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The Impact of Design Swapping on Student Design Sketch Quality

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This study seeks to explore the implementation of design swapping to encourage students to document their designs. Design swapping involves having teams swap design sketches shortly after a design review such that they construct another team's design. Teams are incentivized to document their designs through sketches because other teams build their designs. This study seeks to investigate the effects of the timing of notification of students on the overall quality of design sketches in the setting of an engineering summer camp for middle and high school students and student perceptions of the design swapping activity. Data sources included design sketches, design sketch quality scores, and individual reflective survey question responses. A total of 136 middle and high school students participated in the study, split across 39 teams at 8 different sites. Data were analyzed using descriptive statistics, repeated measures ANOVAs, and thematic analyses. Results showed that students who were notified prior to a design review of an imminent design swap generated higher-quality design sketches than those who were not notified or notified after a design review. Some participants saw design swapping as a positive opportunity for growth and real-world engineering experience, while others found it challenging. Design swapping is a viable pedagogical strategy to encourage students to generate higher-quality design sketches, and provides students with a surrogate client in the absence of a real client.

Keywords: pre-college design; design sketches; design quality; swapping sketches; STEM

1. Introduction

In today's dynamic and innovation-driven world, we are faced with complex problems that cross over disciplinary boundaries and cannot be solved optimally by a single discipline [1], such as the National Academy of Engineering's Grand Challenges for Engineering [2]. In order to prepare our students to tackle these problems, we need to ensure they have (1) strong communication and collaboration skills [3–5], (2) an ability to critically think and solve problems [3–5], and (3) "an ability to function on multidisciplinary teams" [3] that involve social and cross-cultural interaction [5] in geographically distributed teams [4, 6, 7]. These qualities are indispensable in the modern engineering workplace, where design is a social process [8]. College graduates are often placed on multidisciplinary [1] and/or virtual teams [9] which strongly rely on communication and strong processes to be successful [10]. Therefore, as engineering educators we must ensure that students get experience creating higher-quality design documentation as well as experience giving and receiving critiques of design documentation.

We can start by improving the preparation of pre-college students to document engineering designs using sketches. The inclusion of engineering in the K-12 classroom is an active part of the national dialogue on education in the United States, and is a significant part of the Next Generation Science Standards [11] for K-12 schools. It is the responsibility of educators to help students learn the language of their disciplines [12, 13], where language is a representation of their ideas. In engineering, supporting students to see documentation in use in engineering contexts is critical to student development [14], and having them create links across multiple design representations (including sketches) results in better reasoning and meaning making in K-12 students [15]. Designing with multiple representations also makes it easier for K-12 students to transfer STEM concepts to other contexts [16], emphasizing engineering as supporting K-12 education to produce better overall members of society. However, students are often reluctant to thoroughly document their engineering designs in sketches [17]. This necessitates a search for other pedagogical strategies to encourage students to generate high-quality design sketches to document their designs.

In this study, we examine one pedagogical strategy with promise to have positive effects on the quality of design sketches produced by middle and high school students: design swapping. Design swapping involves having teams swap design sketches shortly after a design review such that they construct another team's design [18]. This study focuses on the swapping of design sketches

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in the context of middle and high school summer camps.

2. Background

2.1 Design representations

Representations are important as languages for the communication of designs [19–24]. Representations of designs can take many forms, including verbal or textual statements, graphical representations, shape grammars, features, mathematical or analytical models, or numbers [25–27]. According to Simon [28], all problem solving requires some sort of representation of the problem space. Representations capture and communicate "complex relations in concise ways" [15], allowing practitioners to interact visually with models of their designs [29]. Reisslein, Moreno, and Ozogul [30] found that student cognition is directly affected by the nature of the representations they create (abstract and/or contextualized). The creation of representations is a core analytical function performed by engineers [31, 32], who commonly use multiple representations simultaneously to convey design ideas [33, 34]. According to Nathan et al. [15], standardized rules for interpreting and manipulating representations "are part of the professional discourse and practices in STEM".

According to Jonassen et al. [31], "the most common form of problem representation is drawing". Sketches are an important way for designers to represent their ideas [35], particularly for the purpose of design communication [36, 37]. Sketches support visual reasoning and provide visual cues useful in problem solving [38–40]. Additionally, ambiguity inherent in design activity can be critically captured by sketching [41]. This study focuses specifically on design sketches, which are a representation often used in documenting early-stage engineering designs.

2.2 Design representations and team success

The creation and use of high-quality design representations is an important element contributing to better overall product outcomes in team design projects in undergraduate and graduate settings, motivating extra design representation preparation for pre-college students. For example, Ulrich et al. [42] found that higher quality design documentation results in better overall outcomes for undergraduate capstone design teams. Dong, Hill, and Agogino [43] found a positive correlation between semantic coherence, which is the inclusion of semantic connections to give textual coherence to design documentation, and successful graduate school product design team outcomes. Design teams using sketches were found to design higher quality solutions than those that did not use sketches in a graduate school design program [44].

Conversely, studies of design teams with successful overall product outcomes show a reliance on high-quality documentation. For example, Song, Dong, and Agogino [45] found a "positive correlation between design outcomes and patterns of the average semantic coherence over time," which indicates that successful design teams tend to have high quality documentation. A study of successful geographically-distributed teams by Leifer [46] similarly found that they had better documentation of both products and processes, suggesting a connection between successful collaboration and the quality of design documentation.

In education, student grades have been found to positively correlate with the quality of design documentation. Song & Agogino [47] found "a statistically significant correlation between the total number of individual journal sketches created during the design process and an individual student's class grade," indicating that the undergraduate students who sketched more had higher quality designs. Sketches done in the first quarter of the design cycle that include dimensions are significantly correlated to positive design outcome as measured by final grades [48]. Grades in undergraduate design classes have also been associated with the number of distinct noun phrases in design documentation [49, 50], further suggesting that students will receive higher grades if they produce higher quality design documentation. However, few studies exist examining design swapping in pre-college contexts.

2.3 Preparing pre-college students for the engineering profession

As our students prepare to enter a workforce of geographically distributed teams [4–7], it is increasingly important for them to learn to create and use high-quality design documentation. According to a multiple case study on virtual teams in industry by Jordan and Adams [10], having design documentation that exists, is shared with and used by the entire team was identified across all cases as being important for the team's success. Successful collaboration requires the translation of representations across disciplinary boundaries [51]. Representations promote collaboration and discussion across STEM disciplines by serving as shared artifacts [52–54].

Graduating engineers entering the workplace need strong written and oral communication skills [3, 4, 55–57] to meet the expectations of both employers and clients [55]. Unfortunately, many have found that graduating engineers are inadequately equipped to convey technical information quickly to diverse audiences [58–60], and a "lack of communication skills" was identified as a top competency gap of graduating engineers in a study by the Society of Manufacturing Engineers [61]. To address inadequate preparation of our students to create high-quality design documentation, we need to teach "more communication skills in engineering curricula" [31] and improve design education overall [62, 63].

2.4 Intervention: design swapping

Significant research exists showing that high-quality design representations lead to success on collegiate and professional design teams, but this has not been deeply studied in pre-college settings. Therefore, teaching pre-college students the importance of creating high-quality design representations better prepares them to be successful in undergraduate engineering programs and careers in engineering.

Currently, students often prefer to jump to a solution and build it, rather than following a systematic design process that includes proper documentation of their design ideas. Students sometimes complain that "they do not want to keep logbooks because their work is already 'all in their head'" [17]. Welch, Barlex, and Lim [64] posit that students are "likely to have limited skills and insufficient experience of sketching to be fluent," which discourages them from properly documenting their designs.

Teachers often use grades as a way to force compliance in the documentation of designs, both in pre-collegiate and collegiate settings. This study seeks to explore the implementation of an alternative intervention to encourage students to document their designs: design swapping. Design swapping involves having teams swap design sketches shortly after a design review such that they construct another team's design [18]. Teams are incentivized to document their designs through sketches because another team will be building their designs, rather than just building what is in their own minds. While this idea is anecdotally not new (teachers have had students swap work products for decades), implementation details such as the time that students are notified they will be swapping have not been studied in pre-collegiate or collegiate contexts. This study seeks to understand the effects of the timing of notification of students on the overall quality of design sketches in the setting of an engineering summer camp for middle and high school students.

3. Research design

Little is known about how the pedagogical technique of design swapping impacts the quality of design documentation prepared by middle and high school students. Specifically, the time at which students are notified that they will swap designs is of critical importance because the level of ownership that students feel over their designs may be related to the quality of the design documentation that they produce. The current study addresses this knowledge gap through two investigations: (1) a quantitative experimental study that examines the impact of different design swapping implementations on the quality of design sketches, and (2) a qualitative study focused on student perceptions of the design swapping activity. We sought to answer the following research questions:

RQ1. How does prior knowledge of an imminent design swap affect the quality of design sketches prepared by students for design reviews? *(Investigation 1)*

RQ2. How does the timing of notifying students of a design swap affect the quality of design sketches prepared by students for design reviews? *(Investigation 1)*

RQ3. What are students' perceptions of the design swapping activity? *(Investigation 2)*

To address these research questions, we collected qualitative data (design sketches and individual written responses to reflection questions) in eight summer engineering design camps for middle and high school students. The summer camps (described below in Context: summer engineering design camps) were selected because they were taught with a common curriculum and with similar context across several sites both in the United States and internationally. This common curricular foundation heavily emphasized design documentation, and the limited duration camp format allowed for a quasi-experimental design across camps to test different aspects of the design swapping intervention. Participation in the pre-existing camps was limited to middle and high school students. Design sketch quality was evaluated using a rubric developed by the research team, and the scores used as data for quantitative analyses. Human subjects approval was obtained to use the design documentation, reflections, and survey data prior to data collection. The following sections provide a more detailed description of the dataset.

A quasi-experimental design was used in the experiment, with nonrandomized control groups for RQ1 and RQ2. The dependent variable was the quality of the design sketches created by the teams. The two independent variables were (1) prior knowledge of an imminent design swap (RQ1) and (2) the time at which the students were notified that they would be swapping designs (RQ2). For RQ3, a thematic analysis was conducted on a random sample of qualitative feedback from 46 (out of 136) students on the intervention from participants.

3.1 Context: summer engineering design camps

This study took place in eight 1-week STEAM Machines™ engineering design summer camps for middle and high school students. In each of the camps, students learned the Engineering is Elementary® engineering design process [65] and other science, technology, engineering, arts, and math concepts, and applied them to the design and construction of Rube Goldberg-style chain reaction machines that popped a balloon. Rube Goldberg machines are chain reaction devices that complete simple tasks, such as replacing a light bulb, in overly complex ways. The curriculum has evolved from prior work by the authors [66–68] in partnership with the Gifted Education Resource Institute at Purdue University in the United States. The camps and instructional style are project-based [69], inquiry-based [70], and differentiated to challenge learners with diverse levels of ability [71].

Students worked in teams to design modules for their machines, where each team's module is connected to another team's module, culminating with a module that popped a balloon. Teams prepared design documentation in the form of sketches (see example, Fig.1) capturing all of the steps in their modules and presented them at an initial design review focused on conceptual feasibility. The rationale for design swapping was described to students as handing their designs to another team for manufacturing. The teams that swapped designs were notified of the swap before or after the design review. Design swaps occurred either with another team in the same classroom or with a team at a different camp running at the same time at a different site. Teams swapping designs with other teams communicated with both the design team (the team that conceived the design they built) and the manufacturing team (the team that build the design they conceived). Teams swapping designs with other geographically-distributed teams collaborated using videoconferencing and file sharing. Machine design and construction continued, and upon reaching the machine reliability testing phase teams updated their design documentation sketches and presented them at a final design review focused on reliability. The design teams did not return to build their original designs because the manufacturing teams knew the improved designs best after deeper review and implementation. After further improvements, teams presented their completed designs in a final-day celebration, and completed reflections on their swapping experience.

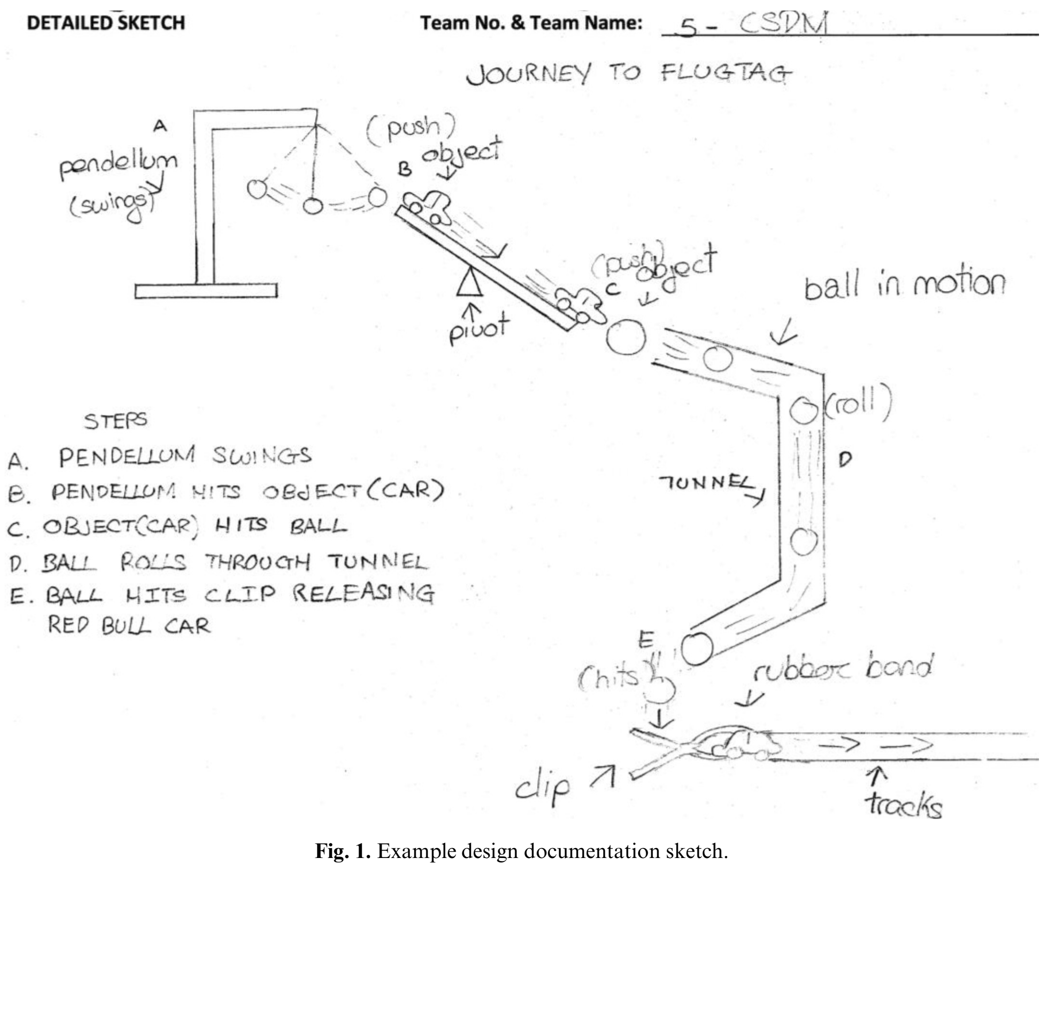

Fig. 1. Example design documentation sketch.

All camps shared the same learning objectives, content material, and pedagogical approaches, but varied in terms of the implementation setting and structure. Some of the specific variations were: number of students, demographic distribution, and cultural and educational background of the students; methods of recruitment; mechanisms for financially supporting students' participation; location and proximity of partnering sites; nature of the team interaction students experienced; and the use of and dependency on online communication tools and technologies. This mix of deliberate and situational modifications allowed us to study in authentic settings the learning effects and affordances of the design swapping intervention.

3.2 Participants

A total of 136 middle and high school students participated in the study, split across 39 teams at 8 different sites (see Table 1). Camps took place at a large research university in the southwest United States, a historically black college on the east coast of the United States, a large research university in the midwest United States, and a high school/college in the Caribbean. Participants ranged in age from 11– 18. Participants were in one of three experimental groups: (1) no design swap (control), (2) notification of design swap approximately 15 minutes prior to the first design review, and (3) notification of design swap after the design review. Students in experimental group 2 had only 15 minutes (12.5%–25% of their overall design time) to update their sketches in preparation for the design reviews, but spent 1–2 hours on their design sketches prior to the design review.

The unit of analysis for RQ1 and RQ2 was the team, because teams rather than individuals created the design sketches. The unit of analysis for RQ3 was each individual student, because student reflections were done on an individual basis. All students enrolled in the eight engineering design summer camps participated in the entire intervention. All groups were required to generate the same types of design documentation.

No design swap. Teams (1) designed a module, (2) participated in DR1, (3) updated their design based on peer feedback from the design review, and (4) built the module that they designed. Each module was interconnected with modules built by other teams. Teams in the *No design swap* group did not swap designs with other teams. After continuing to work, teams updated their design documentation and participated in a second design review.

Notification (of design swap) before design review 1 (DR1). Teams (1) designed a module, (2) were notified they would be swapping designs after DR1, (3) participated in DR1, (4) swapped designs with another team, (5) started building the received module, and (6) updated the received design based on changes implemented during the building phase. Each module was interconnected with modules built by other teams. After spending 1–2 hours working on their design sketches, teams were notified approximately 15 minutes prior to presenting their designs for feedback at a design review that they would be swapping designs with another team. This notification provided teams with time to finalize and improve their design sketches prior to presenting them at the design review. Teams did not know in advance with which team they would be swapping designs. After spending a day building, teams created updated design documentation in preparation for design review 2 for the design that they were building (that was designed by another team). The receiving teams created the documentation for design review 2 because they were most familiar with the changes from the original design implemented during the building phase.

Table 1. Participants and group assignments

Group	Camp—Site	# Teams	# Students
No design swap (control)	1—University in southwest USA	5	18
	1—University in midwest USA	4	8
	Total	*9*	*26*
Notification before design review 1 (DR1)	2—University in southwest USA	5	18
	2—University in midwest USA	5	19
	2—High school/college in the Caribbean	5	20
	Total	*15*	*57*
Notification after design review 1 (DR1)	3—University in southwest USA	5	17
	3—University on east coast USA	5	20
	4—University in southwest USA	5	16
	Total	*15*	*53*
	Grand Total	39	136

Note: Camps with the same number (1, 2, 3, or 4) collaborated across sites.

Notification (of design swap) after design review 1 (DR1). Teams (1) designed a module, (2) participated in DR1, (3) unexpectedly swapped designs with another team, (4) started building the received module, and (5) updated the design based on changes implemented during the building phase. Each module was interconnected with modules built by other teams. Teams were notified immediately after presenting their designs for feedback from other teams at design review 1 that they would be swapping designs with another team. Since teams were notified after the design review that they would be swapping designs, they were not able to improve their design documentation prior to the first design review. After spending a day building, teams created updated design documentation in preparation for design review 2 for the design that they are building (that was designed by another team).

3.3 Instruments

This study used two measures intended to evaluate the quality of the design documentation generated by students and their evaluation of the experience. These measures were a design sketch quality rubric and an individual reflective survey.

Design sketch quality rubric. To address RQ1 and RQ2 (see Table 4), the quality of design sketches created by teams was judged by using a rubric (see Appendix A). A scoring rubric [72, 73] was used to enhance reliability of scoring [74]. Quality can be defined in many ways, "from holistic judgments by panels of experts, instructors, peers, and combinations thereof to rubrics that operationalize the specific dimensions that are assumed to represent quality," [75], and problem solving skill can be judged on artifacts such as sketches [76]. The quality of design documentation can affect the overall success of a project.

There are many ways to judge the quality of design sketches, which are the primary form of design documentation used in this study. The Project Lead the Way STEM program for elementary, middle, and high schools assesses design processes with rubrics that judge the overall design and specific drawings and mechanical assemblies. The quality of the freehand sketches of a design are judged, along with accurate representation of the features of the models, dimensions and annotations, and the overall clear documentation of mechanical assemblies and parts [77]. In the mechanical drafting community, Ullman et al. [35] assessed the quality of drawings by their features, including the text labeling, dimensioning, and calculations. Song and Agogino [47] extended Ullman's work to use metrics of type of sketch, medium, type of representation (2D or 3D), annotation, and level of detail. Neatness and labeling of steps are also important in the assessment of quality in design documentation, particularly in K-12 classrooms doing Rube Goldberg design projects [78–81].

Rubrics are often used to evaluate the quality of design documentation, often measuring at least one of the following types of engineering outcomes: design knowledge, design process skills, and/or design product [82]. Design process skill assessment has been extensively studied by Davis, Gentili, Trevisan, and Calkins who developed a suite of rubric-based assessment tools to measure design process, teamwork, and design communication skills of students in design teams [83]. Brinkman and van der Geest [84] and Song and Agogino [47] also developed metrics for assessing design communication, a critical part of the design process. The overall quality of the design product can also be measured with tools such as the Total Quality Management House of Quality [85]. Pre-existing sketch rubrics (e.g., Sobek & Jain [86]) were not appropriate for this study due to the nature of the design context. The rubric used in this study was developed through a process of reviewing literature related to the evaluation of design sketches and lesson plans for similar curriculum used with middle and high school students (see Table 2). It was also informed by reviewing design sketches and identifying the key factors that differentiated excellent sketches from poor ones.

As shown in Table 2, Rubric factors included inclusion of *team number and name*, *step realism/recognizability*, *step scale*, *step sequence labels*, *component labels*, *step descriptions*, *functional indicators*, and *neatness*. Each criterion was evaluated on a 3-point scale from "None" to "Most". While the neatness criterion was not grounded in literature, it was deemed important by instructors to ensure clarity of communication. The full rubric is provided in Appendix A.

Individual reflective survey. To address RQ3 (see Table 4), participants individually completed a reflective survey at the beginning of the last day of the camps. The survey included the open-ended question, "what are your thoughts about swapping designs among teams?" Responses to this question were used to add a qualitative description of the experience.

3.4 Data collection

This study used two sources of qualitative data collected during the camps to inform analysis of the design swapping intervention. These data were design sketches and an individual reflective survey. A design sketch quality rubric was used to evaluate the quality of the design sketches produced by the students.

Table 2. Literature informing rubric development

Rubric Factors	Literature
Team number and name	Lau et al. [87], McGown et al. [88]
Step realism/recognizability	McKoy et al. [89]
Step scale	McGown et al. [88]
Step sequence labels (A, B, C...; 1, 2, 3...)	Westmoreland et al. [90]
Component labels (e.g., ball, dominoes, car)	Lau et al. [87], McGown et al. [88]
Step descriptions	Lau et al. [87], McGown et al. [88], Cham & Yang [91], Yang & Cham [17]
Functional indicators (e.g., arrows)	Westmoreland et al. [90]
Neatness (e.g., line quality, edges, readability, smudges)	N/A (but important)

Design sketches (see example, Fig. 1) were the primary artifacts that teams used to document their designs for communication to others during design reviews. Model sketches were provided to students as examples of how to document their designs, and expectations for design sketch quality were discussed prior to the creation of the sketches. Groups created at least two design sketches: one prior to design review 1 and one prior to design review 2.

Reflective survey responses were collected from individual students at the beginning of the final day of each camp. Instructors or teaching assistants gave all students the individual reflective survey. Students spent 15 minutes completing the survey.

Design sketch quality rubric scores for the design sketches, three coders individually coded a training dataset and met to resolve coding differences. Then, the coders individually coded the design sketches in actual datasets using the same rubric (see example sketch, Fig. 2 and sketch coding example, Table 3). The inter-rater reliability estimates for the three raters ranged from 0.62 to 0.79.

3.5 Data analysis

The findings are grounded in the quantitative design sketch quality data, and the qualitative reflective survey data. Both quantitative and qualitative analysis methods were used to capture both the statistical trends and richness of the students' experiences

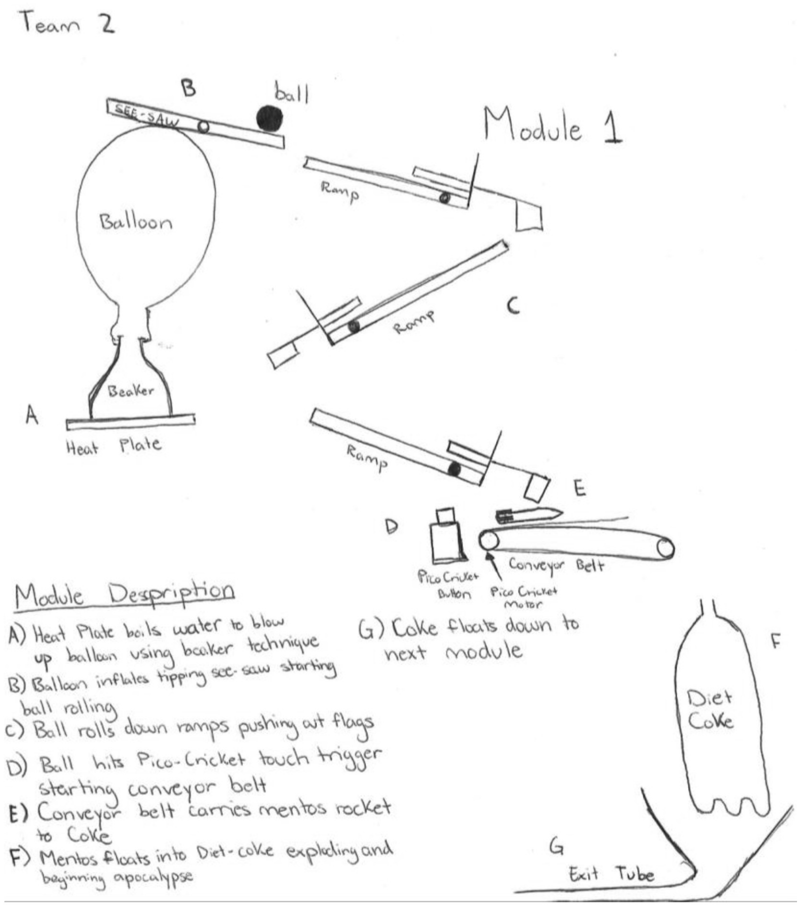

Fig. 2. Example design sketch from camp 2 at a university in the southwest USA.

Table 3. Example application of the design sketch quality rubric to the design in Fig.2

Factors	Rater 1	Rater 2	Rater 3
Team number and name	2 (Some)	2 (Some)	2 (Some)
Step realism/recognizability	3 (Most)	3 (Most)	3 (Most)
Step scale	3 (Most)	3 (Most)	3 (Most)
Step sequence labels (A, B, C...; 1, 2, 3...)	3 (Most)	3 (Most)	3 (Most)
Component labels (e.g., ball, dominoes, car)	3 (Most)	3 (Most)	3 (Most)
Step descriptions	3 (Most)	3 (Most)	3 (Most)
Functional indicators (e.g., arrows)	1 (None)	1 (None)	1 (None)
Neatness (e.g., line quality, edges, readability, smudges)	3 (Most)	3 (Most)	3 (Most)

Table 4. Research questions, data sources, and analysis methods

Questions	Data Sources	Analysis Methods
RQ1. How does prior knowledge of an imminent design swap affect the quality of design sketches prepared by students for design reviews?	Design sketches, design sketch quality rubric scores	Descriptive statistics, repeated measures analysis of variance (ANOVA)
RQ2. How does the timing of notifying students of a design swap affect the quality of design sketches prepared by students for design reviews?	Design sketches, design sketch quality rubric scores	Descriptive statistics, repeated measures analysis of variance (ANOVA)
RQ3. What are students' perceptions of the design swapping activity?	Individual reflective survey	Thematic analysis [92]

with design swapping. Table 4 summarizes the data sources and associated analysis methods for each research question.

Descriptive statistics, including means, standard deviations, skewness, and kurtosis estimates were generated for the samples used for each of the research questions and for the groups within those samples. Average total scores for each of the three raters were converted to percentages for ease of interpretation of results. Repeated measures analysis of variance (ANOVA) were used to compare the average quality scores for the groups from DR1. Eta squared (η^2) was calculated as a measure of effect sizes. Data from DR2 are not included as part of this study.

For the individual reflective surveys, two coders conducted a thematic analysis [92] and individually open-coded the responses. The coders compared results, resolved any disagreements, and jointly created a coding scheme. Using the revised coding scheme, one coder made a final pass through the dataset to code the responses. This strategy improves the reliability and trustworthiness of the qualitative analysis by providing a chain of evidence that can be examined and replicated [93]. The final codes are described in the Results section, and were used to provide an overview of the experiences of students.

In addition to providing a chain of evidence [93], the quality of both the qualitative and quantitative analyses was improved with researcher triangulation [92, 94–96]. At least two researchers analyzed each piece of data, met to resolve differences in coding, and worked as a team to interpret the data.

4. Results

Results for each research question are presented separately since different samples were used to answer each question. Analyses for RQ2 did not include the *no design swap* group because that question focused on the timing of the notification of the design swap.

RQ1. How does prior knowledge of an imminent design swap affect the quality of design sketches prepared by students for design reviews?

Research question 1 (RQ1) focuses on the effects of prior knowledge of an imminent design swap on the quality of documentation, so the sample for RQ1 analyses included the *notification before DR1* group ($n = 15$) and the *no notification* of design swap before DR1 group ($n = 24$), which included both the *no design swap* ($n = 9$) and the *notification after DR1* group ($n = 15$). Table 5 includes descriptive statistics for the *no notification* and *notification before DR1* groups.

Descriptive statistics indicated that the data met the assumptions required for the statistical analyses with skewness ranging from –0.91 to .04 and kurtosis ranging from –0.87 to 0.56. The Levene test of homogeneity of variances yielded equivalent variances between the two groups.

In order to compare the quality scores for sketches in the *no notification* group to the scores

Table 5. Descriptive statistics for the *no notification* and *notification before DR1* groups

Group	*M*	*SD*	Skew	Kurtosis
No notification (n = 24)	74.88	8.05	–0.32	–0.87
Notification before DR1 (n = 15)	85.93	11.79	–0.91	0.55
All Groups	79.13	10.96	0.04	–0.56

Note. SD = Standard Deviation.

Table 6. Comparison of average quality scores for the *no notification* of design swap and *notification before DR1* groups

	No notification (*n* = 24)		Notification before DR1 (*n* = 15)					
	Mean	SD	Mean	SD	Mean Diff.	*df*	*F*	*p*
Overall Quality	74.88	8.05	85.93	11.79	11.05	1	12.10	0.001

Note. SD = Standard Deviation.

for sketches of the *notification before DR1* group, we conducted repeated measures analyses of variances (ANOVA). Results for the ANOVAs are presented in Table 6.

The average quality score for the *notification before DR1* group was significantly higher than the average score for the *no notification* group (F = 12.103, df = 1, p = 0.001, η^2 = 0.246). The higher scores could be due to the notification of design swapping taking place prior to DR1.

RQ2. How does the timing of notifying students of a design swap affect the quality of design sketches prepared by students for design reviews?

Research Question 2 (RQ2) focuses on the timing of the notification of the imminent design swapping. The two groups used for these analyses were *notification before DR1* (n = 15) and *notification after DR1* (n = 15). Descriptive statistics for the two groups are presented in Table 7.

Descriptive statistics indicated that the data met the assumptions required for the statistical analyses with skewness ranging from –0.31 to 0.13 and kurtosis ranging from –1.13 to –0.61. The Levene test of homogeneity of variances yielded equivalent variances between the two groups.

We conducted a repeated measures analysis of variance to investigate if means for the two groups were significantly different from one another. Results indicated that the average quality scores for the *notification before DR1* group was significantly higher than the average quality scores for the *notification after DR1* group (F = 4.656, df = 1, p = 0.040, η^2 = 0.143). These results could indicate that notifying students of an imminent design swap may have had positive effects on the quality of the sketches students produced.

RQ3. What are students' perceptions of the design swapping activity?

Research question 3 (RQ3) focused on qualitatively examining perceptions of the design swapping activity from the perspective of students who participated in a design swap. The themes from student reflections are summarized in Table 9.

The design swapping intervention offers several

Table 7. Descriptive statistics for design review 2 groups

Group	*M*	*SD*	Skew	Kurtosis
Notification before DR1 (n = 15)	82.50	8.21	0.13	–0.79
Notification after DR1 (n = 15)	74.44	11.89	–0.10	–1.13
All Groups (n = 30)	78.47	10.85	–0.31	–0.61

Note. SD = Standard Deviation.

Table 8. Comparison of Average Quality Scores for *notification before DR1* and *notification after DR1* Groups

	Notification before DR1 (*n* = 15)		Notification after DR1 (*n* = 15)					
	Mean (SD)	*SD*	Mean (SD)	*SD*	Mean Diff.	*df*	*F*	*p*
Overall Quality	82.50	8.21	74.44	11.89	8.06	1	4.66	0.04

Note. SD = Standard Deviation.

Table 9. Student perceptions of the design swapping activity

Code	Subcode	Definition
Swap experience	Enjoyment	Expressed overall enjoyment with swapping and/or the final product
	Disliked initially	Expressed initial dislike of swapping but recognized the value after persisting to the end
Opportunity	Learning	Expressed satisfaction with the both the opportunity to learn and the positive challenge afforded by swapping
	"Real-world" engineering	Described swapping as providing "real-world" engineering experience
	Improved teaming	Expressed team-based ownership of design, where swapping helps improve teaming skills
	Improved designs	Described swapping as an opportunity to create higher quality designs
Design experience	Individual	Expressed individual territorial ownership of design
Swap experience	Difficult	Expressed negative (difficult) challenge with swapping
	Dislike	Expressed overall dislike of swapping without rationale

positive affordances, both in the experience and as an opportunity for growth. Many students expressed overall enjoyment with the swapping experience or the final product. For example, one student wrote, "it was very interesting to switch designs." Another student wrote, "I thought that swapping designs among teams added a fun, challenging twist to the [. . .] camp." Other students initially disliked the swapping experience, but recognized the value of it by the end of the camp. According to one student who found the experience challenging at first, ". . .it gave [us] a chance to improve [our] design" which could mean improving his design or another team's design (both of which are desirable learning objectives). Another student expressed initially disliking the design swapping experience: "I didn't like it but I got through it."

Some students saw design swapping as an opportunity for growth—be it learning, real-world experience, teaming, or improving designs. Design swapping was seen as an opportunity to learn and was a positive challenge for some students. One student described how he "had the thoughts and materials already laid out inside [his] . . . head. It was quite interesting to make someone else's design. Yet, it is part of the learning stage." Another student recognized that the challenges his team faced were similar to those in the real world, where engineers optimize toward a goal (albeit usually to minimize rather than maximize). ". . . it gave me a chance to experience real engineering in the real world." Some students also identified teamwork as an area of improvement afforded by design swapping. For example, one student said, "it improved me *(sic)* ability to adapt along with my teamwork." Some students also saw swapping designs as an opportunity for improvement of others' designs. One student said, "I thought it was a good idea as it allows us to appreciate others' work and make it better."

Several hindrances to the design swapping experience exist and should be considered when implementing swapping in other contexts. Some students expressed an individual territorial ownership of their designs, often separated from even their own team. For example, one student said "I don't like it, the person who designed it would be better to build it." Other students found swapping to be very challenging or expressed dislike without rationale. For example, one student's view of swapping was simply "bad idea!!!"

5. Discussion

Results indicated that the quality of design artifacts was superior when students knew prior to a design review that they would be building another team's design. The average quality score for sketches made by teams that had prior knowledge of an imminent design swap was 11.05 quality points higher than those teams that did not know about a design swap or did not swap designs. Therefore, prior knowledge that designs will be swapped can improve the quality of design documentation generated by students. This is discussed by some students in their reflective surveys, where design swapping was seen as an opportunity to create higher quality designs. This is a desirable learning outcome for preparing future engineers, as the creation of design representations is a core analytical function performed by engineers [33, 74]. It also has the potential to improve the overall outcomes for their design teams [42].

Design swapping introduces an audience for designs beyond the team, in a similar way that having a real client can motivate students to communicate their designs more effectively. In their reflective surveys, some students recognized design swapping as providing a real-world engineering experience. *Since real clients are often not feasible or accessible for student design projects, the idea of design swapping can provide a surrogate client in the absence of a real client.* It also simulates a variety of common work practices in industry, including handing off designs ("throwing over the wall") between design and manufacturing teams and 24–7 engineering where designs are handed off between continents every 12 hours.

Next, we investigated whether the timing of notification of a design swap makes a difference in the quality of designs later in the design process. Results indicated that the quality of design artifacts was superior when students knew prior to a design review that they would be swapping designs, rather than being surprised after the design review. The average quality score for sketches made by teams for design review 2 that had prior knowledge of an imminent design swap was 8.06 quality points higher than those teams that did not find out about a design swap until after design review 1. *Therefore, it is better to notify students early in the design process that they will swap designs.* In their reflective surveys, some students expressed finding swapping challenging in either a positive or negative sense, suggesting that earlier notification could benefit these students. In this study, students had been sketching for 1–2 hours and were notified approximately 15 minutes prior to the design review that they would be swapping designs. However, further study of student ownership of designs and time invested into more complex designs that are swapped is necessary to determine the optimal time to notify students of a swap.

Design swapping was found to provide an opportunity for students to learn and grow. In their reflective surveys, some students expressed satisfaction with the opportunity to learn and the positive challenge afforded by swapping. Continuing the practice of thoroughly documenting designs could translate to higher grades [47, 48] if students pursue higher education opportunities in engineering. Students also discussed in their reflective surveys how swapping designs helped strengthen their design teams. Since successful collaboration requires the translation of representations across disciplinary boundaries [51], students must create and use high-quality design documentation. It also addresses the "all in their head" [17] issue common among students who do not want to document their designs by creating a motivation for design documentation and sharing. Design swapping also promotes a team-based ownership of designs, although some students disliked swapping due to an individual territorial ownership they held over their designs. Design swapping could provide a necessary socialization for students learning to share and function in the workforce of the future.

This study has a few limitations that should be considered when interpreting the results. Another limitation is that the study was conducted in summer program and most of the students selected a camp of their interest. Thus, most of the participants had a prior interest in engineering design and potentially in pursuing engineering as a career, which might have biased students' reflective survey responses. However, undergraduate engineering students who might benefit from this pedagogical strategy might also have a prior interest in engineering. Another limitation is the short period of time used for the intervention (design swap). Students in teams that swapped design sketches were notified of the swap approximately 15 minutes before the design review, so they had a limited amount of time to update their sketches in preparation for the design reviews. However, students spent a total of 1–2 hours on their design sketches overall prior to the design review, meaning they had 25%–12.5% of their overall design time to iterate. We believe there should be an optimal amount of time required for students to prepare design sketches for design reviews, but were unable to find that information in existing literature. Future studies should focus on how timing of notification affects the quality of design sketches prepared for design reviews and determining the optimal time to notify students of an upcoming swap, such that they have some ownership over their designs but are still willing to let others build them. Finally, the issue of ecological validity must be discussed since this experiment was integrated into an existing summer program with a set curriculum. This improves the ecological validity of the study, but makes a pure quasi-experimental design more difficult to achieve. Future studies with an experimental design and settings that resemble traditional classroom educational settings may provide additional insights into the effects of design swapping on the quality of the design documentation produced by students. Future studies should also be conducted with undergraduate students to determine the transferability of the benefits of this pedagogical strategy to an undergraduate engineering education context.

6. Conclusions

Based on the results of this study, we recommend that teachers and faculty use this technique in middle and high school settings, and that it be tried in undergraduate settings. Comparisons of quality scores indicated that prior notification of design swapping improves the quality of student design documentation, and student feedback on the design swapping experience indicated an overall satisfaction with the experience, improved teaming experience, and increased opportunities for learning and improving the quality of design documentation. Design swapping is a viable pedagogical strategy to encourage students to generate higher-quality design documentation, and provides students with a surrogate client in the absence of a real client. Results of this study with middle and high school students can potentially have a major impact on the undergraduate engineering education. The positive feedback and improved quality of design documentation produced by participants suggest a future research question: will our undergraduates produce higher-quality design documentation if challenged with swapping designs? These results can help to inform design process structure for faculty teaching design to undergraduates or secondary students, in addition to those wishing to simulate the separation of design and manufacturing engineering in the undergraduate curriculum.

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Appendices

Design sketch quality rubric

Factors	None	Some	Most
Team number and name	Neither team number nor team name	Team number or team name	Both team number and team name
Step realism/recognizability	None of the step sketches are realistic or recognizable	Some of the step sketches are realistic and recognizable	Most of the step sketches are realistic and recognizable
Step scale	None of the steps are drawn to scale	Some of the steps are drawn to scale	Most of the steps are drawn to scale
Step sequence labels (A, B, C...; 1, 2, 3...)	None of the step sequence was labeled	Some of the step sequence was labeled	Most of the step sequence was labeled
Component labels (e.g., ball, dominoes, car)	No components were labeled with text	Some components were labeled with text	Most components were labeled with text
Step descriptions	No steps described in text form	Some steps described in text form	Most steps described in text form
Functional indicators (e.g., arrows)	No steps had functional indicators to show motion	Some steps had functional indicators to show motion	Most steps had functional indicators to show motion
Neatness (e.g., line quality, edges, readability, smudges)	None of the design is sketched neatly	Some of the design is sketched neatly	Most of the design is sketched neatly

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