducted at the structural, symbolic, or individual level, researchers provide unique insights, contribute research in gender and education, and offer suggestions for future gender research.

Productive Thinking

We applied Guilford's (1956) theory of productive thinking to frame the study. Simply put, productive thinking leads to effective decision-making. According to Guilford, productive thinking consists of five operations: cognition, memory, divergent thinking, convergent thinking, and evaluative thinking. Using these types of operations of thinking, individuals draw upon past or present ideas and information to produce new ideas or solutions to problems. Cognition is seen as the most basic category which involves recognition of information or comprehension. Memory operations represent simply storing information and recalling facts or rote memory. Convergent thinking requires analysis and integration of information to come off with one single expected result or end-product. Divergent thinking, on the other hand, requires intellectual operations to create alternative solutions. Both divergent thinking and convergent thinking require analyzing or synthesizing information; consequently, generating new information from existing information. Finally, evaluative thinking represents comparison, judgment, and choice.

A number of studies describe the impact of gender and teams' gender composition on students' productive thinking processes. For example, Gallagher and Achner (1963) investigated classroom interactions in an attempt to study different thought processes (i.e. cognitive memory, divergent, convergent, evaluative) used by boys and girls. The authors found that while the proportion of the different thought processes used by boys and girls was similar, boys produced more divergent responses than girls. Although the authors did not specifically investigate the reasons for such difference in divergent thinking responses produced by boys and girls, they suggested that subject matter and teaching practices (e.g. questions, questioning, techniques) were possible factors for the given differences. In a follow-up study, however, Gallagher, Aschner, and Jenne (1967) confirmed their observation regarding the critical role played by teachers as the facilitator of the kind of thought processes expressed in classrooms. A recent review of Gallagher's research on productive thinking (Gallagher, Courtright, & Robinson, 2015) highlights the impact of teacher, curriculum, and student-student, student-teacher interactions on thought processes produced by boys and girls.

In the context of K-12 science and engineering education, when engaging in design process to solve a design problem, students brainstorm possible solutions, evaluate the feasibility of each solution, and then decide among existing alternatives. In this process of design thinking, students use Guilford's (1956) operations for productive thinking (Aranda et al., 2019). For a successful solution, students need to understand the design task and its criteria and constraints (cognition), consider design requirements and limitations as well as apply scientific and mathematical principles (memory), generate multiple solutions (divergent thinking), and intentionally select a single "best" solution (convergent thinking) as a result of evaluating or analyzing pros and cons of different solutions (evaluation). Producing solutions for design problems can be seen as logical activities since students engage in systematic and creative modes of thinking (Llyod et al., 1995). Students design solutions in a cyclic structure due to the nature of design—an iterative process of problem solving. A cyclical, iterative process encourages productive thinking by providing opportunities for creation, analysis, synthesis, and evaluation of a solution.

Engineering design in K-12 science instruction requires students to bring several design elements into a harmonious balance. This means focusing on science, mathematics, and design knowledge; higher order thinking skills; and personal experiences. Navigating between and among these design elements requires more productive thinking and creativity when working in design teams due to the complexity of learning happening both at the individual and team level. Design teams perform differently in a design task—i.e. success and performance of a team is greatly related to team members and their interactions. While a large body of research address the effects of gender composition in teams on the performance of teams (Lou et al., 1996; Scaife, Rogers, Aldrich, & Davies, 1997; Sluis-Thiescheffer, Bekker, Eggen, Vermeeren, & de Ridder, 2011), there is limited research concerning gender composition in teams in an engineering design task and the results are mixed (Okudan & Mohammed, 2006). Laeser et al. (2003) argue that gender composition of design teams has little impact on the functions of team members. Similarly, a study by Kichuk and Wiesner (1997) found the gender composition was not significantly related to the team performance or success. However, in a series of studies with undergraduate engineering students, Okuman and colleagues (Okudan, 2002; Okudan & Bilen, 2003) found that gender composition of teams has a negative impact on team performance—as the number of female students increased in a design team, the design performance decreased in quality. In contrast, Schnittka and Schnittka's (2016) study of middle-school students' engagement in design in mixed and single-sex collaborative groups supported the use of mixed learning groups. These conflicting results and limited research concerning design conversations demonstrate the need to investigate gender composition of design teams in K-12 context.

Research Design and Methods

The current study is a part of a longitudinal research project that studies students' learning of science through engineering design in 6th–8th grade classrooms. The curriculum units in which students engaged were designed by the project team, including science educators with K-12 teaching experience, education researchers, and an agricultural and biological engineer. The project offered a 3-week summer professional-development program for middle-school science teachers to explore engineering integration in science and learn about the curriculum units. During the subsequent school year, teachers implemented the units in their classrooms. The curriculum unit and the data presented on this paper are from the first year of the project.

Participants

This research was conducted in a 6th grade science classroom in a small, rural town in a Midwestern state. This class was taught by Mr. Walton, a science teacher with almost 10 years of teaching experience who had previously implemented several engineering design–based science curricula. Teaching is Mr. Walton's second career; he previously worked in an environmental engineering firm completing engineering tasks related to waste and pollution management. We purposefully chose Mr. Walton for this study due his comfort and familiarity with integrating engineering in science instruction.

Mr. Walton's class included 27 students: 12 Anglo-males (44.4%) and 15 Anglo-females (55.6%), with approximately 20% of these students receiving free or reduced lunch at the time of the study. The teacher assigned students to their small design teams for the duration of the unit, with the aim of forming heterogeneous teams with respect to level of achievement, interest, and verbal participation. The team composition was designed to ensure the participation and engagement in design activities. There were six teams of four students and one team of three students. Of the seven teams, four teams were mixed-gender, with two boys and two girls in teach team; team 5 was boys-only (4 boys), team 6 was girls-only (4 girls), and team 7 was girls-only with three girls.

Context

The context of the unit was the pollution of a local river. The project team purposefully selected this context and the design challenge to make the engineering design task gender-inclusive and engaging for the students. Environmentally themed tasks or curriculum units have been found engaging and motivating for both girls and boys (Schnittka & Schnittka, 2016). The design task of the unit asks students to design a water filter to help prevent the pollution of a local river. Simply put, in an intense rain, storm water discharges directly to the local river without being treated in the wastewater management plant. The frequent storm water that overflows which contributes to the pollution in the river is a current concern of the city. The students are asked to design a water filter system for the city's wastewater management plant. The science lessons address human impact on the river ecosystem and the interdependent relationships in ecosystems. Mr. Walton implemented the engineering-driven science unit for 15 45-min class periods. During days 11–14, student teams designed prototypes, tested, evaluated, and re-designed water filters. Specifically, in days 11–12, students individually designed by drawing, engaged in meaningful design conversations to share their drawings with team members and identified one team solution, built a prototype, and tested and evaluated their prototype. In days 13–14, students followed a similar design process as teams re-designed their water filter. Teams were also asked to prepare short reports accompanying their designs. Design teams submitted their reports and presented their design solutions to the whole class in day 15. Table 1 provides an overview of the unit.

Data Collection and Analysis

Productive Thought Processes

Audio recorders were placed in the middle of the design teams' tables in an effort to record all design conversations in lesson 5, during days 11–14 of the unit. Approximately 20 h of small team conversations (7 teams and 4 class periods) were recorded and transcribed verbatim. Approaches commonly used in conversation analysis (Psathas, 1995) were employed to analyze the naturally occurring conversations during the implementation of the engineering design challenge. Specifically, the segment of talk in design conversations used for analysis was the turn constructional unit (Sacks

Table 1 Unit overview

Lesson	Objective	Timeline
Lesson 1: introduction to the design challenge	Introduce engineering design challenge, client letter and a short video from an engineer from the city's wastewater management plant, and engineering design process	Day 1
Lesson 2: water cycle and soil percolation	Describe effects of abiotic factors on a habitat and water cycle, and effects of soil types on the percolation of water	Days 2–4
Lesson 3: what plants need to live	Measure and analyze how living things use abiotic factors	Days 5–7
Lesson 4: interactions in the ecosystem	Identify the relationship between various organisms in an ecosystem	Days 8–10
Lesson 5: creating the waterfilter	Construct a water filtration system	Days 11–15

et al. 1974) which represents basic building blocks for turns-at-talk. The majority of the turns, in this study, were composed of single word, phrase, or sentence. For each turn constructional unit, we identified the speaker, boy, or girl in a team and coded turn constructional unit categories for each speaker. The discourse categories for productive thinking drawn from the work of Guilford and Gallagher and Achner (1963) include cognitive memory operations (CM), convergent thinking (CT), divergent thinking (DT), and evaluative thinking (ET). In addition, statements were coded as routine if they were not related to the design challenge (e.g. side conversations). A total of 1377 productive thought units were coded using the coding framework presented in Table 2. This represent, 85.6% of the conversations occurred in days 11–14.

In order to assess interrater reliability, two raters simultaneously and independently coded 14.8% of design conversations. Interrater reliability estimated as Cohen's weighted kappa (κ) was at a preferred level at 0.878 (with 95% confidence interval 0.845 to 0.911.). The weighted kappa was used because of its usefulness in categorical data with an ordinal structure (Hallgren, 2012). The assumption of normality was checked with a Shapiro-Wilk test (Shapiro & Wilk, 1965).

Due to the small sample size ($N = 27$), the data were checked to determine whether they can be considered a normal distribution (Hjalmarson & Moskal, 2018). The data violated the assumption of normality condition ($p < .05$), and therefore, non-parametric tests were carried out. Specifically, this study followed two steps of analyses. As a first step, a Mann-Whitney U (M-W U) test was used to determine if there was a significant difference in productive thought processes expressed by boys and girls as they engaged in an engineering design task. Next, a sequence of two M-W U tests were performed between (1) boys in a boys-only vs. boys in mixed teams, and (2) girls in girls-only vs.

Table 2 Coding framework

Codes	Definition	Examples
Cognitive memory (CM)	Simple reproduction of facts, formulas, or other items of remembered content through use of such processes as recognition, rote memory, and selective recall	"Remember that herbivores are grass-fed."
Convergent thinking (CT)	Analysis and integration of given or remembered that leads to a single answer or solution—*deciding* among alternatives or *making* choices	"So the gravels should be on the top, and the sand would be on the top, too. These … are where big materials may stay."
Divergent thinking (DT)	Generating solutions—*creating* many alternatives or choices	"Do you want anything else after this? Like, maybe … more cotton balls or more gauze pads after this one?"
Evaluative thinking (ET)	Deals with matters of judgment, value, and choice, and is characterized by its judgmental quality—opinions, agreements, and disagreements	"Well, I think … pea gravels can … um … keep big things out … I mean, big materials."
Routine (T)	Includes a large number of miscellaneous classroom activities and inaudible crosstalk, and unrelated talk	"OK, first let us discuss who's going to be doing what."

girls in mixed teams to examine the effect of gender composition of teams on productive thought processes.

Science Learning

The science content test included 15 selected-response questions (4-option multiple choice questions) and 3 constructed-response questions. The content of the test aligns with the science education standards identified for the following units: soil percolation, transpiration, ecosystems, interactions occur in ecosystems, and decomposition. Students learn these concepts specifically in lessons 2–4. The assessment was developed, scaled, and validated following the process described in the Standards for Educational and Psychological Testing (American Educational Research Association, 2014). Item response theory methods (Embretson & Reise, 2000) were used to ensure that items are functioning as desired. Item response theory (IRT)-based reliability was calculated as 0.79 for the test. To ensure that scores are reliable indicators of proficiency, we used Winsteps "person reliability" because of its focus on classifying students via their proficiency estimates (Linacre, 2018). It is important to note that IRT-based reliability is increasingly recommended rather than the traditional Cronbach's alpha (Sijtsma, 2009); however, these estimates tend to be smaller than alpha. To score student responses to the open-ended items, a rubric was developed by researchers with content expertise and middle-school science teaching experience. The responses were coded as incorrect, partially correct, or correct by two researchers who established interrater reliability of 85%.

Prior to statistical analyses, the distribution of the content test scores was tested for normality using the Shapiro-Wilk test (Shapiro & Wilk, 1965). The test showed that the data were approximately normal even with the small sample size: pre-test scores of male students ($p = .256$), pre-test scores of female students ($p = .760$), post-test scores of male students ($p = .548$), and post-test scores of female students ($p = .208$). Hence, parametric tests (t tests) were applied in subsequent analyses. First, between-gender differences in the pre- and post-test scores were tested by independent t tests. Second, within-gender comparisons in the pre- and post-test scores were examined by paired-samples t tests.

Results

In this section, we present our results with respect to our research questions: (1) Are there any differences in the productive thought processes expressed by girls and boys when they engage in an engineering design task in mixed and single-sex teams? (2) What is the effect of the gender composition of teams on students' productive thought processes? (3) Are there any differences between girls' and boys' science learning when they engage in an engineering design task?

Productive Thinking

Table 3 presents mean and median frequency for productive thought units across genders as well as the M-W U test results. It demonstrates that boys were slightly

Table 3 Gender differences in the frequency of productive thought processes

		Productive thought processes				Total
		CM	CT	DT	ET	
Boys ($N = 12$)	Mean	10.5	10.2	25.0	8.3	53.9
	Median	10.5	10.3	23.8	8.0	54.5
	Percent of total	19.5	18.9	46.4	15.3	100.0
Girls ($N = 15$)	Mean	9.6	7.7	24.4	6.9	48.7
	Median	7.0	6.7	19.0	4.5	33.0
	Percent of total	19.7	15.9	50.1	14.2	100.0
Mann-Whitney *U*		Ns	Ns	Ns	Ns	Ns

CM, cognitive memory; *CT*, convergent thinking; *DT*, divergent thinking; *ET*, evaluative thinking; *Ns*, not significant

more verbal than girls. However, the proportion of the different thought processes used by boys and girls was similar. Boys and girls commonly showed the highest proportion of divergent thinking, followed by cognitive memory, convergent thinking, and evaluative thinking. According to the M-W *U* test, no significant differences were found across genders at the significance level 0.05 in any productive thought processes.

The gender composition of teams influenced productive thought processes. Figure 1 shows that boys in a boys-only teams were more verbal than those in mixed teams. According to the M-W *U* tests, significant differences were found in cognitive memory, convergent thinking, and evaluative thinking—i.e. $p = .004$ (CM), 0.004 (CT), and 0.002 (ET). The differences in medians were 13 vs. 8.8 (CM), 13.5 vs. 7.5 (CT), and 10 vs. 7.5 (ET). Boys in mixed teams appeared to talk less than boys in single-sex teams. On the other hand, girls in mixed teams seemed to be more verbal than those in girls-only teams except the area of divergent thinking. Additionally, girls in mixed teams produced a higher percentage of convergent responses than those in girls-only teams with a significantly higher median ($p = .009$): 9.0 vs. 4.3 (CT). It is interesting to note that both divergent thinking profiles of boys and girls follow the same pattern—students produced a lower percentage of divergent responses in mixed teams than in single-sex teams. However, gender composition of teams had no significant influence on divergent thinking for both boys and girls. Moreover, the total thought units did not show statistical difference between mixed and single-sex teams.

Science Learning

According to the independent *t* tests, there were no significant gender differences in the pre- and post-test scores. Boys and girls did not differ in the pre- and post-tests, $t(26) = -0.02$, $p = .985$, and $t(24) = 0.12$, $p = .909$, respectively. However, the paired-samples *t* tests supported that there existed statistical differences between the pre-test and post-test scores for both genders. Boys and girls displayed significant improvements in the post-test. In terms of boys, the mean score for the pre-test was $M = 9.73$, $SD = 2.90$, and increased to $M = 11.32$, $SD = 2.63$ in the post-test (See Table 4). The mean difference of

Table 4 Within-gender differences in the pre- and post-test scores

		N	*M*	*SD*	*t* value	*df*	*p*
Boys	Pre-test	11	9.73	2.90	−3.38	10	**.007
	Post-test	11	11.32	2.63			
Girls	Pre-test	15	9.33	3.01	−2.86	14	**.013
	Post-test	15	11.20	2.53			

**$p < .05$

1.59 was significantly different, $t(10) = -3.38$, $p = .007$. Also, girls showed an increase in the test scores from $M = 9.33$, $SD = 3.01$ to $M = 11.20$, $SD = 2.53$, and there was significant mean difference of 1.87, $t(14) = -2.86$, $p = .013$.

Discussion and Conclusion

Creating learning opportunities that allow students access to engineering practices in science class is essential (NRC, 2012; NGSS, 2013). Much scholarly interest in engineering design considers its central role in science learning (e.g. Berland, Steingut, & Ko, 2014; Dankenbring & Capobianco, 2016; Mehalik et al., 2008; Schnittka & Bell, 2011; Tippett & Milford, 2017; Wendell & Rogers, 2013). However, design thinking and decision-making processes are also a significant aspects of design practice and can demonstrate how creative decisions are made, proposed, and negotiated (Adams, 2015). The thinking processes of individuals in small design teams enable us to explore how students perform design. The goal of this study was to document design conversations of students occurred within a design setting. In addition, the influences of this engineering design setting and gender composition of teams on student learning were explored.

A small but enlightening body of research focusing on productive thinking and K-12 students' science learning provides insights into effective ways of engineering integration in science classrooms. Engineering design provides students a unique learning space to engage with science and engineering practices (English, 2017; Guzey et al.,

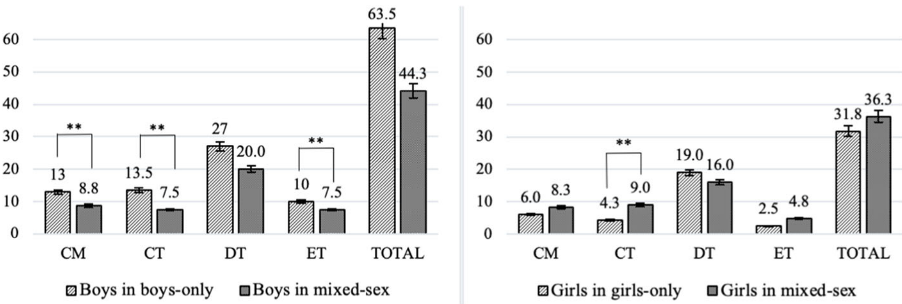

Fig. 1 Productive thought units expressed by mixed and single-sex teams. CM = cognitive memory; CT = convergent thinking; DT = divergent thinking; ET = evaluative thinking; **$p < .05$. The error bars represent 95% of confidence intervals

2019; Tippett & Milford, 2017); however, this context may exclude more students, particularly girls, since many girls still view engineering as a male-oriented field (NAE & NRC, 2009). Information gained from the current study and similar others investigating experiences of boys and girls as they engage in design activities or exploring students' design conversations in small design teams would be of help to curriculum designers and classroom teachers. We believe that engineering curriculum should be well-organized around interdisciplinary science and engineering concepts and student teams need to be well-balanced in terms of gender to improve the participation and learning of *all* students.

By analyzing student design conversations, we explored how collaborative nature of conversations contributed to design understandings and solutions. Analysis of small design team conversations demonstrated the different contributions that girls and boys made to the engineering design teams. Boys were more verbal when working in boys-only teams than boys in the same-sex teams, with statistical differences in cognitive memory, convergent thinking, and evaluative thinking. Girls, on the other hand, appeared to contribute more to the team conversations than girls in the same-sex team as teams were selecting their single solution with which to move forward (convergent thinking). We found that the proportion of different thought processes used by boys and girls was quite similar. Both girls and boys produced a higher percentage of ideas or thoughts associated with divergent thinking, but a lower proportion in cognitive memory, convergent thinking, and evaluative thinking. Divergent thinking is a highly desirable intellectual operation, allowing students to generate ideas or solutions to design problems. However, our findings suggest that gender and gender composition within teams have no significant impact upon the divergent thinking processes that girls and boys expressed. In a study that was conducted in a similar engineering design context, Schnittka and Schnittka (2016) also reported the differences in boys' and girls' participation in teams. In their analysis, the authors focused on how boys and girls used group-oriented and processual speech. Boys seemed to dominate conversations in mixed-gender teams and used more indirect processual speech acts in mixed-gender teams. In line with these findings, Due (2014) observed competitive interactions in groups solving physics problems. It seems that whether it is in a science activity or engineering activity, similarities and differences in girls' and boys' participation in contributing knowledge construction in teams illustrate the importance of understanding complex relationship between gender and learning.

To summarize, in this study, girls and boys voiced their ideas and thoughts and engaged in productive design conversations in mixed and single-sex teams and there were no gender differences with students' science learning. We believe that there are several aspects of the curriculum unit and instruction that possibly contributed to these findings and offer implications of the study. First, a critical aspect of the engineering challenge was its gender-neutral context—water pollution in the local river—and this contributed positively to the performance of both girls and boys. Student talk in small design teams shows that students found the design challenge realistic, and their attitudes toward the design task were positive. It is essential to support student engagement in engineering by providing purposeful learning activities that matter to them or that are connected to their everyday lives, which was supported by previous science education studies (Calabrese Barton et al., 2017; Fields et at., 2018; Murphy & Whitelegg, 2006; Whitelegg et al., 2007). Second, the teacher's strategy of forming teams using his knowledge of students' abilities, achievement, and characteristics possibly helped teams function well throughout the unit. While we analyzed student discourse that occurred as teams were working on their design during the last 4 days of the unit, students had started to work in their teams the first day of the unit and completed work in their teams every day. Teams stayed together and did not change their members over time. Students in teams shared ideas and distributed knowledge among peers, as they asked questions, brainstormed solutions, and negotiated ideas, which are all important practices during peer discussions (Rivard & Straw, 1999). Third, the goal of the engineering design project was not to create competition among teams. Instead, teams were asked to come up with a functioning design that meets the criteria and constraints. Students did not seem competitive on a behavioral level; they collaboratively worked on their initial design and redesign as they described, negotiated, or evaluated ideas. The nature of the learning task seemed to influence student learning and participation in groups as has been documented in prior research (Lou et al., 1996).

However, we do not argue that implementing meaningful and engaging design activities, purposefully arranging students in design teams, and focusing on collaborative work instead of competition in teams are simply progress toward better productive design conversations in mixed and single-sex teams. As the previous research highlighted, we know that student characteristics, creativity, prior experiences, attitudes, beliefs, values, and contextual factors influence student participation and learning in engineering and science (Aranda et al., 2019; Calabrese Barton et al., 2017; Guzey et al., 2016; Schnittka & Schnittka, 2016). Furthermore, the importance of pedagogical practices such as supporting student expertise, multiple iterations, and design discussions to engage students with design thinking have been addressed elsewhere (Fields et al., 2018). In this study, we argue that design is a collaborative, conversational process and examining design conversations is a powerful way to study design thinking. While our study investigated design thought and composition of design teams by analyzing verbal outputs, this technique has both strengths and weaknesses. For example, the verbalization of the individuals may not be a representation of their actual or whole thinking. But studying design talk enables design researchers to understand sources of knowledge or the thought processes and creative thinking that take place during design. Other researchers interested in design thinking explore design products such as prototypes and reports. The analysis of these design products or solutions can offer distinct advantages in design thinking research. For example, researchers can get practical results out of evaluating end products or solutions. But this technique does not allow us to report thought process, lines of thoughts, and directions of thoughts. Clearly design research would benefit from both research techniques, namely product-focused design research and process-focused design research. It is also clear that applying diverse study design techniques or frames would also allow researchers to better address the continued need to examine how gender influences students' participation and learning in science and engineering.

While our study provides unique insights into how boys and girls interact in design teams in a gender-inclusive unit, the study has a number of limitations. One limitation of our study is that there is no control group and there were only 7 design teams (four mixed teams, one boys-only team, and two girls-only teams). Expanding the implementation of the curriculum unit to more classrooms to further examine student design conversations in mixed and single-sex teams appeared to be needed. In such studies, however, the researchers should pay careful attention to the fidelity of implementation of the curriculum units. Even though the sample size was small, the total number of productive thought units (i.e. turn construction units) coded in the present study was 1377 with the mean of 51 per student. While we used statistical tests that are appropriate for the sample size and the number of thought units, a larger number of teams or comparisons with teams in other classrooms or teachers would allow us to arrive at more generalizable findings. Also, a larger number of student teams could allow us to explore the relationship between the performance of science learning and productive thinking between boys and girls. Second, we did not interview students about their perceptions about science, engineering, team work, or gender orientation of the engineering task. By knowing how perceptions differ among gender and how perceptions relate to participation and learning, we can then develop more informed curriculum materials. Finally, we analyzed student discourse with respect to gender at the "individual level" (Scantlebury, 2014). Other social categories such as ethnicity, socioeconomic status, and language proficiency were not included in the analysis since students in the classroom shared similar backgrounds, cultures, and lives outside of school.

In line with the limitations of this study, we have recommendations for future research. Future research is required to investigate the impact of gender-inclusive curriculum units on students' gendered perceptions about science and engineering. In addition, future research is needed for further investigations of the effects of the gender orientation of the design challenges on performance of students and design teams. Comparisons of other curriculum units, classrooms, and teachers will provide a greater understanding of the productive thought processes of students. Finally, an additional line of research should also investigate the effect of intersectionality, especially the intersections of gender identity and ethnic identity, on students' participation on design teams.

In analyzing the small design team conversations and student learning in an engineering-driven science unit, we aim to contribute to the K-12 students' design thinking scholarship. Research in gender and integrated science education is important in understanding students' engagement in engineering and science. With increasing interest and calls for integrating engineering in science instruction (e.g. NGSS), a clear understanding on how to purposefully and meaningfully integrate engineering practices into science teaching in equitable ways remains critical (Ryoo & Calabrese Barton, 2018).

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