Design Science

Investigating the relationship between mindfulness, stress and creativity in introductory engineering design

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Abstract

Mindfulness-based interventions (MBIs) for engineering design are promising for their stress management, cognition and well-being benefits. Prior work concluded that engineering design is stressful and that each engineering design stage has unique stressors. This non-randomized study investigated the effect of an MBI on students' cognitive stress and final design creativity during a multistage, hands-on design assessment. Data were collected using surveys, project deliverables and follow-up interviews. While no significant increase was found in students' measured state mindfulness due to the intervention, students in the MBI condition were more likely to perceive the intervention positively compared to students in the control condition (alternative use tasks). Students in both conditions were found to have similar levels of state stress, which indicates that the MBI had no observable effect on students' measured stress during design. Although students in the MBI condition were found to produce higher-quality final designs, there were no differences in design creativity or novelty. When data were clustered to identify types of student experiences, state mindfulness was found to meaningfully contribute, but state stress was not. Future research should continue to investigate MBIs in engineering design as a potential approach to improve design education and outcomes.

Keywords: Engineering design, Engineering education, Mindfulness, Cognitive stress, Cognitive experience

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1. Introduction

Mindfulness-based interventions (MBIs) for college students have been increasingly implemented within universities due to their ability to support students' well-being. There is evidence that MBIs impact stress management (Mohan, Sharma & Bijlani 2011; Bamber & Kraenzle Schneider 2016), cognition (Zeidan *et al.* 2010) and well-being (Brown & Ryan 2003) – making them a promising intervention for engineering design education. However, there is a lack of research investigating the applicability of MBIs for engineering or engineering design.

Prior research has determined that mental stress is induced during engineering design (Zhu, Yao & Zeng 2007; Petkar *et al.* 2009; Nguyen, Xu & Zeng 2013; Nguyen & Zeng 2014, 2017*a*; Nolte & McComb 2020, 2021). Understanding design stress is critical because high levels of stress are known to decrease performance during problem-solving tasks (Beilock *et al.* 2004; Beilock & DeCaro 2007). Alternatively, a moderate level of stress is theorized to be ideal for encouraging the most creative engineering design outcomes (Nguyen & Zeng 2012). Practicing mindfulness has been shown to reduce students' general perceived stress and anxiety (Bamber & Kraenzle Schneider 2016), and MBIs have been used to manage task-induced stress during stressful tasks like videogames (Mohan *et al.* 2011). Therefore, an MBI is promising for helping engineering students manage the task-induced stress of engineering design. Additionally, a relationship between mindfulness and creativity has also been observed, and it is suggested that practicing mindfulness can support creativity (Baas, Nevicka & Ten Velden 2014; Lebuda, Zabelina & Karwowski 2016; Henriksen, Richardson & Shack 2020). However, there is a lack of research exploring mindfulness and creativity in engineering design, which is important because design creativity is a critical metric of design success in engineering coursework (Chiu & Salustri 2010).

Incorporating MBIs into engineering design courses has the potential to help students manage the stress of design and support students' well-being. This research is crucial to determining effective stress-management interventions for design and contributes unique insights into the effect of MBIs on introductory engineering students. The study presented here will investigate the impact of a longitudinal MBI on students' stress and design creativity during a hands-on multistage design assessment.

2. Relevant literature

2.1. Overview of mindfulness research

The current work will use an accepted definition of mindfulness, specifically a "process of regulating attention in order to bring a quality of nonelaborative awareness to current experience and a quality of relating to one's experience within an orientation of curiosity, experiential openness, and acceptance" (Bishop *et al.* 2004, p. 234). Originally, MBIs, like the prevalent Mindfulness-Based Stress Reduction program (Kabat-Zinn 1982, 2003), were used to treat adults in clinical settings and have been found to improve many conditions, including chronic pain (Kabat-Zinn 1982; Creswell 2017; Creswell *et al.* 2019), anxiety (Creswell 2017) and depression (Creswell 2017). After demonstrating success in clinical settings, MBIs were extended to other populations like healthy adults (e.g., Khoury *et al.* 2015) and additional settings like education (Renshaw 2019).

However, mindfulness-based research within engineering is limited. A majority of this research in engineering has focused on investigating engineers' level of dispositional or trait mindfulness, which is defined as an individual's enduring level of mindfulness that is consistent over time. Dispositional or trait mindfulness in engineering students is associated with higher innovation self-efficacy (Rieken

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et al. 2017); greater business self-efficacy (Rieken, Schar & Sheppard 2016); decreased perceived stress (Lal *et al.* 2019); increased mathematical test scores through reduced test anxiety (Bellinger, DeCaro & Ralston 2015) and improved academic outcomes (Estrada & Dalton 2019). Additionally, recent research found that engineering students who practiced mindfulness-based activities during the COVID-19 pandemic had healthier responses to survey questions indicating clinical health concerns (Beddoes & Danowitz 2021). These results suggest that engineering students' trait mindfulness is associated with many positive outcomes.

Further research has started to investigate MBIs for engineers. First-year students were receptive to a short MBI for stress and resilience (Huerta 2018), and upper-level engineering students were receptive to incorporating brief daily mindfulness practices into an online engineering course during the COVID-19 pandemic (Miller & Jensen 2020). A one-credit course for engineering students also found that non-cognitive competencies like mindfulness can be learned and developed (Ge *et al.* 2019), and other mindfulness interventions led to improved software development (Bernárdez *et al.* 2014) and conceptual modeling (Bernárdez *et al.* 2018). Additionally, a four-workshop MBI for first-year engineering students was found to increase their mindfulness and enhance their intrapersonal and interpersonal competencies (Huerta *et al.* 2021). This prior research indicates that engineering students are receptive to MBIs and that they have a variety of benefits.

While many of the previous research findings support that MBIs would be beneficial to engineering design, mindfulness research in this field is almost non-existent. Yet, prior mindfulness research in other fields has found many improvements in aspects critical to engineering design like improved executive function (Zeidan *et al.* 2010), lower cognitive rigidity (Greenberg, Reiner & Meiran 2012) and greater attention (Zeidan *et al.* 2010; Norris *et al.* 2018). Specifically, in engineering design, students perceived benefits from a brief mindfulness intervention that induced a small increase in students' decentering, which is one aspect of students' state mindfulness (Nolte, Huff & McComb 2022*a*). However, the intervention had no observable impact on students' stress during three short design tasks (Nolte *et al.* 2022*a*). Therefore, further mindfulness research in engineering design is warranted.

Additional mindfulness research with college students indicates that engineering students would further benefit from incorporating MBIs through improved well-being. For example, MBIs could be used to help students transition to college (Dvořáková *et al.* 2017). Also, a narrative review of the literature has found that mindfulness meditation can reduce college students' stress and anxiety (Bamber & Kraenzle Schneider 2016). MBIs are promising for introductory engineering design students as previous research has shown many benefits related to developing important engineering skills and improving students' well-being.

2.2. Stress

Engineering design has been found to induce stress for designers (Zhu *et al.* 2007; Petkar *et al.* 2009; Nguyen *et al.* 2013; Nguyen & Zeng 2014, 2017*a*; Nolte & McComb 2020, 2021; Nolte *et al.* 2022*a*). The stress of engineering design is predominantly due to the cognitive abilities required to do engineering design and the inherent complexity of design problems (Dym *et al.* 2005). Understanding stress across the engineering design process is critical because different stress levels

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can affect a designer's cognitive experience during design and the quality of design outcomes. High levels of stress can reduce a designer's effort (Nguyen & Zeng 2014, 2017*a*), can decrease task performance (Sandi 2013), and are likely to result in less creative designs (Nguyen & Zeng 2012). However, a more moderate stress experience is theorized to lead to the most creative designs (Nguyen & Zeng 2012), better design performance (Yang, Liu & Zeng 2018) and improved concentration (Degroote *et al.* 2020).

Previous research indicates that the acute stress (i.e., stress lasting only short periods of time) brought on by participating in engineering design fluctuates across the design process (Zhu *et al.* 2007; Nguyen *et al.* 2013; Nguyen & Zeng 2014; Nolte & McComb 2021; Nolte *et al.* 2022*a*). When the design process was separated into principal stages, it was found that physical modeling was the most stressful for first-year engineers, followed by concept generation and concept selection (Nolte & McComb 2021; Nolte *et al.* 2022*a*). Correspondingly, prior research with engineering graduate students identified that low to moderate stress is experienced during most of the conceptual design process with less time spent at high stress levels (Nguyen *et al.* 2013; Nguyen & Zeng 2014). Therefore, stress management strategies to help designers manage periods of high stress could be beneficial. However, prior work identified that each stage of the design process has unique sources of stress (Nolte & McComb 2020, 2021; Nolte *et al.* 2022*a*), which would make it incredibly difficult for a stress management intervention to directly target sources of stress throughout the design process. Moreover, many additional factors are likely to affect stress during the design process, like the design prompt (Nguyen & Zeng 2012), time constraints (Yerkes & Dodson 1908), problem-solving strategy (Wang *et al.* 2015; Zhao & Zeng 2019) and individual differences (García-García *et al.* 2019). Consequently, a stress management intervention targeting high stress generally would likely be the most effective. An MBI was primarily chosen for this study because it can target stress generally, and prior research has shown that MBIs can reduce the adverse effects of stress without reducing task performance (e.g., Mohan *et al.* 2011).

Furthermore, engineering students are already experiencing substantial stress (Foster & Spencer 2003) and in recent years, the stress of college students has been rising (American College Health Association 2020). This indicates that engineering students struggle with a considerable amount of chronic stress (i.e., stress lasting extended periods of time), which can adversely impact their health and well-being. In addition, students' well-being has been found to drop significantly during their first year, and while it rebounds by the end of the year, it does not return to pre-college levels (Conley *et al.* 2014). The ability of MBIs to support student well-being (Brown & Ryan 2003; Shapiro *et al.* 2008) also encourages investigating their applicability for introductory engineering design courses. MBIs for engineering students have the potential to improve their engineering design experience and help institutions develop more holistically sound engineers.

2.3. Creativity

Creativity in engineering design is often a measure of both novelty and appropriateness (Miller *et al.* 2020) and is considered a critical metric of design success (Sarkar & Chakrabarti 2011), especially in engineering courses (Chiu & Salustri 2010). Creativity is influenced by many factors (Sarkar & Chakrabarti 2011) and is

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difficult to measure (Chiu & Salustri 2010; Sarkar & Chakrabarti 2011; Denson *et al.* 2015; Miller *et al.* 2020).

Prior work has determined a link between creativity and mindfulness (Baas *et al.* 2014; Lebuda *et al.* 2016; Henriksen *et al.* 2020). A recent meta-analysis determined a statistically significant but relatively weak relationship between mindfulness and creativity that was moderated by the type of mindfulness or aspect focus (e.g., mindfulness focused on open-monitoring aspects may be beneficial to creativity) (Lebuda *et al.* 2016). Another qualitative review found that practicing mindfulness can support the skills for creativity (e.g., awareness, capacity for nonjudgmental description, and restraint from immediate evaluation), and practicing mindfulness could be beneficial in an educational setting (Henriksen *et al.* 2020). Still, more research is needed in this area (Henriksen *et al.* 2020). Therefore, while there is likely a relationship between mindfulness and creativity, more research is required to characterize this connection. For example, each aspect of mindfulness is likely to contribute to creativity differently (Baas *et al.* 2014; Lebuda *et al.* 2016; Henriksen *et al.* 2020). There is a lack of research investigating the relationship between mindfulness and creativity in engineering design.

Stress is theorized to have an inverse U-shaped relationship with creativity according to the Mental-Stress Creativity Relation of Nguyen & Zeng (2012). This theory postulates that mental stress is positively related to mental workload and negatively related to mental capacity (Tang & Zeng 2009; Nguyen & Zeng 2012). Mental capacity is a combination of a designer's knowledge, affect and skill (Nguyen & Zeng 2012). The theory states that "workload can be defined as an external load assigned to a person whereas mental capacity is the person's ability to handle the external load" (Nguyen & Zeng 2012, p. 76). Specifically, this theory predicts that a moderate amount of stress will lead to the most creative design, while low or high stress will result in designs of lower creativity. This theory is supported by a meta-analysis that determined a curvilinear relationship between stress and creativity where low stress supported creativity, and high stress decreased creativity (Byron, Khazanchi & Nazarian 2010). Also congruent with this theory, recent work identified that mental workload was predictive of creative performance during an engineering design activity (Chen, Chang & Chuang 2022). It is predicted that students who participate in an MBI will produce more creative designs due to the MBI helping them manage the stress of design.

3. Research aims and significance

This work will investigate the effect of a longitudinal MBI on students' cognitive experience and design outcome creativity during a hands-on engineering design assessment. An MBI is promising for engineering design to help manage the stress induced during engineering design (e.g., Nolte & McComb 2021), promoting the development of critical engineering design skills (e.g., Rieken *et al.* 2017) and supporting first-year engineering students' well-being (e.g., Huerta *et al.* 2021). Additionally, this work will be the first to investigate stress, mindfulness and design creativity in engineering design. Specifically, the following research questions (RQs) will be addressed:

1. What effect does an MBI have on introductory engineering students' stress during a multistage, hands-on engineering design assessment?

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2. What effect does students' state mindfulness have on the creativity of their design outcomes?
3. What effect does students' state stress have on the creativity of their design outcomes?
4. How do introductory engineering students perceive the inclusion of MBI to affect their mindfulness, stress and creativity during a multistage, hands-on engineering design assessment?

It is hypothesized that the MBI will help students better manage their stress during design, which will lead to a more moderate stress experience during design and more creative final designs. This study will help educators and researchers understand the effect of a longitudinal MBI on students' experience during an engineering design challenge. Therefore, the applicability of the intervention for engineering design education and other disciplines with similar characteristics can be determined. This intervention could also contribute to the improved well-being of engineering students regardless of its effect on the engineering design outcomes.

4. Methodology

This work investigated the effect of an MBI on students' stress and design creativity during multistage, hands-on design assessment for first-year engineers. Students in the MBI condition practiced mindfulness-based meditation (MBM) in-class during the first half of the semester and had two MBM breaks during their assessment. Students in the control condition had class as normal and experienced two control breaks during the assessment where they completed one alternative use task (AUT) during each break. Data were collected during the first in-person semester following online instruction due to the global COVID-19 pandemic.

4.1. Experimental design

In this non-randomized study, students completed a two-part hands-on design assessment consisting of an in-class design challenge and a written project report. Quantitative data were collected during the assessment using multiple surveys and project deliverables. Follow-up interviews were also conducted with a subset of the students who participated in the assessment (i.e., qualitative data). This study puts an emphasis on the quantitative data and results and uses the qualitative data and results to provide a broader perspective of the quantitative results.

4.1.1. Quantitative experimental design

Students from four course sections of a required first-year engineering design course participated in this institutional review board–approved study at a large mid-Atlantic university. This study followed best practices for research within the domain; however, it was not pre-registered. First-year engineering students were chosen as the population because they are learning fundamental engineering design skills for the first time. Therefore, they will rely on the habits they form during this course in the future. Additionally, first-year students are learning how to manage the demands of college and developing behavioral habits that will likely persist into their careers. Students received no compensation for this portion of the study.

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Participants were asked to report demographic information after completing the in-class portion of the assessment. Of the students who reported demographics, the average age of participants was 18.35 years (SD = 0.59 years, Range: 18–20 years), 34.2% identified as women and 64.4% identified as men, and 75.4% identified as white/Caucasian and 23.3% as non-white or a minoritized race or ethnicity. Students were also asked, “Within the six months before the start of the Fall 2021 semester, how often did you intentionally participate in mindfulness activities? Examples may include mediation, yoga, Qigong, Tai Chi, etc.” to assess their previous experience with mindfulness activities. Many students reported having never participated in mindfulness activities (45.2% of students), 15.1% reported once a month or less, 19.2% selected once a week, and 17.8% chose more than once a week or daily. When asked to report their mindfulness activities (if they had previous experience), 17 students listed exercising (e.g., running, yoga), 18 reported deep breathing or meditation, and 14 described other activities (e.g., prayer, journaling). This indicates that a majority of students had limited prior mindfulness experience and did not participate in mindfulness-based practices regularly.

During the first half of the semester, students in the MBI condition completed short MBM practices in class, while students in the control condition had class as usual. Students were assigned to their experimental condition according to the course section they were enrolled in. During the first week of the semester, students in the MBI condition were informed that they would be completing these meditations in class and received access to an educational module briefly explaining mindfulness and its relevance to college students. Students completed 11 MBM practices during the first half of the semester (before the assessment) from the Foundations portion of the Healthy Minds Program App (Healthy Minds Innovations 2021). The Healthy Minds Program App is intended to promote human flourishing by training four core dimensions of well-being including awareness, connection, insight and purpose (Dahl, Wilson-Mendenhall & Davidson 2020), and was previously found to reduce distress and improve markers of well-being (Goldberg *et al.* 2020). Each practice was formatted as a 5-minute guided sitting meditation and was completed in-class. Students listened to the meditation as a group but participated individually. Only one meditation was completed per class period and students did 1–2 meditations a week. Narrators for each practice were randomly selected to create an equal number of meditations narrated by a male and female voice as previous research has shown that voice quality can impact perceptions of the speaker like trustworthiness (O’Connor & Barclay 2017).

During the multistage, hands-on assessment, students experienced two scheduled breaks. Students in the MBI condition completed the Mindfulness of Sound and Counting the Breath meditations from the Awareness section of the Healthy Minds App (Healthy Minds Innovations 2021), which were formatted to match the in-class practices. Students in the control condition completed two 5-minute AUTs, one for a brick and one for a pencil, in which students were asked to brainstorm as many uses as they could for each object different from its normal use. Typically, AUTs (Torrance 1966) are used in engineering design research to measure divergent thinking and, consequently, creativity (Alhashim *et al.* 2020). In this study, the AUTs were used as an active control as task-switching during design has been shown to reduce design fixation and improve design performance (Sio, Kotovsky & Cagan 2017). Break one occurred 35 minutes into the assessment

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Table 1. Experimental methodology for the design challenge

Course section	Condition	Break 1	Break 2
Course section A $N = 19$ (Instructor 1)	MBI	Mindfulness of sound	Counting the breath
Course section B $N = 21$ (Instructor 1)	MBI	Counting the breath	Mindfulness of sound
Course section C $N = 14$ (Instructor 2)	Control	Brick AUT	Pencil AUT
Course section D $N = 19$ (Instructor 2)	Control	Pencil AUT	Brick AUT

during the conceptual design phase, and break two occurred 75 minutes into the assessment during the prototyping phase. A complete experimental methodology can be seen in Table 1.

The assessment included an in-class hands-on design challenge and an out-of-class written project report. The design challenge was 2-hours in duration and was completed individually in-class. The prompt of the design challenge instructed students to design a solution to help elderly individuals maintain their yard (e.g., mow the lawn, rake leaves or pull weeds). Students were asked to understand the problem, conduct background research, identify user-needs, ideate at least four concepts, complete a concept selection matrix and build an alpha prototype. At the end of the design challenge, students were asked to submit a written deliverable detailing their work during the design challenge. After the design challenge, students were given 24 hours to write and submit an individual project report detailing their final solution, explaining their design process, and reflecting on their design process.

The primary data for this study was collected using four surveys during the in-class portion of the assessment. Students took a pre-assessment survey containing the pre-task version of the Short Stress State Questionnaire (SSSQ; Helton 2004; Helton & Nöswall 2010). The students in the MBI took the second survey after completing their first MBM during break one. This survey queried their thoughts on the break and contained the Toronto Mindfulness Scale (TMS; Lau *et al.* 2006). The second survey for the control group contained the AUT and the TMS. The third survey for each condition had the same format as the second survey, except the TMS was removed due to concerns about survey fatigue. The post-assessment survey was the same for both conditions and was taken after completing the in-class design challenge. The post-assessment survey included a modified version (Nolte & McComb 2020, 2021; Nolte *et al.* 2022*a*) of the NASA-Raw Task Load Index (Hart & Staveland 1988, 2006), the post-task version of the SSSQ, and a few questions querying students' sources of stress and coping during the design challenge. A detailed description of each survey measure can be seen in Table 2. Students' written project reports were also collected after the design challenge.

4.1.2. Qualitative experimental design

Only students who indicated that they were willing to be contacted about a follow-up interview were eligible for this portion of the study. Interviewees were originally

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Table 2. Survey measures

Measure	Description
Modified NASA-Raw Task Load Index (NASA-RTLX) (Hart & Staveland 1988, 2006; Nolte & McComb 2020, 2021; Nolte *et al.* 2022*a*)	Measure of cognitive workload that is indicative of mental stress. Participants rate their mental demand, temporal demand, physical demand, performance, effort and frustration. For this work, this measure was modified to expand the description of frustration to include questions for stress, insecurity discouragement, and frustration. The measure is formatted as a visual analog scale from 0–100 bounded by extremes and is taken after the task is completed
Short Stress State Questionnaire (SSSQ) (Helton 2004; Helton & Nöswall 2010)	Measure of participants' change in state stress. A series of 24 questions measure participants' engagement, distress, and worry. The measure is formatted as Likert-type questions ranging from 0 to 4 (adjusted from the original 1–5 to match the TMS) and bounded by extremes
Toronto Mindfulness Scale (TMS) (Lau *et al.* 2006)	Measure of participants' state mindfulness used after a mindfulness practice. A series of 13 questions measure participants' decentering and curiosity. The measure is formatted with Likert-type questions ranging from 0 to 4 bounded by extremes
Sources of Perceived Stress During Design (Nolte & McComb 2020, 2021; Nolte *et al.* 2022*a*)	The measure asks participants to rank their top perceived sources of stress during the design task. A list of 20 common stressors during design was developed and used during the authors' prior work. Participants are typically asked to rate their top five perceived stressors after the task. They are also given a free-response question to list any sources of stress not included in the predetermined list
Managing Design Stress (Nolte & McComb 2020, 2021; Nolte *et al.* 2022*a*)	Free-response question asking students to describe how they managed their stress or any coping mechanisms they used during the design challenge. Students are asked to write 2–3 sentences

recruited using a maximum variation sampling technique aimed to create a diverse sample in terms of students' reported stress during the assessment and their demographic characteristics, including age, gender and ethnicity. The selected students were recruited via email after submitting their written project reports.

However, the response rate for students selected for this group was low. Consequently, recruitment was expanded to invite all students who were willing to be contacted for a follow-up interview. However, only students in the original sample were sent reminder emails. A total of 24 interviews were conducted using an online video conferencing platform. All interviews were conducted within a week of students completing the in-class design challenge. Interviewees from the MBI condition (N = 12) were all 18 years old; eight identified as men and four identified as women; and 10 identified as white/Caucasian and two identified as non-white or a minoritized race. Students from the control condition (N = 12)

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included nine 18-year-olds, two 19-year-olds and one 20-year-old; six men and six women; and eight students who identified as white/Caucasian and four who identified as non-white or a minoritized race or ethnicity. Students in both conditions had a range of previous mindfulness experience.

All interviews were conducted by one interviewer, recorded and transcribed for analysis. Interview questions were semi-structured (Hove & Anda 2005; Rubin & Rubin 2012) to allow the interviewer to ask each interviewee follow-up questions. The interview inquired about students' design process, cognitive experience during design, attitudes toward the scheduled breaks, and thoughts on the inherent difficulty or challenge of engineering. Students in the MBI were also asked about their thoughts on the in-class MBM practices. All interview questions can be seen in the Appendix. Transcripts were created using a secure automatic transcription software and manually verified by one of the researchers to ensure accuracy. Students who participated in the follow-up interviews received a $20 gift card as compensation.

4.2. Procedure

Students consented to this study at least 1 week before completing the assessment. All students individually completed the in-class design challenge portion of the assessment on the same day during their assigned class time. The design challenge was 2 hours in duration, and all students were given the same design prompt. During the design challenge, students were asked to complete four surveys and two breaks. The pre-assessment survey was taken before starting the design challenge. The first break was 35 minutes into the design challenge, and the second survey was taken immediately after the first break. The second break was 75 minutes into the design challenge, and the third survey was completed immediately following the second break. The last survey was taken after completing the design challenge. All breaks were 5 minutes in duration, and the format was dependent on the course section students were enrolled in. At the end of the class period, students submitted a document detailing their work during the design challenge.

Students were then given 24 hours to individually write a project report detailing their final design, their design process, and a reflection on their experience during the design challenge. After submitting their project reports, a diverse subset of students were recruited via email to participate in a 30-minute follow-up interview. After a couple of days, interview recruitment was expanded to invite any student willing to be contacted about a follow-up to participate. All interviews were conducted within a week of completing the in-class design challenge. The entire experimental design can be seen in Figure 1.

5. Results

The results of this study will be presented by measure or analysis for clarity. Quantitative results will be presented before the qualitative results and the relationships between the various results will be detailed in the discussion. While the sample size of the current non-randomized study was similar to others in the domain, the study was unpowered. Therefore, effect sizes are reported with all results to provide additional context. The quantitative analysis was conducted using R Studio and R version 4.0.3, and the qualitative analysis was conducted

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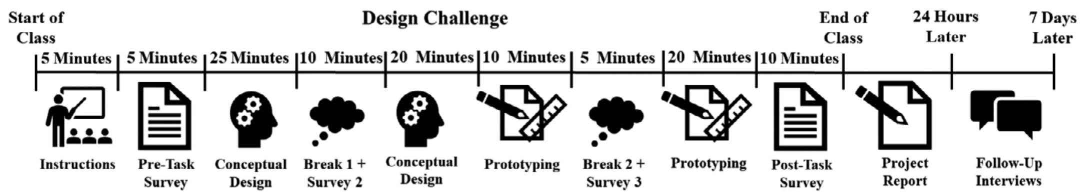

Figure 1. Generalized experimental procedure.

using NVivo 12. All assumptions for statistical testing were met and significance was assessed using an alpha level of 0.05.

5.1. Toronto Mindfulness Scale

Students completed the TMS to evaluate their level of state mindfulness after their first design challenge break. Total TMS scores were calculated for each student by averaging their responses for all 13 TMS questions. Students' scores for each factor of the TMS were calculated by averaging each student's response to the questions associated with each of the factors, curiosity (six questions) and decentering (seven questions). Cronbach's alpha computed across all TMS responses is 0.926, indicating acceptable internal consistency. Results for the mindfulness and control conditions can be seen in Figure 2.

The total TMS, curiosity and decentering scores for the students in the MBI were compared to the scores of students in the control condition using multiple Mann–Whitney *U* tests to determine if the MBM break increased students' level of state mindfulness. Students in the MBI were not found to have significantly different levels of total TMS ($Z = -0.474$, $p = 0.635$, $r = 0.055$), curiosity ($Z = -1.025$, $p = 0.306$, $r = 0.120$) or decentering ($Z = -0.108$, $p = 0.914$, $r = 0.013$) when compared to students in the control condition. Students in the MBI had an average total TMS of 2.22 (SD = 0.95), curiosity of 2.40 (SD = 1.12) and decentering of 2.07 (SD = 0.85), while students in the control condition had an average total TMS of 2.17 (SD = 0.84), curiosity of 2.23 (SD = 1.06) and decentering of 2.09 (SD = 0.87). Future research could include the TMS before and after break one to assess the effect of the breaks more accurately.

It can be seen in Figure 2 that students in the MBI had scores that were highly concentrated around the median even though the range of scores was similar to

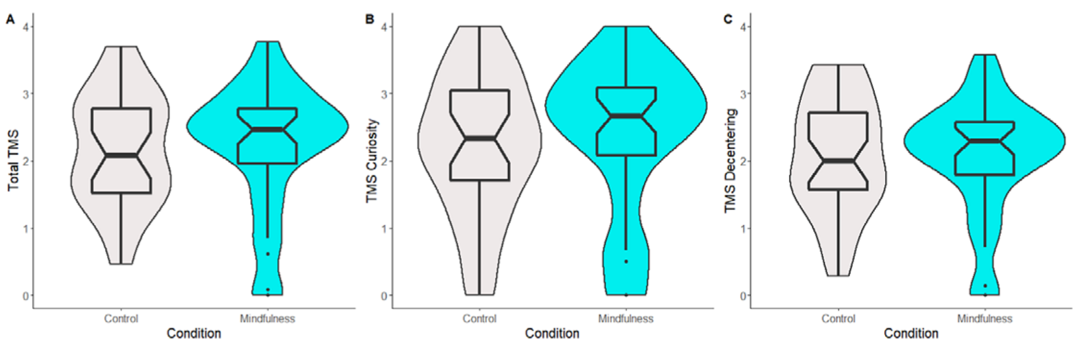

Figure 2. TMS scores for the MBI and the control condition.

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students in the control condition. This trend likely reflects that a subset of students did not fully participate in the first MBM break. While a majority of students did participate in the breaks as instructed, interviews with the students revealed that some students would not fully participate in the break so that they could continue making progress on the design challenge. The scores centered on the median likely reflect students who fully participated in the break, while the large variability in the first quartile represents students who did not participate in the break. Research in the future should ask students to rank their engagement with the MBMs.

5.2. Short Stress State Questionnaire

Students completed the SSSQ during the pre- and post-assessment surveys. The SSSQ was used to evaluate each student's level of multidimensional state stress. For each student, a score was calculated for each factor of the SSSQ by averaging the student's response to each of the questions corresponding to that factor (eight questions per factor). Then each student's change score for each factor of the SSSQ was calculated by subtracting the student's pre-assessment score from their post-assessment score for each factor. Cronbach's alpha computed across all SSSQ responses is 0.790 (pre-assessment) and 0.790 (post-assessment), indicating acceptable internal consistency.

The change scores for students in the MBI were compared to the change scores for students in the control condition using multiple independent t-tests to determine if the MBM breaks had an effect on students' stress during the design challenge. Students in the MBI condition were not found to have different distress ($t(68) = 0.035$, $p = 0.973$, $d = 0.008$), worry ($t(67) = 1.241$, $p = 0.219$, $d = 0.230$), or engagement ($t(69) = 0.061$, $p = 0.952$, $d = 0.014$) scores compared to students in the control condition. Students in the MBI had an average change in distress of -0.13 (SD = 0.59), worry of -0.12 (SD = 0.73) and engagement of 0.15 (SD = 0.53), while students in the control condition had an average change in distress of -0.14 (SD = 0.80), worry of -0.34 (SD = 0.67) and engagement of 0.16 (SD = 0.47). There is likely no difference between conditions for students' SSSQ scores. SSSQ scores by factor and condition can be seen in Figure 3.

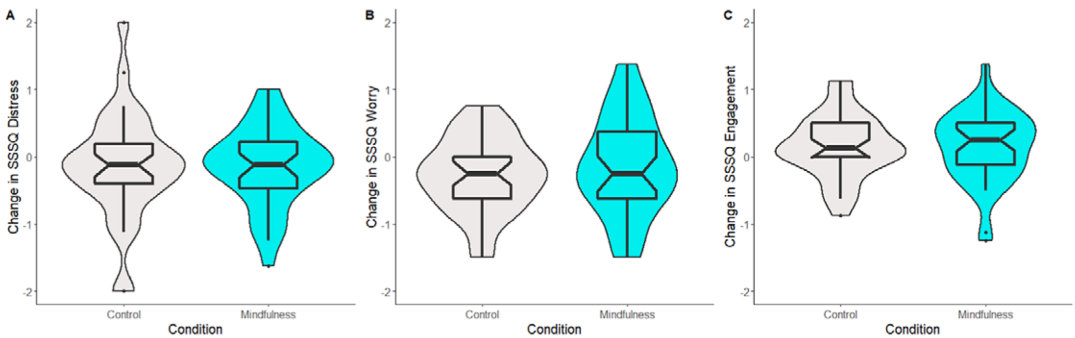

Figure 3. Comparison of SSSQ change scores.

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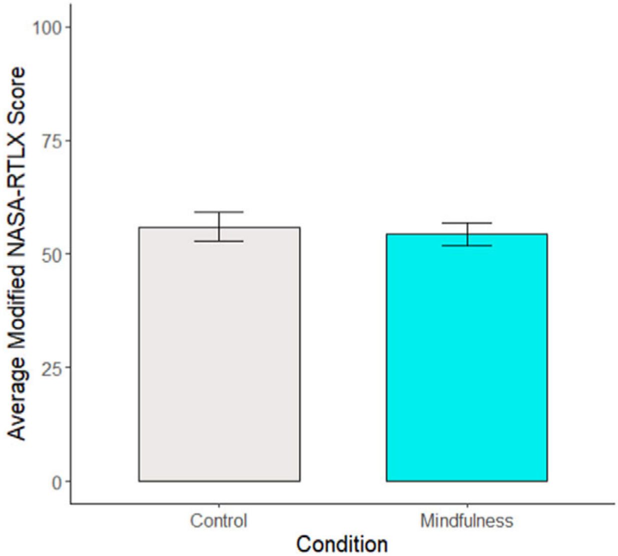

Figure 4. Modified NASA-RTLX scores compared by condition. Error bars represent ± 1 standard error.

5.3. Modified NASA-RTLX

Students completed the modified NASA-RTLX during the post-assessment survey. Cronbach's alpha computed across all NASA-RTLX responses is 0.816, indicating acceptable internal consistency. Each student's modified NASA-RTLX score was determined by averaging their responses for the nine questions. To determine if there was a difference between the modified NASA-RTLX scores by condition, students' scores were compared using an independent t-test. As can be seen in Figure 4, no significant difference was found between the modified NASA-RTLX scores for students in the MBI condition compared to students in the control condition ($t(70) = -0.401$, $p = 0.690$, $d = 0.095$). Students in the MBI condition had an average modified NASA-RTLX score of 54.38 (SD = 15.43), and students in the control condition had an average score of 55.96 (SD = 17.93). Statistical results were similar when the same test was run using comparing students' average NASA-RTLX scores with only the original six measures included. This indicates that the design challenge produced a similar mental workload for students in both conditions that was not significantly impacted by the intervention. Additionally, these results support the conclusion that there were no differences in students' stress experience by condition.

5.4. Final design creativity

Students submitted a written project report detailing their final design within 24 hours of completing the in-class design challenge. These designs were rated for creativity using the Consensual Assessment Technique (CAT; Amabile 1982, 1996; Amabil 1983). CAT is a commonly used technique for measuring creativity in many disciplines that relies on the ratings of subject-matter experts (Baer & Kaufman 2019; Miller *et al.* 2021) and does not depend on a specific definition

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of creativity but instead asserts that creativity is subjective and can be recognized and agreed upon by domain experts (Baer & Kaufman 2019).

For this study, two expert raters were used to rate the designs. The experts had completed at least one graduate degree in engineering and had significant experience in engineering design research and assessment, including multiple engineering design publications. The raters received no information on who made the design or which condition the student was in. Each design was rated for novelty and quality on a Likert-type scale that ranged from one (low novelty or quality) to seven (high novelty or quality) (Besemer 1998; Besemer & O'Quin 1999; Miller *et al.* 2020). Novelty was defined as "original and surprising," and quality was defined as "value, logic, utility, and how understandable the ideas were" (Miller *et al.* 2021, p. 031404-3). To determine a creativity score for each design, the average was taken between the novelty and quality ratings. An inter-rater reliability of $\kappa = 0.675$ was achieved between the two raters, which is considered as moderate agreement among raters (McHugh 2012).

To determine if the creativity of students' final designs depended on their experimental condition, three Mann–Whitney U tests were used to compare total creativity, novelty and quality scores by condition (Figure 5). Students in the MBI condition (M = 4.43, SD = 1.06) were not found to have final designs with significantly different total creativity scores ($Z = -0.912$, $p = 0.362$, $r = 0.107$) compared to the final designs of students in the control group (M = 4.04, SD = 1.51). There were also no significant differences found for final design novelty by condition ($Z = -0.074$, $p = 0.941$, $r = 0.009$). Final designs from students in the MBI had a novelty of 3.42 (SD = 1.87) compared to the final designs from students in the control group 3.53 (SD = 1.93).

However, there was a significant difference found for final design quality by condition ($Z = -2.479$, $p = 0.013$, $r = 0.290$). Students in the MBI condition had final designs of higher average quality (M = 5.43, SD = 1.62) compared to the final designs of students in the control group (M = 4.55, SD = 1.79). These results do not directly align with previous research that found that mindfulness contributes to improved creativity (Lebuda *et al.* 2016) because students in the MBI did not have significantly higher state mindfulness compared to students in the control group as measured by the TMS. It is posited that the time the MBI students had during the breaks to reflect on design decision-making may have led to higher-quality final design.

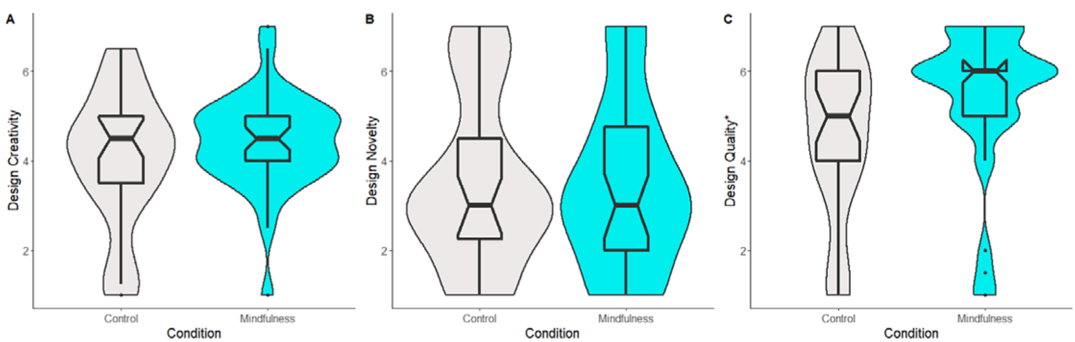

Figure 5. Creativity scores by condition. The asterisk on Plot C indicates a significant difference.

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5.5. Student experience categorization

Finally, all quantitative data were clustered using the k-means clustering algorithm to determine if there were different types of student experiences during the design challenge regardless of experimental condition. The k-means clustering algorithm was chosen because of its versatility and ability to easily discover hidden groups within datasets (Shraddha & Naganna 2014). The data for each measure were normalized using a z-score transformation, which modifies the variable to have a mean of zero and a standard deviation equal to one. The optimal number of clusters for this data was determined to be three using the elbow method (Ketchen & Shook 1996; Makwana, Kodinariya & Makwana 2013), where the amount of explained variance is graphed corresponding to the cluster number and the optimal number of clusters is visually determined as the cluster number that explains the most variance without wasting computational resources (Ketchen & Shook 1996). The ideal number of clusters was confirmed using the silhouette method (Rousseeuw 1987), where the number of clusters is chosen to maximize cohesion (Rousseeuw 1987). Visualizations for each measure by cluster can be seen in Figure 6.

Cluster 2 likely represents a typical student experience as this cluster includes a majority of the students in the study ($N = 41$). This cluster is defined by high state mindfulness scores, slightly higher increases in state stress, average mental workload scores and highly creative final designs. Cluster 2 demonstrates a relationship between high state mindfulness and high final design creativity as these two metrics best characterize Cluster 2. This result likely aligns with prior research that found that mindfulness can support creativity (Baas *et al.* 2014; Lebuda *et al.* 2016; Henriksen *et al.* 2020). Alternatively, mindfulness may support students choosing to proceed with more creative designs, which leads to higher final design creativity. Previous research has found that the creativity of students' design reduces throughout the design process (Starkey, Toh & Miller 2016). While students in Cluster 2 have high state mindfulness, they also have no decrease or slight increases in state stress. This contradicts previous research, which determined that practicing mindfulness can induce a relaxation effect (Mohan *et al.* 2011). It is likely that students in this cluster were easily able to focus on the task because their high state mindfulness helped them focus on the present moment. They are also able to produce final designs with high creativity but will not experience a decrease in their state stress due to participating in the design task.

The first alternative student experience, Cluster 3 ($N = 15$), is characterized by low state mindfulness, moderate change stress scores, average mental workload scores and highly creative final designs. Cluster 2 and Cluster 3 have similar mental workload and final design creativity. However, Cluster 3 has lower state mindfulness and slightly greater decreases in state stress than Cluster 2. Cluster 2 likely represents an alternative relationship between state mindfulness and final design creativity. It is likely that mindfulness supports creativity during design but is not the only route for producing creative designs. It is also possible that mindfulness has a U-shaped relationship with creativity. Alternatively, a third factor could have contributed to these students proceeding with highly creative designs like their level of risk aversion (Toh & Miller 2016). It is likely that while students in Cluster 3 do not have the same focus on the design task as those in Cluster 2, as demonstrated by their lower state mindfulness, they can still accomplish the design

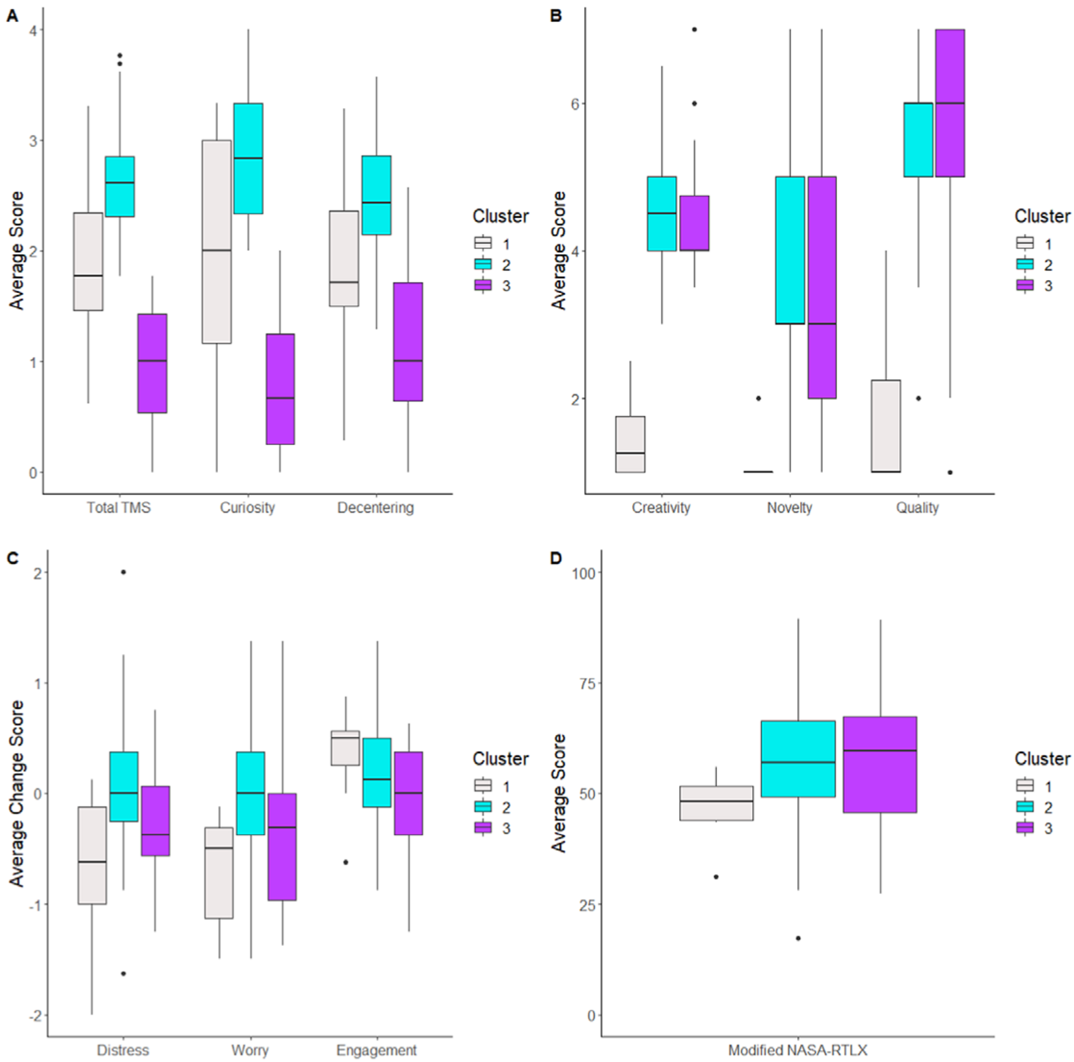

Figure 6. Quantitative data by cluster.

task and produce equally creative final designs. Students in Cluster 3 also experience slight decreases in state stress due to participating in the task.

Cluster 1 ($N = 7$) is distinguished by an experience of moderate state mindfulness, slightly greater decreases in state stress (except for engagement), lower mental workload scores and low creativity final designs. Cluster 1 appears to be the opposite of Cluster 2; whereas Cluster 2 has high mindfulness and highly creative final designs, Cluster 1 has average mindfulness and final designs with low creativity. Additionally, Cluster 1 has greater decreases in distress and worry while also having increased engagement. This indicates that students were engaged and concentrated on the design challenge but could not produce final designs of high creativity. It may be that these students struggled with an aspect of the design challenge or may have been experiencing fixation during the design process.

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Previous research has shown that design fixation can lead to less novel designs (Jansson & Smith 1991). However, stress is theorized to contribute to design fixation (Nguyen & Zeng 2017*b*), which does not match the experience of this cluster. Cluster 1 likely indicates students that were engaged in the task but struggled to produce a creative final design. Students in Cluster 1 are expected to need additional help or instruction.

5.6. Design challenge intervention

The interview transcripts were analyzed using a directed content analysis approach (Hsieh & Shannon 2005) to qualitative analysis through a post-positivist lens (Guba & Lincoln 1994). The focus of directed content analysis is to validate or extend current theory or research findings by identifying how they are represented in the data (Hsieh & Shannon 2005). The work sought to extend the Mental Stress-Creativity Relation and the findings of relevant literature for a hands-on engineering design assessment with a MBI through the experiences of the participants. This analysis uses a post-positivist paradigm (Guba & Lincoln 1994), which contends that the results of analysis indicate context-dependent generalizations but not fully generalizable results (Charney 1996; Cooper 1997). Interview responses detailing students' perception of the design challenge intervention were first reviewed to identify any references to perceived effects of the intervention (i.e., scheduled breaks), and these references were then compared to the Mental Stress-Creativity Relation (Nguyen & Zeng 2012) to develop operational code definitions. While the transcripts were exclusively coded by the first author, codebook development and iteration were discussed through a collaborative process with other authors and colleagues, and therefore, did not warrant inter-rater reliability.

Students had mixed responses when asked about the intervention they experienced during the design challenge. All students experienced two scheduled 5-minute breaks during the design challenge where they either did an AUT or MBM. Overall, students in the MBI perceived the breaks more positively compared to students in the control condition. Five themes were prevalent when students described their thoughts and feelings on the scheduled breaks, (1) *breaks as a distraction*, (2) *breaks caused a change in emotion*, (3) *breaks impacted design time*, (4) *breaks encouraged thinking and reflection* and (5) *breaks improved creativity.*

Many students reported that the breaks were a distraction from the design challenge. While some students described the breaks as a positive distraction from the design challenge (MBI = 7, C = 6), others described the breaks as a negative interruption to their work (MBI = 8, C = 8). Students who described the breaks as positive often reported them being a good opportunity to think about a topic other than the design challenge and how the breaks allowed them to clear their minds and refocus on the design challenge. However, students who described the breaks as a negative distraction from their work expressed that the breaks interrupted their focus and train of thought. These students also described having trouble reorienting themselves to the design challenge after completing the break. Participant 42 describes why they thought the breaks were a negative distraction:

> Me personally, when I'm doing a task, I like to stay focused on that task. I don't take breaks normally when I'm studying or doing homework. I have to sit down in one fell

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> swoop and do it all in a session. So taking "brain breaks" doesn't really help me, it more derails my train of thought and then I have to do more work to get back on whatever thing I was doing before.

Students also reported that the breaks caused them to experience different emotions or emotional states. When discussing the effect of the breaks on their emotions, students often used terms such as stressed, calm and relaxed to represent emotion or change in emotion. Some students experienced increased positive emotions or an improved emotional state in response to the breaks (MBI = 5, *C* = 1). In contrast, others reported experiencing new or increased negative emotions in response to the breaks (MBI = 5, *C* = 5). Students who described a positive emotional experience in response to the breaks often stated that it helped them be calmer and reduced their stress. For example, Participant 3 describes how the MBM break allowed them to manage the stress of the design challenge:

> I think that having the mindfulness activity was positive, because it was able to help me relax for a few minutes and it helped with the stress that I had during the design process.

Students who described negative emotions due to the breaks often reported that the interruption to their work caused the negative emotions rather than the break activity itself.

In addition, students perceived an effect on their design time due to the breaks. In this theme, most students reported that the breaks were a waste of design time (MBI = 3, *C* = 4). However, a couple of students reported that the breaks helped them better manage their time during the design challenge (MBI = 1, *C* = 1). Students who described the breaks as a waste of design time often stated that the breaks were 5 minutes they would have preferred to use for design. Participant 72 describes how they would have rather been designing than doing the breaks:

> When I heard about like the five minute breaks and even when I started, like the first one, I was like "wow, this like looks like a waste of time" just because its five minutes taken out of what I could be using for like designing or something else.

Conversely, a couple of students discussed how the breaks helped them better manage their time during the design challenge. Participant 7 described that the breaks helped them make a timeline for the design challenge, and Participant 42 explained how the breaks helped them evaluate the appropriateness of their pace during the design challenge.

Students, mainly in the MBI condition, described that the breaks encouraged them to do more thinking and reflection (MBI = 5, *C* = 2). A couple of students explained that the breaks helped them be more self-reflective; however, it was more common for students to report using the breaks to reflect on and think about their design process up to that point. Participant 37 explains how the breaks encouraged them to think about their design decisions:

> I think [the breaks] worked out pretty well. They definitely let you like have time to sit there and gather your thoughts and reflect on the decisions that you made, like the past half hour or so. They also helped you think about what you will do moving forward.

Lastly, some students, largely in the control condition, reported a perceived increase in their creativity due to the breaks (MBI = 2, *C* = 6). Students who

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described an increase in their creativity typically stated that the breaks helped them think outside the box. For example, Participant 72 describes how the breaks helped them improve their design:

> I specifically, I remember after the break, I immediately was thinking of the uses for the brick and then I immediately thought of something for my own design. I thought of my fourth design during the five minute break, so it definitely impacted my design, because I started off having trouble brainstorming and it kind of helped me out.

While it is possible that students did experience an increase in creativity due to the break activity, students might be recalling their first introduction to this activity in their course when it was presented as a technique for "thinking outside the box" during their idea generation unit. It may also be that they were creating an open goal of creativity, that is, a goal for a task that has yet to be completed (Moss, Kotovsky & Cagan 2007).

6. Discussion

Students complete a multistage, hands-on design assessment either with two MBM or AUT breaks. Data were collected using multiple surveys, project deliverables and follow-up interviews. This section will detail results related to mindfulness, stress, creativity and the intervention to answer the proposed research questions.

6.1. Mindfulness

No significant difference was found for total TMS, decentering and curiosity scores by condition. This indicates that students did not experience increased state mindfulness due to the first meditation break as measured by the TMS. This lack of increased state mindfulness does not align with previous research, which found that similar mindfulness-based practices can improve students' levels of state mindfulness (Mahmood, Hopthrow & Randsley de Moura 2016; Nolte *et al.* 2022*a*). While it is possible that students did not experience a change in their state mindfulness due to the MBM, it is also plausible that the TMS did not accurately measure the change due to its focus on curiosity and decentering aspects of mindfulness.

However, the TMS scores of students in the MBI were more centralized around the median TMS score compared to the scores of students in the control condition. This likely reflects that a majority of the students participated in the MBM as instructed and experienced an effect. However, a portion of students likely did not participate in the MBM during break one and, therefore, did not experience an effect. Students' interview responses support that not all students fully participated in the mediation breaks. A few students mentioned either ignoring the breaks or multitasking during the breaks by continuing to work on the design problem for the assessment. Participant 22 describes how they did not fully participate in the first break but did participate more in the second break:

> I kind of did a mixture, whenever I was like at the beginning, I definitely ignored [the break activity], I was like "What did he say?" Then, towards the end, once my anxiety started to go down a bit, I actually started to focus towards [the break activity]. I know for the last one that we did I actually did follow, along with like the voice person, but the first one I like ignored.

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Therefore it is likely that not all participants in the MBI condition fully experienced the intervention. Additionally, it is unknown if students experienced an increase in mindfulness after the second break because students did not retake the TMS due to concerns of survey fatigue. It may be that students benefited more from one break over another.

The qualitative results also support the MBM breaks having an effect on students. Students in the MBI were more likely to report an increase in positive emotions due to the break or thinking and reflection during the break despite a similar number of students in both conditions reporting negative break experiences. Moreover, students in the MBI reported being more relaxed and having less perceived stress during the breaks when compared with students in the control condition. This likely indicates that some students were experiencing the effects of increased mindfulness. Alternatively, students in the MBI condition may have had a more positive experience because they were more familiar with the style of breaks as they had been doing similar activities throughout their course, while the control condition had break activities that they had less experience with.

Regardless of the effect of the intervention, students' level of state mindfulness contributed to their experience during the design challenge. When the quantitative data were clustered to identify types of student experiences, students' level of state mindfulness was unique for each cluster, while other quantitative measures showed more overlap between clusters. Students in Cluster 1 reported moderate levels, Cluster 2 had high levels and Cluster 3 had low levels of state mindfulness. This indicates that students' level of state mindfulness meaningfully contributed to their experience during the design challenge. Therefore, continued research to understand how the mindfulness of designers impacts design is warranted.

6.2. Stress

In response to RQ1, *what effect does an MBI have on introductory engineering students' stress during a multistage, hands-on engineering design assessment*, no significant difference was found for students' change in stress scores when compared by condition. This suggests that there is no difference in students' net stress when compared by condition. This aligns with previous work by the authors that determined that even though a brief MBM resulted in a small change in students' decentering, there was no observable impact on students' stress (Nolte *et al.* 2022*a*). However, this contradicts reports from the interviews where students reported a change in emotion and stress due to the breaks. For example, Participant 4 from the MBI condition underscores the impact of the breaks on their perceived stress:

> The general meditation practices that we did were very, I could say positive because again it helped calm me down a bit more and reduced any little bit of stress that was there. It definitely helped me focus on myself to realize what I needed to do to continue the process.

The qualitative results indicate that a subset of students were experiencing reduced stress due to the MBMs likely through increased mental capacity by improved affect (Nguyen & Zeng 2012).

However, students from the MBI who did not report reduced stress often reported an alternative experience with increased negative emotions due to the

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breaks. For example, Participant 22 describes how their anxiety increased due to the MBM breaks:

> I felt like my anxiety actually kind of raised a little bit, which was ironic considering it was meant to, I'm pretty sure, to help calm you down and help you deal with your stress because it was focusing on mindfulness. But I felt like it actually increased my anxiety.

When beginning meditation, it may bring the practitioner's attention to unpleasant experiences or feelings. The increase in negative emotions reported by students in this study likely contributed to the stress they were experiencing by changing their mental capacity through affect (Nguyen & Zeng 2012). Overall, this suggests that at an aggregate level, there was likely no change in net stress because some students were experiencing less perceived stress, while others had experiences that likely contributed to increased stress. However, clustering results also indicate that differences in stress were not a meaningful indicator of students' experience during the design challenge. Students' change in SSSQ stress was not the most predictive variable of their experience during the design challenge or there is a discrepancy between students' perceived stress as described in their interviews compared to their measured stress (i.e., SSSQ scores).

6.3. Design creativity

In response to RQ 2, *what effect does students' state mindfulness have on the creativity of their design outcomes?*, the final designs produced by students in the MBI condition had significantly higher quality when compared to the final designs produced by students in the control condition. However, no significant differences were found for final design creativity or novelty by condition, likely because the design prompt used in this study implicitly prioritized quality. Prior work has found that the design prompt can affect design creativity (Starkey *et al.* 2016).

Students in the MBI were not found to have significantly higher state mindfulness as measured by the TMS. Therefore, it is improbable that the higher-quality designs produced by students in this condition were due to the relationship between mindfulness and creativity (Baas *et al.* 2014; Lebuda *et al.* 2016; Henriksen *et al.* 2020). However, it may be that students in the MBI did have increased state mindfulness that was not measured by the TMS, which contributed to increased final design quality. Alternatively, another aspect of the MBM could have led to the increased final design quality or students choosing final designs of higher quality. It is posited that the MBM breaks provided students with a better opportunity to think and reflect on their design, as indicated by the qualitative results of the study. This opportunity to reflect on their design decision-making likely led to higher-quality designs.

Intriguingly, some students, largely from the control condition, perceived an increase in their creativity due to the breaks during the design challenge, which contradicts the quantitative creativity results. It is possible that these students experienced an increase in their creativity due to the breaks that was not captured in the rating of their final designs as prior work has shown that students do not always choose to proceed with their most creative ideas (Starkey *et al.* 2016). Three out of the six control condition students who reported increases in their creativity due to the breaks had a final design with a creativity above five (range 1–7).

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Alternatively, it may be that these students were setting an open goal for creativity (Moss *et al.* 2007) (i.e., a goal that had yet to be achieved for increasing the creativity of their designs) and that completing the AUT (i.e., a measure of divergent thinking and creativity) fulfilled this open goal without increasing the creativity of their final designs.

Alternatively, the clustering results suggest two disparate relationships between students' level of state mindfulness and their final design creativity. However, there was no discernable relationship between state stress and final design creativity. These results further inform RQ 2 (*What effect does students' state mindfulness have on the creativity of their design outcomes?*) and RQ 3 (*What effect does students' state stress have on the creativity of their design outcomes?*). Cluster 2 had high levels of state mindfulness and Cluster 3 had low levels of state mindfulness, but both produced highly creative final designs. This suggests that there are either two avenues to final designs of high creativity, one supported by mindfulness and one facilitated by a third factor, or there is a U-shaped relationship between mindfulness and design creativity. While mindfulness can support creativity (Baas *et al.* 2014; Lebuda *et al.* 2016; Henriksen *et al.* 2020), it is more likely that it is not the only contributor to highly creative final designs. Students' state stress levels did not vary meaningfully by cluster, and therefore, no distinguishable relationship could be found between students' state stress and their design creativity. Interventions to increase designers' mindfulness may help them produce more creative final designs, but there are also other routes to improving design creativity, like reducing design fixation (Jansson & Smith 1991).

6.4. Design challenge intervention

This section addresses RQ 4, *how do introductory engineering students perceive the inclusion of an MBI to affect their mindfulness, stress, and creativity during a multistage, hands-on engineering design assessment?*. In general, students in the MBI were more receptive to the scheduled breaks than students in the control condition. Five themes were present regarding students' perceptions about the design challenge breaks. These themes included (1) *breaks as a distraction*, (2) *breaks caused a change in emotion*, (3) *breaks impacted design time*, (4) *breaks encouraged thinking and reflection* and (5) *breaks improved creativity.*

All five of these themes can be directly related back to the Mental-Stress Creativity theory by Nguyen & Zeng (2012) and indicate that the breaks likely affected students' stress during the design challenge. The breaks being a distraction likely impacted stress through a temporary increase or decrease in mental workload depending on how positively or negatively they perceived the breaks. Similarly, students' change in emotion due to the breaks could have increased or decreased their mental capacity through affect depending on their experience. The effect of the breaks on design time likely contributed to reduced mental capacity through affect as many students in this theme reported that the breaks were a waste of design time. Similarly, the thinking and reflection students did during breaks could have increased mental capacity through affect (i.e., when students were self-reflective) or knowledge (i.e., when students reflected on their design decision-making). Lastly, the perceived increase in creativity due to the breaks could have affected mental capacity through skill (i.e., genuine increase in creativity) or affect (i.e., positive emotion due to fulfilling a goal). These results

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suggest that students likely experienced an increase or decrease in their stress depending on their experience during the breaks. Future research should measure students' stress immediately following the breaks.

Additionally, aspects of these themes align with prior MBI research. For example, thinking and reflecting during the breaks was mainly reported by students in the MBI. Increased self-reflection was previously found to be an indication of an improved intrapersonal competency when first-year students experienced a different MBI (Huerta *et al.* 2021). Prior research has also found that practicing meditation can induce a relaxation response (Mohan *et al.* 2011), which aligns with the experiences of students who described increased relaxation and less perceived stress due to the MBM breaks (i.e., the breaks causing a positive change in emotion). Students in the MBI were more likely to report positive experiences during the breaks than students in the control condition.

Students who had a negative experience with the breaks often described the breaks as negatively interrupting their work or focus, having increased negative emotions due to their work being interrupted, and the breaks wasting time they could be using for design. A similar number of students in both conditions reported having these negative experiences. The intervention breaks in this study were prescheduled and, therefore, may have occurred at inconvenient points in the design process. Students likely would have had better experiences with the breaks if they occurred at natural stopping points in the design process. However, many students reported that they did not need a break during the design challenge because 2 hours was a manageable duration for them to focus. Alternatively, while task-switching has previously been shown to reduce design fixation and improve performance (Sio *et al.* 2017), it may be too difficult for first-year engineers. Instructors could consider allowing students to choose when to take their breaks or make the breaks optional to encourage a better student experience.

Students who described having a positive experience with the breaks frequently reported them as being a positive distraction from the design challenge or experiencing an increase in positive emotion or emotional state due to the break. A couple of students also reported that the breaks helped them manage their design time. Positive emotional experiences were more common among students in the MBI than students in the control group. Positive emotional experiences for students in the MBI were often described as leading to less stress and more relaxation, which likely indicates that the MBMs did help some students to manage their stress. This aligns with previous research, which found that practicing meditation before playing stressful tasks like videogames can reduce the stress response to the task (Mohan *et al.* 2011). Alternatively, students in the MBI condition may have more positive emotional experiences because they were familiar with the MBM practices from their course, while students in the control condition had less experience with the AUTs. To preserve the effects experienced by some students, instructors could consider incorporating an MBM before beginning an activity like the design challenge.

Some students also reported the breaks as an opportunity for thinking and reflection. Students typically reported that their thinking was related to the design process, including their progress up to this point and planning for how they will continue the process going forward. Schön (1983) posits that reflective practice is an essential skill for professionals and argues that engineers will have to develop reflection-in-action skills or the ability to learn and correct during the process.

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While reflective practice is typically incorporated in engineering using reflective essays (e.g., Turns *et al.* 1997), these breaks may provide better opportunities for engineers to be reflective during the design process.

Lastly, several students stated that the breaks improved their creativity. As described above, while some students might have truly experienced an improvement in their creativity due to the breaks, it is also possible that these students set open goals for creativity that were fulfilled by the break activities. Prior research has determined that some MBMs can be practiced to support creativity (Henriksen *et al.* 2020), but alternative break activities to encourage creativity should also be explored and tested for design.

6.5. Limitations and recommendations for future research

This study had many promising, interesting and significant results (summary in Table 3). For additional recommendations for implementing mindfulness-based practices into engineering courses and an analysis of qualitative data focused on mindfulness-based practice in introductory engineering design courses, please see Nolte *et al.* (2022*b*). A principal limitation of the current non-randomized study was the power, sample size and participant diversity (i.e., race/ethnic diversity). This study should be replicated at an institution with more diversity to investigate if this MBI impacted minoritized students uniquely. Another limitation is that the MBMs used for this intervention are from one program. While this makes it easy for instructors to implement these practices, it is unknown if these results are unique to this program. Additionally, the MBI was only implemented by one of the two course instructors in this study. However, all four course sections utilized the same core instructional materials, a unique teaching assistant was responsible for delivering a portion of the instruction to each course section and prior research has only identified minimal effects due to the instructor (Nolte & McComb 2021; Nolte *et al.* 2022*a*). Therefore, while it is unlikely that the results of this study are due to the instructor, this study should be replicated with more course sections and instructors to ensure that none of the results are dependent on the instructor. Lastly, this data was collected during the first semester of in-person classes after the classes were moved online due to the COVID-19 pandemic. It is unknown how this may have influenced the data in this study.

Future research should be conducted to continue understanding students' stress during design and explore how MBIs uniquely affect engineering students. Future work investigating mindfulness in engineering should use various methods for measuring mindfulness as the quantitative and qualitative mindfulness results in this study were often incongruent. Measures including neuroimaging, physiological measures or behavioral tests may be more indicative of true changes due to MBIs (Tang & Posner 2013). Additionally, the results of this study could be used to create alternative interventions to help students during design. Promising interventions could include directly targeting challenging design stages or increasing students' self-efficacy through additional hands-on experiences. Lastly, this study identified a relationship between students' state mindfulness and the creativity of their final designs. These results suggest a novel line of research in engineering investigating the effect of MBIs on design creativity, which should be further explored. For example, future research should examine the creativity of all

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Table 3. Recommendations to instructors based on the principal results of this study

Area of interest	Result	Interpretation	Recommendation
Creativity	Students in the MBI had higher-quality designs	It is posited that the time students had to think during the MBM promoted creativity	Instructors should consider incorporating more time for thinking and reflection during design activities to promote learning and creativity
	Students in Cluster 2 and Cluster 3 had highly creative designs	While higher mindfulness levels support creativity, this is not the only conduit to creative designs	Instructors can promote mindfulness to increase creativity along with encouraging other creativity-promoting activities. They should also offer extra help to students identified to be having a Cluster 3–type experience
Mindfulness intervention	Negative experiences due to the breaks were often related to interrupted work and wasted design time	The prescheduled nature of the breaks interrupted the design process	Instructors should consider using the break activities either before beginning an activity like the design challenge or in the middle of the task at a natural break point (e.g., between conceptual and physical design)
	More positive experiences were reported related to the MBM breaks	Students were more receptive to the MBM breaks and perceived them to have more benefits	Instructors should consider the goal of the breaks before deciding on a style. Alternative break styles could include true breaks, active breaks or breaks for collaboration

brainstormed designs as prior work has shown that the most creative designs are not always chosen as the final design (Starkey *et al.* 2016; Zheng & Miller 2018).

7. Conclusion

This study investigated the effect of an MBI on first-year engineering students' stress and final design creativity during a multistage, hands-on design assessment. Data were collected using a mixed methods approach. While no significant increase was found in students' measured state mindfulness due to the MBI, state mindfulness was a significant contributor to students' experience during the design challenge. Students' interview responses indicated that they perceived an impact on their stress during the design challenge due to the breaks; however, no statistical differences were found in students' stress scores by condition. Students in the MBI condition were found to have higher-quality final designs, and high and low state

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mindfulness were found to have a relationship with highly creative final designs. Future research should continue to investigate MBIs in engineering design to improve design education and design outcomes.

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A. Appendix. Semi-structured interview questions

1. Can you briefly walk me through your design process during the in-class portion of the super quiz? (How did you develop a solution to the design prompt?)

2. What was your level of confidence while participating in the in-class portion of the super quiz?
   a. Were there any aspects of the in-class portion of the super quiz that you were highly confident about? Why?
   b. Were there aspects of the in-class portion of the super quiz that you were not so confident about? Why?
3. What parts of the in-class portion of the super quiz were easy? Why?

What parts of the in-class portion of the super quiz were hard? Why?

4. I would like you to think back to the way you felt during the in-class portion of the super quiz. What emotions did you experience?
   a. Did you experience any positive emotions during the super quiz? If so, what caused those emotions?
   b. Did you experience any negative emotions during the super quiz? If so, what caused those emotions?
   c. Were you worried during the super quiz, or did you experience anxiety? If so what were the sources of your worry or anxiety?
   d. Did you find the super quiz to be stressful? If so, what was stressful about the super quiz?
   e. How well do you think you were able to regulate your emotions during the super quiz? Why?
5. How would you define your ideal level of stress when completing a design task like the super quiz? Why do you think this is the best level of stress?
6. Would you describe yourself as someone who thrives under pressure? Why or why not?
   a. How do you think this impacted your design process or experience during the super quiz?
7. What were your feelings about the scheduled breaks during the in-class portion of the super quiz? Why?
   a. Were there other activities you would have rather liked to do during the 5-minute breaks? Why?
   b. Were there aspects of the breaks you found to be either positive or negative? Why?
8. Do you think these scheduled breaks impacted your design process? How?
9. If you were to do a design project like the super quiz again in the future, would you schedule breaks? Why or why not?
10. [Mindfulness] I would like to talk about the daily mindfulness exercises that you have been completing in-class since the beginning of the semester. How did you feel about the daily mindfulness practices?
    a. [Mindfulness] What were the positive or negative aspects of these practices? Why?
    b. [Mindfulness] Do you think practicing mindfulness had any impact on your engineering abilities? If so, can you describe this impact?
    c. [Mindfulness] How would you change these daily practices for other classes if you were to do them again in the future?
    d. [Mindfulness] Will you continue to practice mindfulness after this class? Why or why not?

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11. Would you describe engineering design as an inherently difficult or challenging topic? Why do you think this?
    a. Why do you think engineering design is perceived this way by others? OR Why do you think others might perceive engineering design to be difficult or challenging?
    b. What are the positives or negatives of this perception?
    c. How well do you think you are able to manage the level of difficulty or challenge in engineering (generally)?
12. Do you currently practice any methods for managing stress? What methods and how often do you use them?
    a. When did you learn that these methods were effective for managing your stress?
    b. Would you be interested in learning more methods for managing stress? Are you interested in any specific methods?
13. Are there other questions you think we should be asking?
14. Are there any other experiences you had during the super quiz that you would like to share? This could include the in-class or out-of-class portion of the super quiz.

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