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Exploring the Effects of Variations in the Timing of a Sustainable Design Educational Intervention*

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The accelerating depletion of natural resources has brought environmental sustainability to the forefront of engineering and therefore, design educators must integrate sustainability into the engineering design curriculum. Several researchers have proposed educational interventions and design tools for sustainable design education. The timing of introducing such interventions, particularly in project-based courses, could influence the effectiveness of these interventions, and these effects remain largely unexplored. Our aim in this research is to investigate this research gap through a mixed-methods experiment conducted with first-year engineering design students. Specifically, we introduced a two-day module on sustainable design either in the first or sixth week of an 8-week long design project. The effects of this variation were compared by analyzing (1) changes in students' trait empathy, (2) changes in their beliefs, attitudes, and intentions towards sustainability, and (3) their responses to a reflection assignment collected at the end of the semester/design project. From the results, we see that the timing of the sustainable design intervention did not relate to changes in students' trait empathy or their beliefs, attitudes, and intentions towards sustainability. However, students from both timing conditions reported significant increases in their attitudes and intentions towards sustainable action. Finally, students who received the intervention later more frequently mentioned the use of sustainable design heuristics in their reflection responses. Taken together, these findings suggest the need for educators to consider the timing of sustainable design interventions, especially when integrating them into longer project-based courses.

Keywords: engineering design education; sustainability; empathy; student experiences

1. Introduction

Over the past decade, there has been a push to reform engineering education from primarily focusing on technical skills towards the development of 'holistic' engineering educational practices [1–3]. This approach emphasizes exposing engineering students to global economic, social, and environmental issues through project-based learning [1, 4, 5]. Given the ever-increasing importance of sustainability in engineering [6], several researchers proposed interventions for integrating sustainability into engineering education [7–10], and in particular engineering design education [11]. These interventions range from shorter modules and workshops (e.g., see [12–14]), to semester-long courses [15] and specialized programs at the undergraduate and graduate levels [16–20]. Moreover, researchers have identified the need to develop competencies beyond technical skills (e.g., "engaging and connecting with diverse individuals") through sustainable design education [20].

In addition to several formal educational interventions, researchers have also proposed design tools and methods to support designers – especially, novice designers – to integrate sustainability into the design process. For example, Ross et al. [21] present a study exploring the effects of introducing design-for-the-environment guidelines during the conceptual design stage. They observe that designers who were provided with these guidelines better integrated sustainability into their decision-making process. Similarly, Luiz-Pastor et al. [22] and Maccioni et al. [23] present a series of studies exploring the relationship between creativity and sustainable design. While the former demonstrates the possible role of motivation and problem affinity on designers' problem-solving strategies, the latter suggests a method for extracting sustainable design heuristics by analyzing designer behavior. To help designers effectively apply sustainable design tools, researchers have also attempted to consolidate the constantly growing number of sustainable design guidelines and heuristics to identify common themes [24]. These efforts have helped designers easily seek and apply appropriate sustainable

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design tools in different design contexts [25]. Faludi [26] further extend their review to include the need for sustainability-focused mindsets among designers and emphasize the importance of thinking about sustainability in a broader context, an argument made by other researchers [10].

Despite these efforts towards integrating sustainability into engineering design education and practice, little attention is given to the timing of these interventions, particularly, when positioned in longer project-based courses. Prior research suggests that the timing of educational interventions could influence designers' learning of new knowledge [27]. Moreover, research suggests that the timing of information introduction could also influence designers' use of this knowledge at different stages of the design process [28]. However, limited research has explored the effects of the timing of sustainable design educational interventions on student learning, and our aim in this paper is to investigate this research gap. Specifically, we aim to investigate whether the timing of a sustainable design educational intervention placed in a larger design project relates to (1) changes in students' trait empathy, (2) changes in their beliefs, attitudes, and intentions towards environmental sustainability, and (3) their reflections on the utility of the intervention in the context of the longer design project.

Towards this research aim, we first present a review of prior work that informed this research in the next section. In Section 3, we present the research questions we seek to explore in this research, and our predicted hypotheses. This section is followed by a discussion of the experimental methods used to answer the research questions, presented in Section 4. The data collected from the experiment are analyzed using qualitative and quantitative methods, and the details of the analyses as well as the corresponding results are presented in Section 5. Next, the implications of these results for design education are discussed in Section 6 followed by concluding remarks in Section 7, and limitations and directions for future work presented in Section 8.

2. Related Work

Our aim in this research is to investigate the impact of the timing of a sustainable design educational intervention on (1) students' trait empathy, (2) their beliefs, attitudes, and intentions towards sustainability, and (3) their perceived utility of the intervention. Before doing so, prior research on individual differences in sustainable design and the importance of timing of educational interventions is reviewed, as discussed next.

2.1 Role of Individual Differences and Interpersonal Skills in Sustainability Education

Individual differences and interpersonal skills have been identified as important predictors of behavior in several contexts, including pro-environmental [29] and pro-social behavior [30, 31]. One such individual difference observed to be related to pro-environmental behavior is an individual's empathy, or "the reactions of one individual to the observed experiences of another" ([32, p. 183], p. 113). Empathy has been reported to be a core component of engineering design education as it can help student designers to develop a deeper understanding of the design problem and the stakeholders involved. For example, Fila and Hess [33] conducted a qualitative study in which they observe that designers' empathic tendencies relate to effective teamwork and design inspiration.

Similarly, researchers in environmental psychology and sociology observe that empathy development can be a stimulant to pro-social and pro-environmental behavior [34, 35]. Therefore, empathy and empathy development could be used as potential mechanisms to teach future designers about the importance of integrating sustainability into the design process. This potential could be particularly important when teaching sustainability to certain demographics of students, as designers' ability to empathize with the user is strongly impacted by their prior experiences [36]. For example, designers in western regions might have limited experiences with the negative effects of sustainability compared to other parts of the world. Therefore, empathy invoking educational interventions could help emphasize the criticality of these issues among students with little prior experience with sustainability. Prior research in design also suggests that designers' empathy could be related to the evaluations of the sustainability of their solutions [37].

In addition to empathy, individuals' beliefs, attitudes, and intentions toward sustainability have also been shown to predict pro-environmental behavior [38]. Specifically, beliefs represent an individual's inherent beliefs about the need for sustainable actions and one's ability to take such action [39, 40]. Similarly, attitudes represent one's tendency to engage in certain actions in the present [41–43] whereas intentions represent one's tendency to engage in certain actions and behaviors in the future. For example, Kaiser et al. [44] discuss that positive attitudes towards the environment positively predicted ecological behavior. In the context of engineering design, prior research reported that student designers' intentions towards sustainable actions positively correlated with their identification of environment-focused requirements [45].

These findings suggest that student designers' beliefs, attitudes, and intentions towards sustainability could influence their motivation to learn about and practice sustainable design. Consequently, design education might be more effective if these efforts have a positive impact on students' beliefs, attitudes, and intentions towards sustainability.

Taken together, the effectiveness of interventions in sustainable design education could hinge on the influence of students' individual differences and interpersonal skills. Such effects could particularly manifest in the context of sustainability since the outcomes of sustainable design might not always directly benefit the designer. However, limited research has explored how educational interventions could be formulated to positively influence students' trait empathy and their beliefs, attitudes, and intentions towards sustainability. Furthermore, limited research has investigated the effect of the timing of sustainable design educational interventions on these individual differences and our aim in this research is to investigate this gap. Before doing so, prior research on the role of timing of educational interventions is reviewed, as discussed next.

2.2 Influence of Timing on Learning and Domain Knowledge Use in Engineering Design

Domain knowledge plays an important role at different stages of the design process. For example, the Concept-Knowledge Theory of Design [46, 47] proposes two distinct spaces that comprise one's design approach: (1) the knowledge (K-) space and (2) the concept (C-) space. While the K-space represents all the existing knowledge available to the designers, the C-space represents all the new concepts or solutions generated through the design process. Moreover, the C-K theory suggests that designers operate to transition between or within the two spaces to identify concepts (i.e., new propositions) based on knowledge (i.e., existing propositions). Similarly, Amabile's [48] Componential Model of Creativity suggests that domain knowledge and domain-relevant skills play an important role in creative cognition. Specifically, the model suggests that designers employ domain knowledge and skills in two stages of the creative process. First, designers collect domain knowledge to prepare a set of information that can help them generate solutions. Second, designers employ domain knowledge to evaluate their solutions in the solution validation stage, and these evaluations are used to assess the success of the creative process. Both these stages are analogous to the $C \rightarrow K$ and the $K \rightarrow C$ operators in the C-K Theory [49]. From these models, we see that designers employ domain knowledge at different stages of the design process and that the purpose of employing domain knowledge could vary based on the stage in which it is used. Moreover, we can also infer that different domains of knowledge might be useful at different stages of the design process. For example, while some domains of knowledge might help designers generate solutions, other domains might help them effectively validate solutions. Therefore, the stage of the design process in which new knowledge is introduced to designers could influence the utility of said knowledge.

In addition to the use of different domain knowledge in different stages of the design process, the timing of an educational intervention could also influence designers' learning of new concepts. Specifically, prior research suggests that providing learners with multiple opportunities for information recall supports the deeper processing of the information [50]. The deep processing of information, in turn, results in effective learning and successful future recall of information. Furthermore, researchers suggest that repeated recall through external cues – e.g., through tests – could also lead to more effective learning [51]. Therefore, introducing a sustainable design educational intervention earlier in time could provide students with more opportunities to apply the various design heuristics at different stages of the design process (e.g., problem definition, concept generation, and concept selection). This repeated, externally cued recall could, in turn, result in better learning of the concepts, especially at future points in time.

Taken together, we see that the timing of design educational interventions could influence student designers' learning and their use of domain knowledge in the design process. Consequently, the timing of a sustainable design educational intervention relative to the different stages of a longer design project could influence the outcomes of said intervention. However, little research has investigated the effects of the timing of sustainable design educational interventions and our aim in this research is to investigate these effects. Towards this aim, we seek to answer the RQs presented next.

3. Research Questions

Our aim in this research is to explore the effects of the timing of a sustainable design educational intervention on changes in student designers' individual differences and their perceived utility of the intervention. Towards this aim, we seek answers to the following RQs:

- *RQ1: Does the timing of a sustainable design educational intervention relate to changes in students' trait empathy, and if so, how?* We hypothe-

size that students who receive the sustainable design intervention earlier in the project would report greater increases in their trait empathy. Prior research suggests the importance of components of trait empathy in effectively identifying problem requirements [52, 53], especially in human-centered design projects [54]. Therefore, introducing the sustainable design intervention earlier in the design project – when designers are identifying problem requirements for their 8-week-long design projects – could help them gain experience with empathizing with the target users, thereby increasing their trait empathy.

- *RQ2: Does the timing of the sustainable design educational intervention relate to changes in students' beliefs, attitudes, and intentions towards sustainability, and if so, how?* We hypothesize that introducing the sustainable design educational intervention earlier in the design project would have a greater positive impact on students' beliefs, attitudes, and intentions towards sustainability. Prior work suggests that providing students with multiple opportunities for cued recall results in better information processing and learning [50]. Therefore, introducing the intervention earlier could provide students with more opportunities to apply sustainable design techniques to their projects, thereby reinforcing their tendency to act sustainability.
- *RQ3: Does the timing of the sustainable design educational intervention relate to students' reflections on the utility of the intervention, and if so, how?* We hypothesize that introducing the sustainable design educational intervention earlier in the design project would result in students' reporting a higher perceived utility of the intervention. This hypothesis is based on previous research which suggests that providing students with multiple opportunities for information recall supports the deeper processing of the information [55]. Therefore, the earlier introduction of the intervention could provide students with more opportunities to apply sustainable design knowledge at various stages of the design process. These opportunities to apply the new information could result in more positive perceptions of the utility of the intervention.

To test these hypotheses, we conducted an experimental study with novice designers and the details of the experiment are discussed next.

4. Experimental Methods

To answer our RQs, we conducted an experiment with student designers in the form of a sustainable design workshop. The experiment was reviewed and approved by the Institutional Review Board before it was conducted. The details of the experiment are discussed next.

4.1 Participants

Participants in this study (N = 87) were recruited from a first-year introductory Engineering Design course at a large public university in the northeastern United States. The participants primarily comprised first-year engineering students (n = 70), with five students in their second year, one student each in their third and fourth year, and some participants missing information about their year of study. The participants were recruited from four sections (two in the fall semester and two in the spring semester) of the first-year course with all sections having the same instructor and following the same course structure. Students from this first-year design course were selected for this study since both empathy and sustainability are part of the learning outcomes of this course [56, 57]. Moreover, the course encourages students "to identify affected stakeholders and their needs, and incorporate those needs into the project description and design goals" (p.3, [58]). However, we acknowledge that the choice of participants being primarily in their first year of study is a potential limitation of this research and future work will expand our findings towards students with different levels of experience.

4.2 Procedure

The experiment was introduced as a module on sustainable design in four sections (two in the fall and two in the spring semester) of a semester-long introductory Engineering Design course. The course includes a 1-week introductory design project, a 2-week 'making' project, a 2-week introduction to SolidWorks, a 2-week project on advanced SolidWorks, and an 8-week design project focused on redesigning the grocery store experience. For the 8-week-long project, students are introduced to the complete design process starting with the identification of problem needs to prototyping and testing solutions. Additionally, sustainability is an important aspect of the course, and previous offerings of the course have included modules on sustainable design [59]. The intervention investigated in this study was introduced in place of this sustainable design module and was placed within the 8-week-long design project.

While the overall structure of the intervention was the same between the four sections, the key difference between the two semesters was the timing of the intervention in the 8-week-long design project. While the experiment in the fall semester was conducted in Week 6 of the design project, the experi-

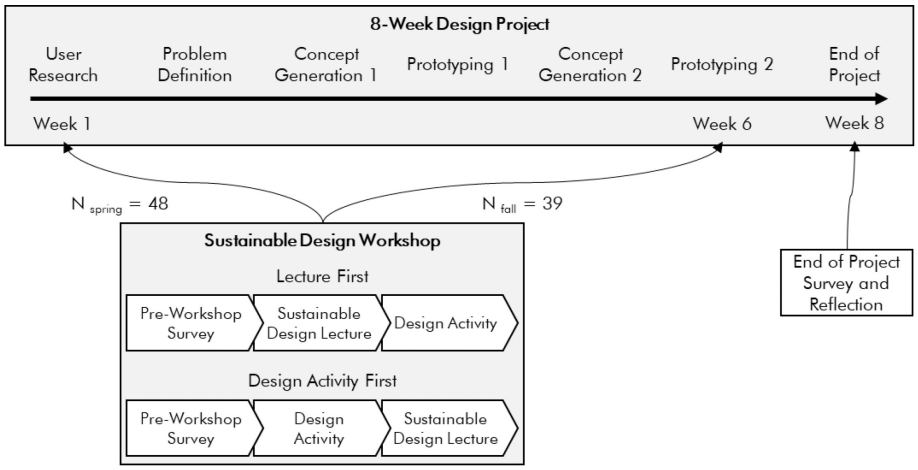

Fig. 1. Overview of the experimental procedure followed in the study.

ment in the spring semester was conducted in Week 1 of the design project. The overall experimental procedure and its placement within the longer design project are presented in Fig. 1, and the various stages of the experiment are discussed next.

4.2.1 Pre-intervention Survey

First, students were asked to complete a pre-intervention survey in which they were asked to report (1) their demographic information (e.g., year of study and gender), (2) their responses to the 28-item Interpersonal Reactivity Index (IRI) measuring their trait empathy (see Section 4.3.1), and (3) their responses to the 25-item survey measuring their beliefs, attitudes, and intentions toward sustainability (see Section 4.3.1). Students' responses to the pre-intervention survey were used as a baseline for these constructs and were used to answer RQs 1 and 2.

4.2.2 Sustainable Design Lecture

Next, students were introduced to sustainable design and the United Nations Sustainable Development Goals (UN SDGs) through a short 10-minute lecture. In this lecture, the instructor briefly discussed lifecycle assessment, 'cradle to grave' solutions, and Blevis's [60] ten sustainable design principles: (1) disposal, (2) salvage, (3) recycle, (4) remanufacture for reuse, (5) reuse as is, (6) longevity, (7) sharing for maximal use, (8) achieving heirloom status, (9) finding wholesome alternatives, and (10) active repair of misuse. These design principles were chosen in part due to their alignment with Telenko et al.'s [24] design for the environment strategies. The 17 UN SDGs were presented to the students with a special focus on SDG #6: Clean Water and Sanitation, due to its alignment with the design activity that followed. Additionally, it should be noted that the sustainable design lecture was developed as part of a series of studies (e.g., [45, 61]) and was based on the sustainable design module offered as part of previous iterations of the introductory engineering design course.

4.2.3 Design Activity

After attending the lecture, students were asked to individually complete a design activity comprising four stages: (1) problem introduction, (2) problem requirement identification and definition, (3) concept generation, and (4) concept evaluation and selection. First, they were introduced to the design problem and its context. The problem and persona developed in [45] were used in this study. As part of the design task, the students were asked to improve access to clean water and sanitation for a family in remote Sub-Saharan Africa. In addition to this design objective, participants were given a fictitious persona with information such as access to natural sources of water, profession, and income. Any questions related to the problem were answered before moving to the next stage.

Next, students were asked to generate problem requirements based on the design problem. Specifically, they were asked to generate up to five problem requirements and use the Analytical Hierarchy Process (AHP) Chart to organize the importance of each requirement. Students were then asked to individually ideate solutions for the design problem. They were asked to generate as many solutions as they had time for by sketching their solution and describing their solutions using text. Students were also asked to record the strengths and weaknesses of each solution. Finally, students were asked to complete a concept scoring matrix to select one best idea to move forward with, based on which idea most successfully met their problem requirements.

4.2.4 End of Semester Survey and Reflection Essay

At the end of the semester, students were asked to complete an end-of-semester survey capturing their trait empathy and their attitudes towards sustainability using the same measures as the pre-intervention survey (see Section 4.2.1). Students were also asked to submit an essay reflecting on the sustainable design workshop in which they were asked to reflect on the following: (1) their experiences with the workshop, (2) the impact of the workshop on their final design outcomes in your grocery experience project, (3) the impact of the workshop on the ability to empathize with your user for your grocery experience project, and (4) how they incorporated concepts of lifecycle assessment in their grocery experience project. The students' survey responses were used to answer the first and second RQs, whereas their reflection essays were qualitatively analyzed to answer RQ3. The details of the metrics and coding schemes used in our study are discussed next.

4.3 Metrics and Coding Schemes

Two metrics were used in our study: (1) a quantitative survey and (2) a qualitative analysis of students' reflection essays. The details of each metric are discussed next.

4.3.1 Survey Instruments

The students' trait empathy and their beliefs, attitudes, and intentions towards sustainability were measured using two scales:

1. *Interpersonal Reactivity Index (IRI):* Using the framework proposed in [62], we aimed to measure empathy conceptualized as students' empathic orientation and operationalized as their empathic tendencies. Therefore, we measured students' trait empathy using the Interpersonal Reactivity Index [32]. The 28-item survey measures trait empathy on four components: (1) perspective-taking, (2) fantasy, (3) empathic concern, and (4) personal distress. This measure has been used in previous research studying the empathy of engineering design students (e.g., see [54, 63, 64]). The reliability of the students' responses was tested through an observed Cronbach's α [65] > 0.7 for each subscale.
2. *Beliefs, Attitudes, and Intentions towards Sustainability:* Prior research suggests that individuals' beliefs, attitudes, and intentions towards action are strong indicators of their behavior and their tendency to take said action [40]. This role of beliefs, attitudes, and intentions is particularly seen in the contest of prosocial and pro-environmental behavior [66]; individuals who report more positive attitudes towards pro-social and pro-environmental behavior also tend to act more altruistically and sustainably [66]. Students' beliefs, attitudes, and intentions towards sustainability were measured using the 25-item survey proposed by Tang [41]. The survey measures both, individuals' beliefs about the need for environmental sustainability, and their tendency to act pro-environmentally in the present (i.e., attitudes) and future (i.e., intentions). The reliability of the responses was tested through an observed Cronbach's α [65] > 0.7 for each component.

4.3.2 Coding Scheme for Reflection Essays

Students' reflection essays were analyzed using abductive content analysis [67]. In this approach, prior literature is used as a foundation for the coding while also considering that each individual views the world differently [68]. Specifically, the authors generated an initial codebook using prior research – in this case on empathy and sustainability – as a baseline. This initial codebook was then adjusted based on any new themes observed in the data. The data were coded by an Assistant Professor of Industrial Engineering using the codebook presented in [69]. The validity of the ratings was established through sequential testing of interrater reliability. Specifically, the primary rater coded an overlapping subset of 10% of the data with a second rater (an Assistant Professor of Engineering Design) and a second overlapping subset of 10% of the data with a third rater (an Assistant Professor of Mechanical Engineering). Acceptable interrater reliability [70] was observed between the primary and secondary raters (Cohen's Kappa = 0.67 and 0.62, respectively), and therefore, the primary rater coded the remaining data.

5. Data Analysis and Results

The data collected from the experiments were analyzed using statistical methods. The statistical tests used to answer the various RQs along with the results are presented in the remainder of this section. It should be notated that only 77 of the total 87 students completed both, the pre-intervention and end-of-semester surveys and therefore, data from this subset was used for the analyses for RQs 1 and 2.

5.1 RQ1: Does the timing of the sustainable design educational intervention relate to changes in students' trait empathy, and if so, how?

We hypothesize that introducing the sustainable design educational intervention earlier in the

Table 1. Comparing changes in students' trait empathy between the two sections

Variable	*F*	*p*	*Partial* η^2
Perspective Taking			
Time (Pre-Intervention vs End-of-Semester)	0.14	0.71	<0.01
Timing in the Project (Week 1 vs Week 6)	2.19	0.14	0.03
Time X Timing	0.02	0.88	<0.01
Fantasy			
Time (Pre-Intervention vs End-of-Semester)	1.87	0.18	0.02
Timing in the Project (Week 1 vs Week 6)*	**4.27**	**0.04**	**0.05**
Time X Timing	0.90	0.35	0.01
Empathic Concern			
Time (Pre-Intervention vs End-of-Semester)	0.29	0.59	<0.01
Timing in the Project (Week 1 vs Week 6)	2.64	0.11	0.03
Time X Timing	<0.01	0.96	<0.01
Personal Distress			
Time (Pre-Intervention vs End-of-Semester)	2.67	0.11	0.03
Timing in the Project (Week 1 vs Week 6)	1.10	0.30	0.02
Time X Timing	2.15	0.15	0.03

* Indicates $p < 0.05$.

design project would lead to a greater increase in trait empathy. To test this hypothesis, first, we performed a three-way mixed ANOVA to test for interaction effects. Specifically, the four components of students' trait empathy were used as the dependent variables. The timing in the project (i.e., Weeks 1 and 6) and treatment condition (i.e., lecture first and design activity first) were used as the between-subjects variables. Finally, time (i.e., pre-intervention and end of the semester) was used as the within-subjects variable.

We did not observe any significant three-way interaction effects between time, the timing in the design project, and the treatment group ($p > 0.05$). Therefore, only the effects of the timing of the intervention in the design project (i.e., Weeks 1 and 6) and time (i.e., pre-intervention and end-of-semester) were tested through a series of two-way mixed ANOVA. From the results, summarized in Table 1 and Fig. 2, we see a significant impact of the timing in the project (Week 1 vs Week 6) on students' fantasy tendencies, with students receiving the workshop earlier in the project (Week 1) reporting an increase in their fantasy tendencies compared to students that received the workshop later in the project (Week 6). However, we see no significant effects of time or timing in the design project on all other components of students' trait

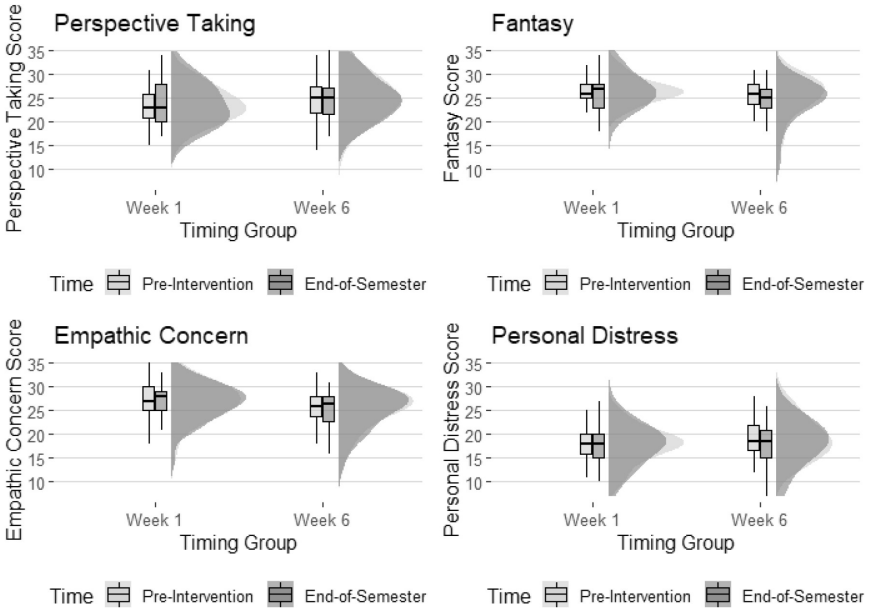

Fig. 2. Changes in students' trait empathy from before the intervention to the end of the semester.

empathy. The implications of these results are discussed in Section 6.

5.2 RQ2: Does the timing of the sustainable design educational intervention relate to changes in students' beliefs, attitudes, and intentions towards sustainability, and if so, how?

We hypothesize that introducing the sustainable design educational intervention earlier in the design project would have a greater positive impact on students' beliefs, attitudes, and intentions towards sustainability. To test this hypothesis, first, we performed a three-way mixed ANOVA to test for interaction effects. Specifically, students' beliefs, attitudes, and intentions towards sustainability were used as the dependent variables. The timing in the project (i.e., Weeks 1 and 6) and treatment condition (i.e., lecture first and design activity first) were used as the between-subjects variables. Finally, time (i.e., pre-intervention and end of the semester) was used as the within-subjects variable.

We did not observe any significant three-way interaction effects between time, the timing in the design project, and the treatment group on students' trait empathy ($p > 0.05$). Therefore, the treatment condition was removed from the model and only the main effects of the timing of the intervention in the design project and time (i.e., pre-intervention and end-of-semester) were tested through a series of two-way mixed measures ANOVA. From the results, summarized in Table 2 and Fig. 3 we see that students reported a significant increase in their attitudes and intentions towards sustainable action. This positive change was not related to the timing of the intervention (Week 1 vs Week 6 of the project), thereby refuting our hypothesis. The implications of these results are discussed in Section 6.

5.3 RQ3: Does the timing of the sustainable design educational intervention relate to students' reflections on the utility of the intervention, and if so, how?

We hypothesize that introducing the sustainable design educational intervention earlier in the project would relate to more positive perceptions of the utility of the intervention. To test this hypothesis, students' reflection responses collected at the end of the semester were qualitatively analyzed using abductive content analyses (see Section 4.3.2 for details about the coding scheme).

As part of this analysis, we first aimed to test whether the timing of the intervention in the design

Table 2. Comparing changes in students' attitudes towards sustainability between the two sections

Variable	*F*	*p*	*Partial* η^2
Beliefs			
Time (Pre-Intervention vs End-of-Semester)	0.57	0.45	<0.01
Timing in the Project (Week 1 vs Week 6)	0.08	0.79	<0.01
Time X Timing	0.13	0.72	<0.01
Attitudes			
Time (Pre-Intervention vs End-of-Semester)*	**10.51**	**<0.01**	**0.12**
Timing in the Project (Week 1 vs Week 6)	0.10	0.76	<0.01
Time X Timing	0.09	0.76	<0.01
Intentions			
Time (Pre-Intervention vs End-of-Semester)*	**26.26**	**<0.01**	**0.26**
Timing in the Project (Week 1 vs Week 6)	0.18	0.67	<0.01
Time X Timing	1.03	0.31	0.01

* Indicates $p < 0.05$.

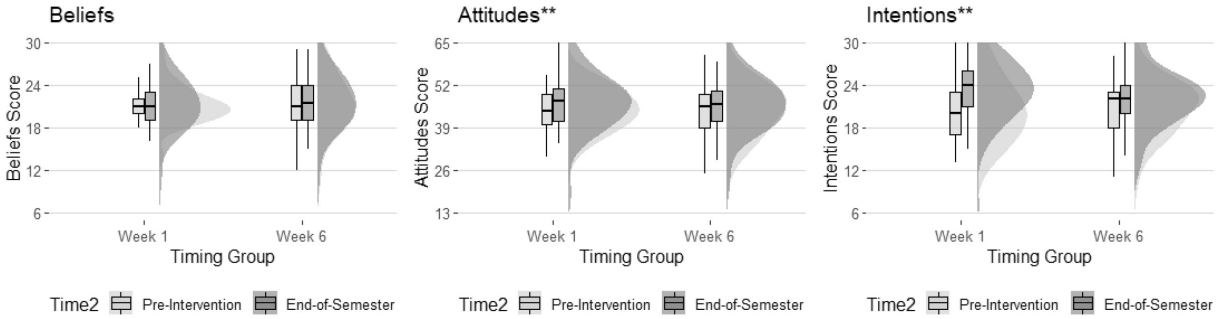

Fig. 3. Changes in students' beliefs, attitudes, and intentions towards sustainability.

project related to the number of students that discuss the various sustainable design and empathy-related concepts in their reflection responses. Therefore, we investigated the percentage of students from each group that discussed the various nodes from our codebook. From the results of this analysis, we see that a majority of students (n = 83) reported positive experiences with the intervention, irrespective of its timing. For example, participant 49, who completed the activity in Week 1, reported, "I thought that the sustainability design challenge was a good introduction to the design process and other concepts we discussed later in the course." Similarly, participant 37, who completed the activity in Week 6, mentioned, "[the workshop] was a very interesting and unique experience; a lot of factors were considered in the design challenge that I haven't really considered before." This finding highlights the importance of introducing explicit and formal educational interventions focused on sustainable design in engineering design education.

Additionally, we see that the timing of the intervention within the project (Week 1 vs Week 6) did not relate to the percentage of students that discussed the relationship between sustainable design and the different design stages (see Fig. 4). Similarly, similar portions of students from the two groups discussed the different sustainable design heuristics in their reflection responses (see Fig. 5). Finally, we see no differences in the percentage of students from the two groups that discussed either empathy or their beliefs, attitudes, and intentions towards sustainability. Taken together, these results suggest that irrespective of the timing of intervention in the design project, a similar proportion of students discuss the various sustainable design and interpersonal concepts in their reflection responses.

From the first part of the analysis, we observe that the timing of the intervention did not relate to the number of students within each group that discuss the various sustainable design concepts or the interpersonal concepts (i.e., trait empathy and beliefs, attitudes, and intentions towards sustainability). However, to further understand the extent to which students reflected on these concepts, we investigated the frequency of occurrence of each node, normalized by the number of participants within each group. From the results, we see that the timing of the intervention did relate to the frequency of occurrence of the various nodes.

Specifically, we observe that students' beliefs,

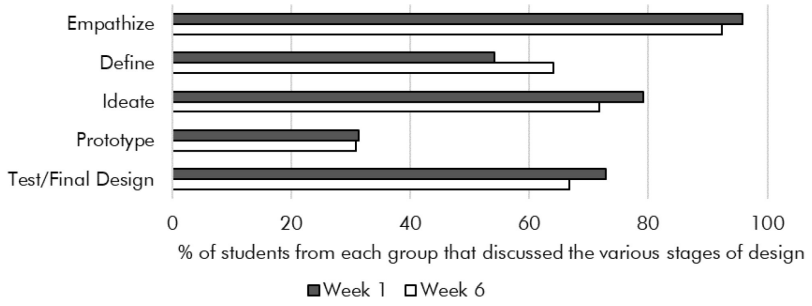

Fig. 4. Percentage of students in each group that discussed the relationship between the sustainable design workshop and the five stages of design.

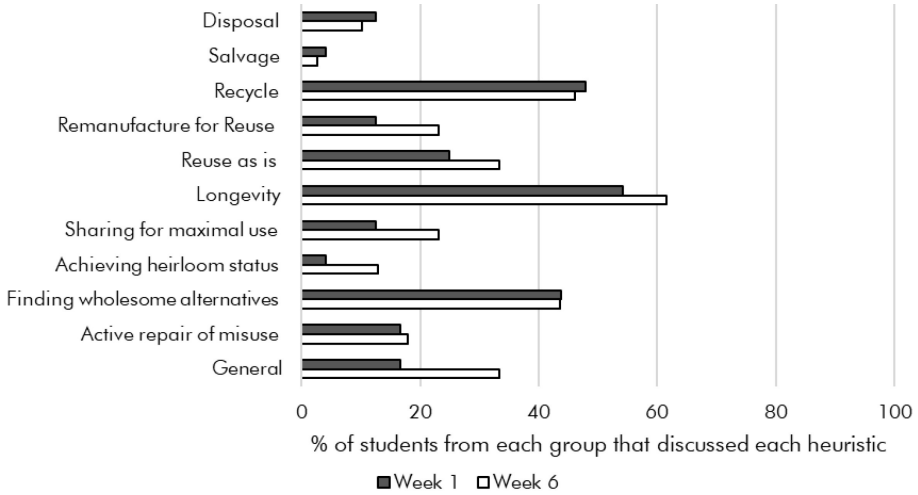

Fig. 5. Percentage of participants in each group that discussed the ten sustainable design heuristics.

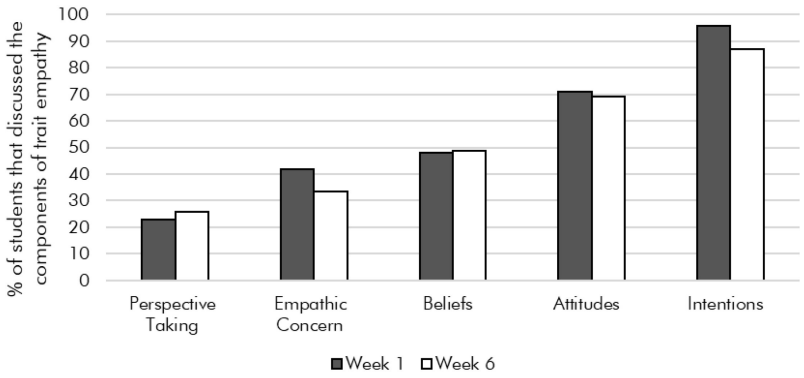

Fig. 6. Percentage of participants in each group that discussed empathy and beliefs, attitudes, and intentions towards sustainability.

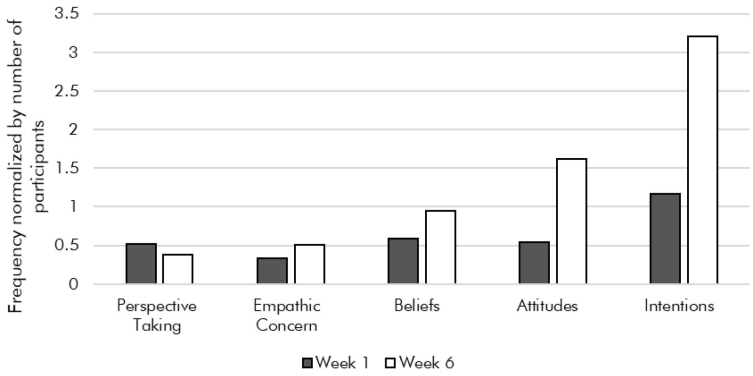

Fig. 7. Frequency of occurrence of the components of trait empathy and beliefs, attitudes, and intentions towards sustainability in students' reflection responses (normalized by the total number of participants in each group)

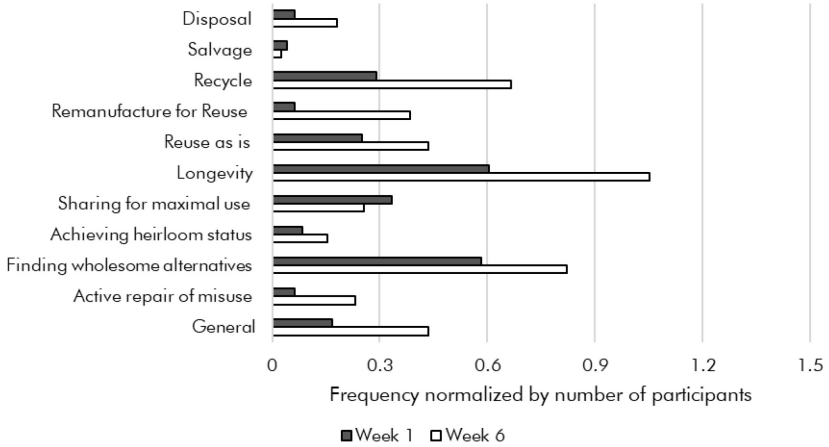

Fig. 8. Frequency of occurrence of the ten sustainable design heuristics in students' reflection responses (normalized by the number of participants in each group).

attitudes, and intentions towards sustainability were more frequently discussed by students who received the intervention later in the project (Week 6) compared to those who received the intervention earlier (Week 1), see Fig. 7. We also see that the timing of the intervention did not relate to students' reflections on their trait empathy (see Fig. 6 and Fig. 7). Despite the lack of differences, one interesting finding is that none of the participants explicitly discussed the trait empathy components of personal distress or fantasy.

Additionally, the timing of the intervention related to students' reported usage of the sustainable design heuristics. Specifically, students who received the intervention *later* discussed a majority of the ten sustainable design heuristics to a greater extent compared to those who received the intervention *earlier* (see Fig. 8). Taken together, we see

that while the timing of the intervention in the semester did not relate to the number of students that discussed the sustainable design and interpersonal concepts, it did relate to the extent to which they discussed these concepts in their reflection responses. The implications of these results for design education are discussed in Section 6.

6. Implications of Results on Engineering Design Education

Our aim in this research is to investigate the relationship between the timing of a sustainable design educational intervention and (1) changes in students' trait empathy, (2) changes in their beliefs, attitudes, and intentions towards sustainability, and (3) their reflections on the utility of the intervention. Towards this aim, we conducted an experiment with student designers and three main findings were observed:

- The timing of the intervention did not have a significant relationship with changes in students' trait empathy.
- Students reported a significant increase in their attitudes and intentions towards sustainable action, irrespective of the timing of the intervention.
- Introducing the intervention *later* in the project related to the higher reported use of sustainable design heuristics.

The implications of these findings are discussed next.

6.1 The timing of the sustainable design intervention did not relate to changes in students' trait empathy

The first key finding from the results is that the timing of the intervention did not have a significant effect on changes in students' trait empathy from before the intervention to the end of the semester. This result refutes our hypothesis that students who receive the sustainable design intervention earlier in the project would report a greater increase in their trait empathy. This result could be attributed to the fact that the intervention did not explicitly ask students to consider sustainable design in relation to their empathy. Additionally, students were not asked to explicitly use their empathy in the design activity; this lack of explicit instruction could have resulted in limited empathy development. For example, prior research suggests that involving empathy-evoking interventions (e.g., providing simulated scenarios) could increase designers' perceived ability to understand the end-user compared to designers who were simply briefed about the user [71, 72]. This line of research also suggests that such empathy-invoking interventions could help students better identify the latent needs of users [73, 74], and therefore, could provide more opportunities for empathy development.

Similarly, this lack of significant effects could be attributed to the difference between the focus of the design prompt used in the sustainable design intervention (i.e., clean water and sanitation) and the prompt used for the 8-week design project (i.e., redesigning the grocery store experience). Although both these prompts are human-centered and involve empathizing with the user, the difference in context and setting could have acted as a barrier to the students' ability to transfer learnings from the sustainable design intervention to the semester-long project. This inference calls for further research into the role of problem context and setting on students' learning and transfer of knowledge between design experiences. Such future work could also investigate the effects of variations in the content of the sustainable design lecture. For instance, students could be introduced to sustainable design heuristics that are more relevant to the 8-week ling design project in an attempt to highlight the relevance of the heuristics and encourage more effective application. Additionally, this lack of change in empathy in the sample studied could also be explained by prior research which suggests that trait empathy is a stable construct and could be resistant to variations due to external factors [75, 76].

Taken together, these findings suggest that the timing of the currently studied intervention may not significantly contribute towards developing empathy in the context of sustainability. These findings call for further research into the formulation of effective sustainable design educational interventions that encourage empathy development through explicit instruction and targeted pedagogical strategies.

6.2 Students reported a significant increase in their attitudes and intentions towards sustainable action

The second key finding is that irrespective of the timing of the intervention, students reported a significant increase in their attitudes and intentions towards sustainable action. The measure of 'attitudes' towards sustainable action used in this study measures one's tendency to act sustainably in the present. Similarly, the measure of 'intentions' towards sustainable action used in this study measures one's self-direction to act sustainably in the future. Prior research suggests that one's attitudes and intentions towards actions – especially towards pro-environmental action – strongly predict their behavior and their tendency to take such action [66]. Therefore, the increase in students' attitudes and intentions towards sustainable action from

before to after participating in the intervention is a positive outcome as it suggests that the intervention could encourage them to actively engage in sustainable action.

Specifically, this result indicates that such an educational intervention has the potential to encourage students' active consideration of environmental sustainability in engineering design. Additionally, the finding that similar, positive changes were observed among both groups of students (i.e., students who received the intervention in Weeks 1 and 6) suggests that the timing of the intervention does not significantly impact the positive change. This finding could be attributed to the higher sensitivity of students' attitudes and intentions towards sustainable action to external nudges. That is, even interventions of relatively small duration and intensity could have a large impact on students' attitudes and intentions towards sustainable action. This inference is partially observed in the results of RQ2; the effect size for the relationship between time and students' intentions towards sustainable action was of moderate size (partial $\eta^2 = 0.26$). This finding, therefore, indicates the importance of explicitly including sustainable design interventions in engineering design education, even if the interventions are introductory and short in duration.

6.3 Introducing the intervention later in the project related to the higher reported use of sustainable design heuristics

The third key finding from our study is that the timing of the intervention is related to students' reported use of the sustainable design heuristics. Specifically, students who received the intervention later discussed the sustainable design heuristics more frequently compared to those who received the intervention earlier. Similarly, students who received the intervention later in the design project discussed their beliefs, attitudes, and intentions towards sustainability more frequently compared to those who received the intervention earlier.

These findings could be attributed to the recency with which students were exposed to the intervention. Notably, both groups of students completed the reflection essay at the end of the project. Therefore, students who received the intervention later had a more recent experience with the sustainability concepts compared to those who received it earlier in the design project. As a result, they might have been able to better reflect on their attitudes, beliefs, and intentions towards sustainability compared to students who received the intervention earlier. This finding corroborates previous research arguing that as time passes, it gets more difficult for individuals to retrieve information [77]. The difficulty in recalling such experiences can be caused by factors such as context shifts [78], information decay as time passes [79], and interferences [80]. Taken together our findings call for educators to emphasize timing when developing and introducing sustainable design educational interventions in engineering design education. However, these findings are primarily informed by descriptive statistics obtained from the qualitative analyses. These findings call for a further mixed methods investigation linking the quantitative findings from the first two RQs to the qualitative data obtained from the results of RQ3.

7. Concluding Remarks

Our aim in the research was to investigate the relationship between the timing of a sustainable design educational intervention and (1) changes in students' trait empathy, (2) changes in their beliefs, attitudes, and intentions towards sustainability, and (3) their reflections on the utility of the intervention. The results of our experimental study indicated that the timing of the sustainable design intervention does not relate to changes in students' trait empathy or their beliefs, attitudes, or intentions towards sustainability. However, students from both timing conditions reported significant increases in their attitudes and intentions towards sustainable action. Additionally, the qualitative findings indicated that introducing the workshop later in the project related to the higher reported use of the sustainable design heuristics. Taken together, these findings highlight that the timing of the currently studied sustainable design educational intervention might not have a significant effect on students' trait empathy or their beliefs, attitudes, and intentions towards sustainability. On the other hand, the timing of the intervention could influence the extent to which students reflect on their experience with sustainable design, with a later timed intervention relating to a greater extent of reflection.

8. Limitations and Directions for Future Work

Despite the insights revealed from our study, it has some limitations, providing avenues for future research. First, the participants in our study were primarily in their first year of engineering education. Prior research suggests that student designers' behavior is impacted by educational level [81–83]; therefore, future work must work towards extending these findings with designers with higher levels of experience such as upper-level and graduate students. Second, this study used the three-component measure of attitudes towards sustainability

and the Interpersonal Reactivity Index measure of trait empathy to capture individual differences. However, students' sustainable design behavior could be influenced by other individual differences such as gender, motivation [84, 85], and personality [29, 86]. Therefore, future research must more comprehensively investigate the role of individual differences in sustainable design behavior. Such investigations could also reveal potential relationships between these various individual differences in the context of sustainable design. Additionally, in this study, we relied on self-reported factors to assess the relationship between the timing of the intervention and students' individual differences. Self-report measures are prone to measurement error and therefore, we envision extending the findings of this study towards assessing the students' design outcomes. Such future work will involve the evaluation of students' designs both, from the workshop and the longer design project. This direction of future work could also incorporate assessing trait empathy beyond self-report survey data, through measures such as empathic self-efficacy [72] and empathic accuracy [87].

Next, the results of our study did not reveal any practical effects of the timing of the intervention on trait empathy and this lack of effects could be attributed to the design of the intervention. Specifically, the intervention did not comprise any empathy-invoking elements and future research could explore the explicit introduction of empathy-related aspects as part of the sustainable design intervention. Such empathy-invoking elements could include lecture components on the relationship between empathy and sustainable design [34] and immersive experience with different user groups through interviews and simulations [71]. Finally, in this study, we investigated the role of the timing of the intervention across the different design stages in an 8-week-long project. Future research must explore the effects of the timing of introducing sustainability in a four-year undergraduate engineering program (i.e., first-year, second-year, third-year, or senior year) to promote sustainable design outcomes.

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