

Navigating Mistakes: How Undergraduate Engineering Students Learned to Achieve in a Mastery Learning Course at a Hispanic-Serving Institution*

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Mastery learning can help the development of engineering students at Hispanic-Serving Institutions (HSI) by offering multiple opportunities to succeed and allowing for individualized instruction. This educational strategy has been shown to positively affect student performance and learning. Making and correcting mistakes is a key feature of mastery learning courses, yet, there is a lack of understanding of how students react to mistakes and the factors that help students learn from mistakes. We conducted a longitudinal qualitative study with seven engineering students from a Hispanic-Serving Institution who experienced a mastery learning engineering course. The data sources examined were longitudinal interviews, course syllabi, and course grades. We utilized reflexive thematic analysis and longitudinal analysis to explore how individual students described changes in their reactions to mistakes, identify cross-participant patterns in their reactions to mistakes, and examine the factors that facilitated students' learning from mistakes. We found that students experienced an increase in their abilities to learn from mistakes due to some of mastery learning's architectural features. Even after making several mistakes on exams, students experienced an increase in positive emotional reactions and a reduction in negative emotional reactions. Towards the final weeks of the course, some students started to feel negative emotional reactions to mistakes due to the lack of opportunities to achieve the learning objectives. Mastery learning's focus on academic growth fostered a stronger sense of belonging among the women in the study. This investigation provides evidence of ways HSI students may benefit from mastery learning courses, its effects on HSI students' academic development and wellbeing, and women's sense of belonging. HSI servingness can be enhanced by providing equitable opportunities for all students to succeed and fostering a supportive learning environment via mastery learning.

Keywords: mastery learning; mastery-based grading; Hispanic-Serving Institution; longitudinal; qualitative

1. Introduction

The American Society for Engineering Education and the National Academy of Engineering are preparing broad recommendations on how educators can systemically transform engineering education based on inclusive and student-centered practices [1]. They encourage more implementation of assessment practices to support students' mastery of engineering as a way to shift the focus from *selecting* talent to *developing* talent [1–3]. Mastery learning is one such educational practice that incorporates assessments aimed at supporting students in mastering course learning objectives. This educational strategy allows each student the time they need to achieve mastery of a learning outcome and encourages them to persevere through the learning process. In a mastery learning implementation, students are given multiple opportunities to master learning objectives and are not penalized for the mistakes it took to achieve them [4]. Bloom [3, 5] described how mastery learning was designed

to accommodate students' individual learning needs and provide focused support tailored to each learner. Mastery learning, through its use of competency or mastery assessment practices, has recently seen increased use in engineering courses [4]. In mastery learning, students go through a process of making and correcting mistakes in order to understand the methods to solve a learning objective [3, 6]. The process of making and learning from mistakes is especially relevant in engineering courses where achieving the final answer to a typical problem requires students to take several well-defined steps. Each step the student needs to take in solving an engineering problem is a juncture where mistakes can occur. Yet, in mastery learning, mistakes are not detrimental but are part of the learning process, and students are given ample time throughout the semester to learn from their mistakes [3, 4].

A systematic literature review of undergraduate engineering courses using mastery learning found that mastery learning had a positive effect on

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engineering students' homework, final course grades, pass rates, and most students acknowledged that mastery learning helped them learn better [4]. Kaw and Clark [7] also presented evidence that a variant of mastery learning, standards-based testing, led to students attaining higher course grades. The top three benefits of mastery learning reported by instructors were that "mastery learning turns assignments into formative assessments," that "students have to make sure their work is correct," and that instructors are more confident in the relationship between student grades and what students accomplish [4, p. 1377]. Mastery learning may be compared to a hands-on learning approach because students work with engineering problems for longer periods of time, reflecting on new problems until they achieve a mastery grade. Hands-on learning approaches have been associated with better cognition and professional preparedness [8]. Several studies that applied mastery learning in engineering or other STEM courses describe students' thoughts about learning from mistakes [9–14]. Some studies briefly discuss how students held a positive view of mistakes and the opportunities they present for learning [9, 11]. Students appreciated the chance to demonstrate their ability to learn from mistakes [13] and found that mastery learning helped them learn from mistakes [10, 12, 14]. These studies have focused on describing their learning implementations and have presented limited evidence on student experiences. To our knowledge, no study has longitudinally documented students' reactions to mistakes or the reasons why students might be learning from mistakes in a mastery learning course.

The achievement metrics reported in one study suggest mastery learning holds promise for realizing equitable educational outcomes for minoritized students [12]. Specifically, Leonard et al. [12] showed that minoritized students achieved higher course passing rates in a mastery learning course sequence than in the same traditional course sequence. However, little attention has been given to understanding how minoritized students at a Hispanic-Serving Institution learn to achieve in a mastery learning environment. Of the 23 studies that reported implementing mastery learning in the systematic literature review [4], 77% percent of the institutions were Predominantly White Institutions. While scholars claim that mastery learning promotes equitable practices [3, 12], more evidence is needed to show how mastery learning produces more equitable outcomes for minoritized students. Additionally, current literature on HSIs lacks discussions on alternative educational strategies that can equitably serve Latinx populations. The discussion on how researchers conceptualize HSI

servingness does not include alternative educational strategies that might be beneficial for Latinx students [15]. Thus, there is a need for research directed at understanding if and how mastery learning may be helpful for students at HSIs.

The purpose of this study was to understand how students enrolled at an HSI reacted to mistakes in a mastery learning course and to explore the reasons why they may have learned from mistakes. Mastery learning emphasizes the importance of providing students with a safe space to make mistakes and turns these mistakes into opportunities for development [3]. The process of making and correcting mistakes enhances memory for the correct response, and it guides the learner to focus their attention in the right direction [16]. Perkinson [17] notes that a common standpoint among learning theorists is "learning from our mistakes;" in this view, mistakes are not something to be avoided at all costs but form a natural part of the continuous generation of knowledge. Mistakes are seen as part of an organic process of inquiry and discovery. *How students learn from their mistakes is related to how they react to their mistakes.* Positive reactions to mistakes have been connected to greater persistence and engagement [18] and greater learning outcomes [19], while negative reactions to mistakes diminish effort and reduce one's desire to fix their mistakes [18]. Thus, it is important to understand how mastery learning impacts students' reactions to mistakes and the reasons behind the process of learning from mistakes. Despite mastery learning's importance in the current discussion of transforming engineering education, its relevance to HSI's servingness, and the preliminary evidence on students' perspectives toward mistakes, there is little evidence on how students *actually* react to making mistakes and the reasons why students might learn from mistakes in mastery learning engineering courses. Understanding how students react to and learn from mistakes in engineering courses that utilize mastery learning is important for assessing its impact on students' mental health and wellbeing, as well as why students in these courses may exhibit greater academic development compared to students in traditional courses.

The current study examines these topics qualitatively for undergraduate engineering students from an HSI who experienced a mastery learning course. We conducted a longitudinal investigation to examine students' reactions to mistakes before and during their participation in a mastery learning course and investigated the reasons students attributed to learning from their mistakes. Specifically, the research questions we investigated were:

RQ1. What temporal changes were observed in participants' descriptions of their reactions to mistakes during a mastery learning course?

RQ2. What facilitated students' learning from mistakes in mastery learning courses?

1.1 Theoretical Framework: A Student's Process of Learning from Mistakes

We used Tulis et al.'s [20] Learning from Mistakes framework to understand students' changes to their emotional and cognitive reactions as they described making mistakes and learning from them. The learning-from-mistakes process starts when an individual encounters a mistake and ends when learning from the mistake occurs (see Fig. 1). The process comprises a chain of reactions: Initial Reaction, Secondary Reaction, and Managing Emotional and Motivational Responses, learning strategies; and learning outcomes. All the steps are influenced by the learner's personal char-

acteristics, like their motivational beliefs, self-concept, or goal orientation [20]. As well, every step of the mistake reaction process is potentially affected by the situation. The situation includes the characteristics of the task, for example, a creative task vs. a routine task, and the learning environment, for example, mastery learning versus a traditional course structure [20, 21].

1.1.1 Initial Reaction to a Mistake: Evaluating the relevance of one's mistake to their goal(s)

When a student makes a mistake, they evaluate the relevance of their mistake to their goals, determining if the mistake jeopardizes their goals [22]. For example, when students fail an exam, they consciously or subconsciously evaluate whether the mistake is relevant to their goal of graduating. If the mistake thwarts a student's achievement goal, a negative emotion follows. Students may experience a variety of emotional responses after assessing the

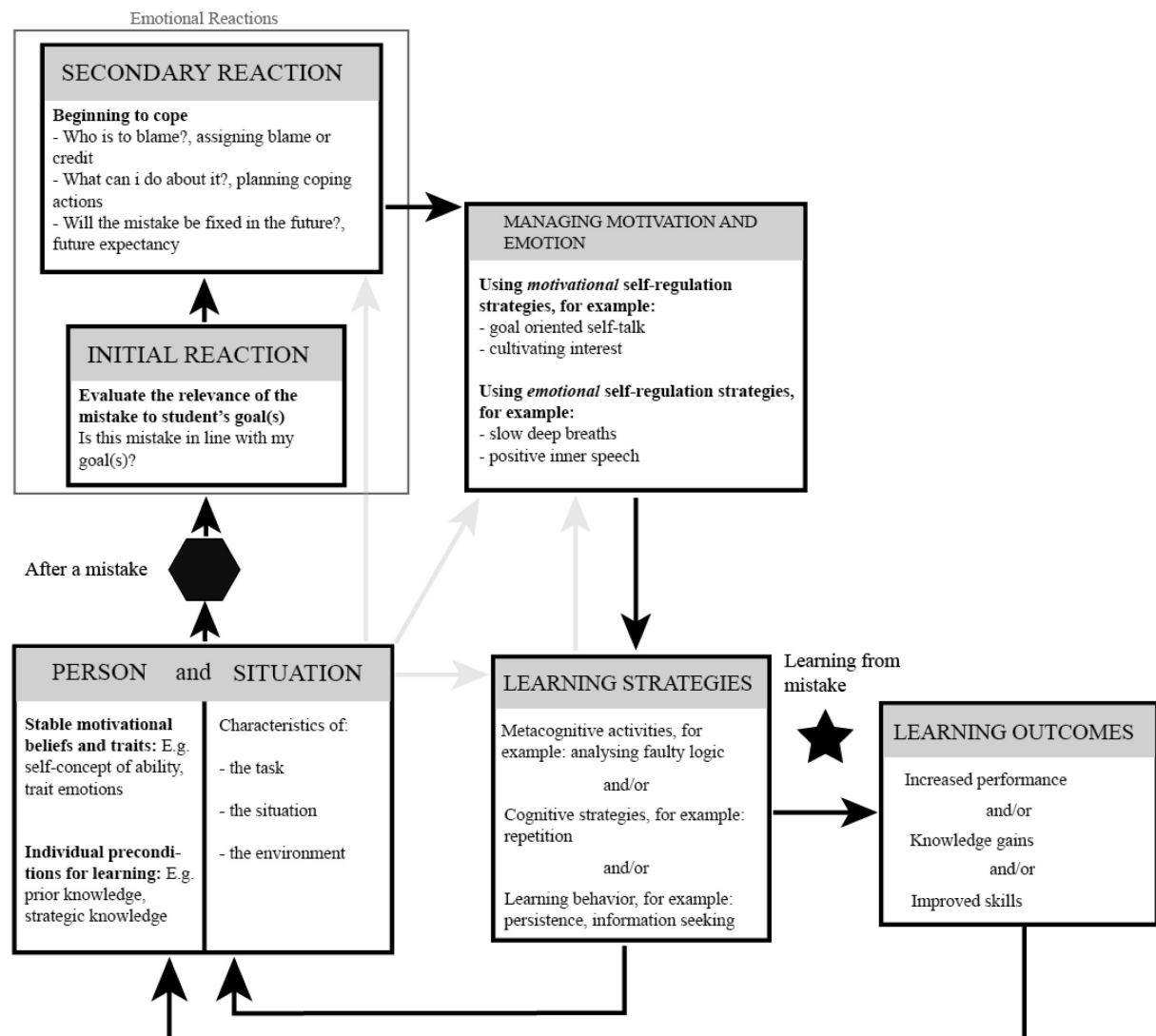


Fig. 1. Learning from Mistakes integrative theoretical framework adapted from [20].

impact the mistake has on their academic goals [22]. For example, a student who finds that a mistake goes against their goals for a class might experience frustration, while a high-achieving student who typically might expect to get the right answer might experience surprise after encountering a mistake.

1.1.2 Secondary Reaction to a Mistake: Beginning to Cope

After students process how failing an exam or answering problems incorrectly impacts their academic goal, students then begin to cope with the mistake. Whereas the initial evaluation was directed to answer the question, “Is this mistake in line with my goal?” the secondary evaluation addresses one of these three questions. The secondary evaluation can address “Who is to blame for the mistake? by assigning blame or credit, “What can I do about it?” by planning coping actions, and “Will the mistake be fixed in the future?” by considering future expectancy [22].

When students are trying to assign blame or credit to their mistakes, they are evaluating whether to attribute their mistakes to their own ability or whether to associate the mistake with the difficulty of the task [23]. If a student attributes their mistake to their own ability, this can decrease their self-concept and motivation. Conversely, if a student attributes a failure to a task difficulty, they may be motivated to try again under a different circumstance [23]. Those who plan to cope reflect on how they can respond to the demands of the mistake [22]. In the last response of this phase students direct their attention to the future and reflect if, for any reason, the mistake is likely to be fixed (i.e., future expectancy). This is relevant in mastery learning courses where students know they have multiple opportunities to fix their mistakes in the future.

The secondary evaluation is also followed by an emotional reaction [20]. If a student decides a mistake contradicts their achievement goal (i.e., initial reaction), they might choose to believe that the mistake occurred because they lacked ability (i.e., assigning blame), and this secondary evaluation might lead to an increase in students’ emotional reaction (e.g., frustration). Students’ reactions to mistakes may be conscious or unconscious. In any given case, a student reacting to a mistake will likely have a mixture of conscious and unconscious evaluations. It is possible that some of the components of the initial and secondary evaluations happen simultaneously. Additionally, it is possible that some components of the evaluations (i.e., planning to cope or future expectancy) may not happen at all [22].

1.1.3 Managing One’s Motivational and Emotional Responses

Following the Secondary Reaction, students proceed to implement strategies aimed at managing their motivation and emotions to help achieve their goals [20, 24–26]. Specifically, students employ motivational strategies to sustain the effort needed to remain engaged in their learning [26]. Emotions can trigger actions in the form of goals and can direct students’ attention. Pekrun et al. [27] demonstrated that emotions can prepare and sustain students’ responses to important events. Through emotional regulation, students maintain their motivation and persevere toward completing academic tasks [27, 28].

Strategies for regulating one’s motivation include assigning consequences to one’s behavior, goal-oriented self-talk, cultivating interest in the activity, and restructuring the environment by decreasing the possibility of off-task behavior or defensive pessimism [26, 29]. Under some conditions, some of these strategies to regulate motivation may be used by students unconsciously. Regulating one’s emotional reactions is necessary to decrease negative affective responses to mistakes and the damaging effects related to negative performance evaluations [30]. Emotions are thought to guide subsequent learning behavior through persistence, attention focus, or information seeking. When a student encounters a mistake, regulating their emotions becomes necessary to maintain task engagement [20]. Some strategies that students may use to manage emotional reactions include applying breathing techniques, wishful thinking [31, 32], and positive inner speech [33].

1.1.4 Learning Strategies

The previous reaction steps (i.e., Initial Reaction: evaluating the relevance of one’s mistake to their goal(s), Secondary Reaction: beginning to cope, and Managing Emotional and Motivational Responses) lead to the use of learning strategies. In this phase, students may leverage a number of learning strategies including using cognitive and metacognitive strategies, and engagement in learning behavior, such as information-seeking, to persist through the initial mistake. Cognitive strategies may include repetition of information, making the information more meaningful by rearranging or grouping, categorizing or constructing networks, or creating connections between the new information and stored knowledge [34]. Students’ reflections about their thought processes (i.e., metacognitive strategies) may be used to monitor progress in their understanding of course material [35, 36]. For example, when a student reviews a

failed problem and goes over what parts they did not understand, they are engaging in metacognition. Metacognitive strategies can also lead the student to establish new goals and use other cognitive strategies [35, 36].

1.1.5 Learning Outcomes

Knowledge, skills, and performance gains are learning outcomes that can result from productively applying learning strategies. Students' learning outcomes can be assessed by evaluating their understanding of concepts, their ability to apply their knowledge productively or in different situations, or through performance metrics (e.g., exam grade, course grade, etc.).

To summarize, after encountering a mistake, like getting a problem wrong in an exam, a student goes through the initial evaluation where they determine if the mistake goes against their goals for the class and experience an emotional response like frustration. In the secondary evaluation, a student may determine that the blame rests in their lack of ability, and their frustration is intensified. As a result, they may use self-regulation techniques to prepare themselves to go back to learn from the mistake. The motivational regulation technique they might use could be goal-oriented self-talk, and the emotional regulation technique they might use could be positive inner speech. The student then engages in learning strategies such as evaluating the flawed logic behind the mistake and information seeking. These learning strategies lead the student to find their faulty logic and understand the reasoning necessary to solve the problem. By undergoing this process, a student acquires the knowledge needed to learn from their mistakes to improve their performance. We used this theoretical framework to help interpret students' descriptions of the reactions to mistakes they experienced before and during a mastery learning course.

2. Methods

This study is part of a larger research project aimed at investigating students' experience in a mastery learning course environment [37]. Mastery learning courses were offered in the Fall 2022 semester at a Hispanic-Serving Institution in the Southwest of the U.S., herein referred to as West Coast University. The College of Engineering at this institution faces high D/F/W rates, with more than 50% non-completion rates in gateway engineering courses. Grading practices were hypothesized as a reason behind the large equity gaps. As a result, the faculty who taught Statics, Strength of Materials, and Embedded Systems Programming I joined a learning community to help redesign their courses

using mastery learning with the aim of improving student performance. The College of Engineering at West Coast University has a Latinx enrollment of 67%; 54% are first-generation college students, and 58% of their students were eligible for a Pell Grant.

2.1 Mastery Learning Course Architecture Implemented at West Coast University

Mastery learning is a student-centered educational strategy encompassing grading techniques and an equity-focused teaching philosophy [3, 6]. How mastery learning is implemented in practice may vary; see [4] for a synthesis. In this section, we described the implementation for the three engineering courses specific to this study: Statics, Strength of Materials, and Embedded Systems Programming I. In these implementations, formative tests were considered part of the learning process and not an evaluation of learning; rather, the number of mastered learning objectives was used to assign a final course grade. The formative tests occurred often throughout the semester, so students had multiple opportunities to show mastery. Learning objectives are specific units of knowledge the instructor aims for the student to master and are related to major course learning outcomes.

In Table 1, we outlined the important components of the mastery learning architecture for each course. The table shows which assessments were used to evaluate mastery, the frequency of assessments, the grading type, the feedback provided, and the requirements for a passing course grade. The three courses' architecture aligned with some of the ways mastery learning has been implemented at other institutions [4]. The courses assessed mastery of the learning objectives through exams, homework, quizzes, or design projects. Several opportunities to demonstrate mastery of learning objectives were provided. Students were required to attain a mastery grade in each learning objective. However, in Statics and Strength of Materials, an indication of progress was given to students about how far from mastery they were. All instructors were taught the importance of providing guided feedback to aid students in achieving mastery of the learning objectives, and during the faculty learning community meetings, they discussed implementing some form of feedback throughout. To assign the final grade, each course specified which set of learning objectives had to be mastered.

2.1.1 Statics Course

The Statics mastery learning course assigned weekly homework, in-class group work, quizzes, and exams. There were 27 learning objectives that could be mastered, which were divided into Fundamental (ten), Comprehensive (six), and Expanded

(eight). For example, a Fundamental objective was “I can find 2D moments.” The class also had three Procedural Abilities objectives related to the practice of engineering. Learning objectives were graded “mastery,” “close to mastery,” or “far from mastery.” A student who did not achieve a grade of “mastery” in a learning objective was required to retake the assessment associated with that objective. A grade of “close to mastery” meant that minor mistakes were made, and the student demonstrated no major conceptual misunderstandings. Those who received “far from mastery” demonstrated major conceptual misunderstandings. The learning objectives were evaluated via six exams, including the final exam. The syllabus indicated what learning objectives were primarily being assessed on each exam. For example, the fourth exam primarily evaluated Fundamental objectives four through ten, Comprehensive objectives one and two, and Procedural Abilities objectives one through three. However, if students had failed a learning objective on the first exam, they could retake it in any other exam.

The grading system was based on which learning objectives students mastered by the end of the course. To attain a “C” grade, students had to master all ten Fundamental objectives, and two Procedural Abilities. To achieve an “A” in the course, students had to master all ten Fundamental objectives, the six Comprehensive objectives, one Expanded objective, and the three Procedural Abilities.

2.1.2 Strength of Materials Course

Students in this course had homework, in-class group exercises, and exams. Students could master

a total of 16 learning objectives. There were three types of objectives: Fundamental (nine), Expanded (five), and Comprehensive (two). An example of a Comprehensive learning objective was “Solve problems of combined loading.” Students needed to demonstrate mastery of the problems identified as Fundamental before receiving credit for the higher-level problems (i.e., Expanded or Comprehensive). The grades for each learning objective also had a three-tier system using the following convention: “mastery achieved,” “revise,” or “retake.” A “retake” was defined as a learning objective that presented significant mistakes in the solution, misconceptions on problem type or misapplication of theory, incorrect methodology, or multiple calculation errors. Learning objectives graded “revise” were those that presented minor calculation or sign errors and could be corrected and resubmitted within a specified period after the exam. “Mastery achieved” meant the objective had been correctly solved, and no more attempts were needed.

Students had opportunities to demonstrate mastery of the learning objective in six exams, including a final exam. Each exam tested a limited set of objectives, but all learning objectives were tested multiple times. For example, the first two Fundamental objectives were tested in exams one, two, three, and six; the Fundamental objectives three to seven were tested in exams two, three, four, and six. To receive credit for an objective on an exam, students had to complete the homework for that learning objective. Their course grade was based on the number of completed learning objectives and cumulative homework grades. For example, to pass the course with a “C” grade and progress to higher-level courses, students had to master all nine

Table 1. Architectural components of each mastery learning course outlined in the syllabus

Architectural Components	Mastery Learning Courses		
	Statics	Strength of Materials	Embedded Systems Programming I
Learning objectives	Assessed using exams	Assessed using exams and homework	Assessed using quizzes and design projects
Number of assessments to achieve mastery of learning objectives	Five exams plus a final exam	Five exams, a final exam, plus homework assignments. For each learning objectives, mastery had to be attained in exams and homework	Each learning objectives was assessed at least four times
Grading type	Mastery/Close-to- mastery/Far-from-mastery	Mastery-achieved/Revise/Retake	Check/No-check
Feedback	No mention of feedback on the syllabus, however observations at the faculty learning community show that feedback was provided to students	Feedback was provided on each learning objective along with the grading “Revise” or “Retake”	Feedback was provided on each learning objective, and more detailed feedback was given in reflection assignments
Passing course grade	“C” grade required ten learning objectives labeled Fundamental and the 2nd Procedural Abilities objective	“C” grade required nine Fundamental learning objectives and a 73% cumulative homework grade	“B” grade required mastery of all “B-level” learning objectives twice

Fundamental objectives and attain a minimum of a 73% homework grade. To earn an “A” course grade, students had to master nine Fundamental objectives, five Expanded objectives, one Comprehensive objective, and achieve a cumulative 93% homework grade.

2.1.3 Embedded Systems Programming I Course

The Embedded Systems Programming I course had homework, reflections, quizzes, and design problems. A total of 29 learning objectives were divided into “B-level” and “A-level.” There were 22 “B-level” objectives and seven “A-level” objectives. An example of a “B-level” learning objective was “Use descriptive variable names that include type information and data purpose.” Learning objectives were evaluated on four quizzes and design projects. Each quiz problem or design project had a set of objectives that the solution had to meet. There were at least four opportunities to demonstrate mastery of each objective. Grading was done using a checkmark system to indicate which learning objective was mastered. If the student did not master an objective, it was not “checked.” The instructor provided feedback on failed objectives. In addition, the instructor used the reflection assignments to understand students’ thought processes and provide more detailed feedback.

Students could obtain only three baseline grades in the course: “A,” “B,” and “No Credit.” To earn a “B” grade, the minimum passing grade, students had to demonstrate mastery of each “B-level” learning objective at least twice. To attain an “A” grade, students had to demonstrate mastery of “A-level” objectives at least once and on “B-level” learning objectives at least twice. If students submitted most homework and reflections, they

attained a plus modifier in their course grade. For example, if students demonstrated mastery of the “B-level” learning objectives and also submitted all of the homework and reflections, they would attain a “B+” grade.

2.2 Recruitment and Participants

All students enrolled in the Statics, Strength of Materials, and Embedded Systems Programming I mastery learning courses were invited to participate in this study. Only seven participants completed the interview questions related to reactions to mistakes. Table 2 shows the demographic characteristics of the seven participants whose interviews were used in the current study. Most of our participants were male, from Latinx backgrounds, first-generation college students, and enrolled in a mechanical engineering program. Almost all students had no experience with a mastery learning class before the Fall 2022 semester, while some students were concurrently enrolled in mastery learning courses unrelated to this project. Those enrolled in other mastery learning courses were asked to think about their course specific to this project when answering the interview questions. All student names in Table 2 are pseudonyms.

2.3 Data Collection

We used three data sources to obtain a deep understanding of participants’ reactions to mistakes and learning from mistakes: (1) three rounds of interviews, (2) courses’ syllabi, and (3) final course grades. Additionally, we had access to the course instructors implementing the mastery learning intervention to ask questions about their course architecture, and we observed faculty learning community meetings.

Table 2. Participants’ demographic characteristics and mastery learning course taken in the Fall 2022 semester

Pseudonym	Major	Class Standing	Race/Ethnicity	Gender	First-gen ¹	ML Course (Fall 2022)	Prior ML experience
Alexander	Electrical Engineering	Sophomore	Latinx	Male	Yes	Embedded Systems Programming I	No
Amy	Mechanical Engineering	Junior	White	Female	Yes	Strength of Materials	Concurrently enrolled
Andres	Mechanical Engineering	Junior	Latinx	Male	No	Strength of Materials	Concurrently enrolled
Diego	Mechanical Engineering	Senior	Latinx ²	Male	No	Statics	No
Jack	Mechanical Engineering	Junior	Asian	Male	Yes	Strength of Materials	Yes, and concurrently enrolled
Nicole	Mechanical Engineering	Junior	Latinx	Female	Yes	Strength of Materials	No
Rafael	Mechanical Engineering	Sophomore	Latinx	Male	Yes	Strength of Materials	No

¹ First-generation college student is defined as neither parent having a bachelor’s degree.

² International student from Guatemala

Our primary data sources were longitudinal interviews. Semi-structured interviews were conducted three times in a longitudinal research design during and after the mastery learning classes in the Fall of 2022. The first interview was completed within the first few weeks of the mastery learning course, the second interview took place nine weeks into the mastery learning semester, and the last interview was conducted in the middle of the Spring 2023 semester after the mastery learning course. Interview 1 contained questions related to students' reactions to mistakes in traditional courses. Interview 2 had questions about students' reactions to mistakes in the first half of the mastery learning course. Interview 3 contained questions about students' reactions in the last half of the mastery learning course, questions comparing their reactions in traditional courses versus those in the mastery learning course, and questions about learning from mistakes in the mastery learning course.

With some exceptions, almost all participants completed the three consecutive interviews. Nicole did not participate in Interview 2. However, she did agree to participate when invitations were sent for Interview 3. During Interview 3, she was asked about her reactions to mistakes in the mastery learning course and questions related to Interview 2. Amy chose not to participate in Interview 3. All interviews were video recorded using Zoom.

2.4 Data Analysis

We used reflexive thematic analysis [38] in conjunction with longitudinal analysis strategies [39] to find themes that addressed our research questions. Fig. 2 presents a schematic of the process of analysis we followed. The overall process of analysis was guided by the steps of reflexive thematic analysis proposed by Braun and Clarke [38]. Reflexive thematic analysis is a type of thematic analysis that values a subjective, situated, and questioning researcher. It sees subjectivity as a resource rather than an undesirable influence on the analysis process and encourages reflexivity throughout the research process. The process of reflexive thematic analysis follows these steps: (1) familiarization, (2) coding, (3) generating initial themes, (4) developing and reviewing themes, (5) refining, defining and naming themes, and (6) writing.

In the first step of data *familiarization*, we prepared and studied the data in several ways. After the interviews were conducted, data were transcribed by Rev.com. Transcripts were compared with the interview audio recording, and corrections were made to transcription when needed. As an initial step in the data analysis process, memos were written during and after data collection to generate ideas that could help later in the analysis process. A

summary for each interview was developed to help us become familiarized with the types of responses in each transcript, the kind of data available, and the theories that could be used to describe the data.

After the familiarization step, the data was *coded* first inductively and, later, deductively. We first coded inductively using open coding, which employs in-vivo and process coding [40]. Inductive coding was initially applied to help us find the most appropriate theoretical framework to use with the data and to help us begin to find common patterns. Later, we employed deductive coding using the concepts in the Learning from Mistakes theoretical framework [20]. Deductive coding allowed us to organize the data and provided us with a logical frame of reference for the diverse reactions expressed by the participants. Coding was primarily conducted by the first author and was reviewed, evaluated, and modified by the second author.

To *generate initial themes*, we used longitudinal analysis strategies [39] to examine the change process in students' reactions to mistakes and learning from mistakes before and during a mastery learning course. Longitudinal analysis strategies are particularly suitable for assessing interventions because they can help researchers understand the mechanisms through which the intervention operates [41]. We used two longitudinal analysis strategies [39]: (1) individual trajectory analysis to describe participants' trajectories in their reactions to mistakes before and during a mastery learning course, and (2) recurrent cross-sectional analysis to describe common temporal trends in reactions to mistakes and learning from mistakes across participants. Researchers recommend that longitudinal studies employ individual and cross-sectional approaches to more fully characterize temporal changes in the experiences of a group of participants [41, 42].

Individual trajectory analysis. We employed individual trajectory analysis to study participants' reactions to mistakes over time [39]. Longitudinal trajectory analysis is recommended when the researchers are interested in temporal changes in individual experiences. The theme presented in each description encapsulates the arc observed between a student's reactions in traditional courses and reactions in a mastery learning course. The individual descriptions of students' reaction trajectories allowed us to illustrate the diverse ways students reacted to mistakes in traditional courses, how they reacted to mistakes in a mastery learning course, and the differences in their reactions to mistakes between traditional and mastery learning courses. The focus on describing individual reaction trajectories can help educators understand how students are reacting to mistakes in their mastery learning course.

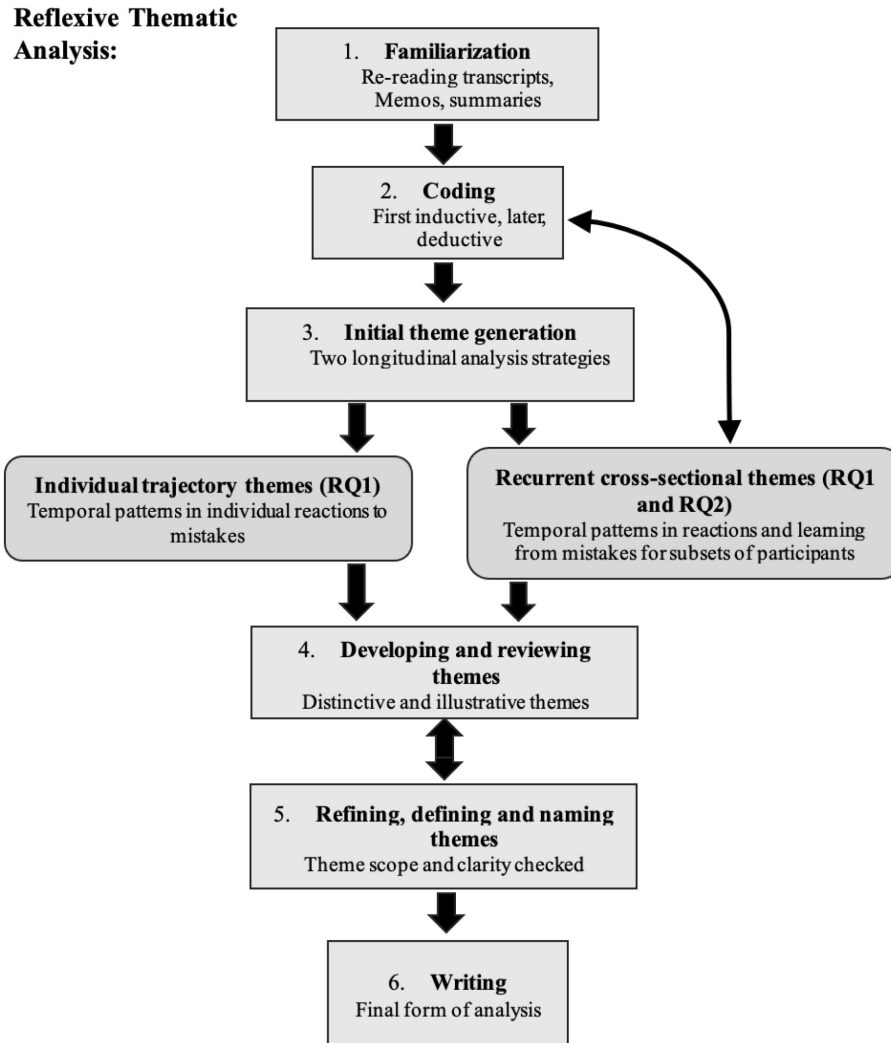


Fig. 2. Process for the generation of themes using reflexive thematic analysis [38] and longitudinal analysis strategies [39]. Arrows with two heads indicate steps where a recursive process was used.

Recurrent cross-sectional analysis. A recurrent cross-sectional analysis is ideal when researchers want to understand how the collective experiences of participants evolved over time [39]. In recurrent cross-sectional analysis, patterns across subsets of participants are extracted at each time point. Following this, differences or similarities between time points are recorded. For conciseness, the results from the recurrent cross-sectional analysis focus on salient group patterns occurring during the mastery learning course and do not emphasize describing group patterns in the traditional courses. Recurrent cross-sectional analysis themes captured the significant ways subsets of participants reacted to mistakes in mastery learning courses (i.e., RQ1) and why participants learned from mistakes in mastery learning courses (i.e., RQ2). In the process of finding initial themes using individual trajectory analysis and recurrent cross-sectional analysis, we modified the questions in Saldaña's [43] longitudi-

nal analysis guide to investigate temporal changes in the data.

The subsequent steps in the process (i.e., 4–6) were applied to each initial theme. When *developing and reviewing themes* we engaged with all the coded extracts and the entire data set to validate the quality and scope of the initial themes. In reflexive thematic analysis, a quality theme is built around a singular idea, illustrates the richness manifested in the data, is distinctive, and the themes do not merge into each other [38]. In the following step of *refining, defining, and naming themes*, the scope and theme clarity were checked, and the structure and flow of the analysis were refined. The last step in the process, *writing* the analysis, included formalizing the analysis to fit the needs of the final article. In this step, there was deep analytic work to shape the flow and detail of the analysis and tell the whole analytic story. As recommended by reflexive thematic analysis, we approached the generation and description

of themes as a recursive process where, when necessary, we went back to previous steps to modify the analysis to create a precise and nuanced story around the themes [38].

2.5 Research Quality

We employed various strategies to augment the trustworthiness of the research presented [44–47]. The strategies listed below were employed throughout the research process to continuously improve research quality as suggested by Walther et al. [48]. We present our strategies for trustworthiness using Lincoln and Guba's [44] model of credibility, transferability, dependability, and confirmability. We also describe our strategies to mitigate validity threats as recommended by Maxwell [49].

The credibility of the research process was enhanced by *developing familiarity* with the research participants and the mastery learning course instructors [44, 45]. We obtained familiarity with the research participants through the three longitudinal interviews that included background questions and through the demographics survey taken at the beginning of the mastery learning course. We gained familiarity with the mastery learning course instructors by attending faculty learning community meetings where they discussed their mastery learning implementation. Data from the interviews were *triangulated* with additional data sources and longitudinal interviews. The first method of triangulation came from conducting iterative questioning: questions related to previous interviews were asked in subsequent interviews. This style of questioning allowed us to evaluate the consistency of participant responses and allowed for a richer interpretation. Triangulation was also undertaken using course syllabi and course grades. We compared course syllabi with participants' narrations of how many learning objectives they had achieved and what grade they were expecting. We also included participants' narrations of their reactions to mistakes in the context of the final course grade they had achieved. Participants were asked to review our results and search for misinterpretations or misunderstandings (i.e., *member checking*).

Transferability was supported by rich contextual descriptions of students' reactions to mistakes [45]. To aid in contextual understanding, we included descriptions of the participating institution and details of the data collection methods employed. The study's dependability was improved by providing sufficient details of the methods used so that other researchers could replicate the study. Confirmability was enhanced by centering on participants' meanings rather than the investigator's preferences, the researcher's positionalities, and the study's limitations. The validity threats of

misinterpretations, reactivity, and bias were addressed (bias and reactivity from [47]). Possible misinterpretations of the data were not only addressed by the credibility strategies but also by centering interpretation on the meaning that the participants intended, using all available data to evaluate an interpretation, and looking for negative cases. The validity threat of reactivity was mitigated by encouraging participants to speak freely, honestly, and openly, informing them that their statements would not be criticized or judged, and refraining from asking leading questions. Bias was addressed by the first author, CLP, through a reflexivity journal where he maintained a record of ways in which his biases, perspectives, and experiences could influence the research. Additionally, to address possible biases by the first author, CLP and DV conducted debriefing sessions where coding categories, data interpretation, and theory interpretation were evaluated until a consensus was reached.

2.6 Positionality

2.6.1 CLP's Positionality

The first author is a Latin American postdoctoral scholar who graduated with a PhD in engineering education from a Hispanic-Serving Institution. CLP perceives the mastery learning educational approach to be a more humanistic approach toward education due to its provision for second chances. However, understanding this inclination, he consciously adopted a mindset of fair evaluation when examining students' perspectives on mastery learning. His previous journey through an engineering research tradition was embedded in post-positivist and positivist paradigms. In the past, he conducted engineering research under the perspective of an objective search for truth and the separation of researcher and data. Now, as an engineering education researcher, he has come to appreciate and incorporate the constructivist paradigm, where data is created through the interactions between researcher and participant.

2.6.2 DV's Positionality

The second author is a faculty member in an engineering education program at a Hispanic-Serving Institution and identifies as a Latina of Mexican heritage. She believes that issues of access span throughout a student's educational pathway and is acutely aware of the American educational injustices that systemically disenfranchise some students while privileging others. Her focus on the first-generation college student population in engineering stems from being a first-generation college student herself. Through her

own lived experiences, she recognizes the challenges first-generation college students, minoritized students, and those who live at the intersection face in the current engineering culture. Her motivation to embark on research focused on mastery learning stems from the belief that engineering educators need pedagogies that meet students where they are and provide opportunities to help *develop* their capabilities.

2.7 Limitations

The limitations of our study were the small number of interview participants, minimal gender representation, and the lack of focus on actions taken after mistakes. The small number of interview participants was not by design but was constrained to the number of students in the mastery learning courses who responded to our invitation email. Even though our recruitment process was inclusive of all identities our sample of students is mostly male, Latinx, first-generation, mechanical engineering students, thus limiting the transferability of our findings. However, assessments of transferability could be made by considering the full story of the participants' reactions to mistakes and the contextual information presented in the individual descriptions. Our study focused on investigating the variety of cognitive and emotional reactions that students can experience in mastery learning courses and the patterns in those reactions found across students. While we reference students' *actions* (e.g., seeking information), action reactions were not the focus of the study. The focus was to understand the differences in these emotional and cognitive reactions between traditional and mastery learning courses.

3. Results

We present five individual trajectory themes and three recurrent cross-sectional themes to describe students' reactions to mistakes in their mastery learning course (RQ1). In the individual descriptions, we compare students' reactions to mistakes in a traditional course to their reactions to mistakes during their mastery learning course. Specifically, we contrast individual participants' reactions to mistakes before the mastery learning course, during the first half of the course, and during the last half of the course to show different reactions-to-mistakes arcs that are possible for engineering students in a mastery learning course. The individual descriptions of Alexander, Amy, Andres, Nicole, and Rafael offered varied and nuanced reactions-to-mistakes arcs that may help instructors and researchers understand how students are experiencing a mastery learning environment better. Student's reactions to

mistakes before and during the mastery learning course are presented in alphabetical order. We also used recurrent cross-sectional analysis to obtain patterns of reactions common across multiple students to answer RQ1. The recurrent cross-sectional analysis themes discuss the role of a positive future expectancy on students' emotional reactions to mistakes, how mastery learning supported a sense of belonging, and the adverse emotional reactions to mistakes experienced in the last half of the mastery learning course.

To answer the second research question (RQ2), we present a salient recurrent cross-sectional theme that describes how mastery learning's structural features led students to learn more from mistakes. We found that retake opportunities and a focus on mastering learning objectives encouraged students to learn more from mistakes in their mastery learning course. We highlight students' views on why those mastery learning structures benefitted their journey of learning from mistakes.

3.1 Individual Trajectory of Students' Reactions to Mistakes (RQ 1)

3.1.1 Alexander: Shifted from feeling guilty in the traditional course to feeling optimistic in the first half of the mastery learning course.

Reactions to mistakes in a traditional course

Alexander described experiencing various reactions to mistakes that touch upon most of the phases described by Tulis et al.'s [20] Learning from Mistakes framework. He described evaluating the mistake against his goal, assigning blame to himself, feeling self-hatred, planning to persist, performing emotional management, looking for the reasons for the error, and asking other people in the class for help with his mistake.

After a mistake, Alexander evaluated the effects of the mistake on his overarching goal, recognizing that "It'd be harder to be able to get my engineering degree in the future, so I can help others in the future or help in molding the future" [Interview 1]. Alexander blamed himself for the mistake, "I should have been able to do better" [Interview 1]. The blame he felt escalated to feelings of guilt, and while it was difficult for him to disclose, he acknowledged he felt self-hatred, a sense that he "failed" himself, and his self-esteem deteriorated as he put himself in "lower regards." Nevertheless, Alexander elevated his emotions from a low emotional state to a higher emotional state where he "scrape[d] . . . [himself] back all the way up to pass the class" [Interview 1]. He tried to find the reason for the mistake, asking himself, "how did this happen?" [Interview 1]. Finally, he described actively seeking support from his peers, which is

part of the learning strategies phase, bringing him one step closer to learning from his mistakes.

Reactions to mistakes during the mastery learning experience

In the first half of the mastery learning course, Alexander described how his reactions to mistakes revolved around optimism about learning the material in the future and self-affirmation of his abilities. He reminded himself that he could correct his mistakes and learn the material (i.e., positive future expectancy), affirmed his capabilities, and told himself what to do about the mistake (i.e., planning coping actions).

Alexander acknowledged that he had another opportunity to learn the material, thinking: "I have time to try to relearn this," "I have a second chance at it. . .," and "I have the chance of doing this" [Interview 2]. His thoughts affirmed his abilities: "I can do this . . . I have the capabilities of doing this" [Interview 2]. Alexander planned to cope with the mistake and achieve a better outcome by stating: "I need to actually learn this correctly" and "I need to go back to the notes and learn this topic better" [Interview 2].

Alexander's reactions to mistakes in the first half of the semester were characterized by optimism about the possibility of correcting his mistakes and confidence in his abilities. Even after a mistake, Alexander was encouraged to believe that he could still succeed in his goals of passing the course and learning the material. With that encouragement, he affirmed his academic capability and planned to put effort into relearning the material.

However, during the last half of the mastery learning course, Alexander's reactions to mistakes were predominantly filled with fear of being unable to pass the course. He knew that at the end of the course, there were few opportunities to show mastery of the learning objectives; therefore, he experienced a heightened fear of failing the course. Specifically, he described why he felt fearful, stating, "The lack of time being [left in the course] . . . results in the lack of opportunities to try to retake it . . . the fight or die situation . . . takes occurrence" [Interview 3]. Alexander stated that the "fight or die" mentality was also how he typically felt in traditional courses due to their lack of retake opportunities.

There was a marked difference in how Alexander reacted to mistakes in the first half of the mastery learning course compared to the last half. Specifically, in the last half of the mastery learning course, Alexander's reactions to mistakes were marked by negative emotions and dominated by fear of failing the course due to the reduced retake opportunities. These negative emotions were similar to what he experienced in a traditional course, where he felt

self-blame, guilt, self-hatred, and lowered self-esteem. In contrast, Alexander's reactions to mistakes in the first half of the mastery learning course were supported by a spirit of optimism and confidence in his abilities. His optimistic reactions to mistakes in the first half of the mastery learning course resulted from knowing that his mistakes were not final and that he had additional opportunities to learn the material and pass the course. In the end, Alexander received a "B" course grade, indicating a likelihood that his optimism about being able to learn the material was followed up with learning from his mistakes and mastering some of the learning objectives.

3.1.2 Amy: Went from feeling hopelessness and shame in a traditional course to feeling hopeful in the first half of the mastery learning course.

Reactions to mistakes in a traditional course

When Amy made a mistake on an assessment in a traditional course and received a low grade, she remembered that her mistakes were final, and the low grade weighed her final course grade down. Amy experienced a barrage of negative emotions, evaluated her abilities negatively, rethought her belonging in engineering, and sometimes chose to drop the course. After a mistake caused her to have a low grade on an assessment, Amy considered that her mistake was final and that the low grade had repercussions on her course grade (i.e., negative future expectancy). She said:

"It makes you feel like there's no way to come back . . . Each test is usually maybe what? 15% of your final grade. So, if you get a bad score on that, there's no coming back from that." [Interview 1]

Amy experienced hopelessness in not being able to achieve a good grade in the course and shame for having failed. Her mistake made her evaluate her intrinsic abilities and intelligence negatively, stating, "It kind of destroys your confidence . . . I mean it makes you feel like you aren't kind of good enough, that you're not smart enough . . ." [Interview 1].

She re-evaluated her belongingness in engineering, thinking she did not "have what it takes." [Interview 1]. When Amy faced a mistake in a traditional course, she experienced a downward spiral of emotions and cognitive evaluations that sometimes culminated with her dropping the course. She felt hopelessness and shame, which led her to negatively evaluate her abilities and sense of belonging in engineering.

Reactions to mistakes during the mastery learning experience

When Amy made a mistake in the first half of the mastery learning course and did not pass a learning

objective, she felt somewhat down but hopeful that she could still pass. She stated: “I usually don’t feel too great, but I know there’s still hope” [Interview 2]. Her sense of hope emanated from a positive future expectancy that she had other opportunities to pass the objective and that she could correct her mistake. She stated:

“A low grade on mastery [learning] . . . doesn’t necessarily mean you’re going to get a bad grade in the course because it’s not necessarily a grade, because it just means you didn’t master it this time, but you have another four opportunities down the road.” [Interview 2]

In the mastery learning course, she did not experience negative self-evaluation of her knowledge in the same way she did when she made mistakes in a traditional course, stating, “with mastery-based grading, even if you don’t do well, you don’t feel like that . . . feel like you know nothing.” [Interview 2]. She also didn’t experience thoughts that challenged her belonging to engineering. When she made a mistake in the mastery learning exam, she reflected on her reasoning to identify where she went wrong (i.e., a metacognitive strategy) and sought to correct it on the next exam. When she realized the cause of her mistake was that she did not adequately learn the topics, she made a conscious effort to study the material for the next exam (i.e., cognitive activities). She stated:

“Okay, I mess something up, try and obviously figure out what that is, and then correct it on the next one. Or, for example, the last one I didn’t really learn a couple topics, learn it for the next one, but pretty much find out where I mess up and then make sure that does not happen again.” [Interview 2]

Amy’s reactions to mistakes in the first half of the mastery learning course were marked by the emotion of hope that originated from the knowledge that she had more opportunities to correct her mistakes. Additionally, in the first half of the mastery learning course, Amy described engaging in learning strategies such as understanding her errors and studying poorly understood topics to pass the learning objectives on the next exam. These reactions in the first half of the mastery learning course were markedly different from her reactions in the traditional course, which included the emotions of hopelessness and shame about failing. After a mistake in a traditional course, Amy also negatively evaluated her abilities and her belonging in engineering. While in the first half of the mastery learning course, Amy had an attitude of persevering and solving the problems brought about by her mistakes, in a traditional course, a mistake led to negative emotions and negative self-evaluations.

Unfortunately, Amy did not participate in the third interview, which was conducted a few weeks

after the mastery learning course had ended. We later learned that she also failed the course, obtaining a “D” course grade. She likely did not participate in the third interview because she was busy with her work-related duties. Amy was working for a company for which she “worked [her] way up to an engineer” [Interview 1]. While Amy held a positive attitude in the first half of the mastery learning course, she perhaps had difficulty achieving a passing grade on most learning objectives due to the requirement of a “mastery” level grade. Despite being unable to ascertain why Amy did not pass the mastery learning course, her description of her reactions in a traditional course and the first half of the mastery learning course is valuable for understanding how students, particularly women, are experiencing mastery learning.

3.1.3 Andres: Moved from simply considering learning from his mistakes to actually strategizing about how to do better in subsequent exams.

Reactions to mistakes in a traditional course

In a traditional course, Andres acknowledged that he evaluated whether he needed to learn the failed material for future exams. If he didn’t think he needed to know the material for future exams, he moved on and did not attempt to learn from his mistakes. If he felt he needed to know the material, he studied the mistake and tried to simplify the problem until he solved it, stating:

“‘Is this applicable? Do I need to know this for future exams or future classes?’ If not, then forget it. If I do, then I’ll try to simplify it as much as I can.” [Interview 3]

Andres only sought to learn from his mistakes if he thought it would help him achieve his goal of a good grade. He evaluated whether fixing his mistake was worth it. If he deemed the effort unworthy, he did not proceed to the learning phase.

Reactions to mistakes during the mastery learning experience

Andres went through various reactions when he encountered a mistake in the first half of the mastery learning course. He evaluated the mistake with respect to his goal of getting a good grade. He thought, “[the mistake] costs me more time on my next exam, which kind of hinders me from ever getting an A” [Interview 2]. He felt he would be hindered from an “A” grade because he would not have enough time to demonstrate mastery of all the learning objectives in the subsequent exam. Upon encountering a mistake, Andres also evaluated his intelligence negatively: “it . . . makes me feel dumb” [Interview 3].

However, after experiencing a mistake, Andres reminded himself that he had another opportunity

and might do better next time (i.e., positive future expectancy). He engaged in the metacognitive activity of investigating the reason for his faulty logic. Andres made a concerted effort to prepare reference sheets (i.e., sheets with equations that can be used in exams) to improve for the next exam. The preparation of his reference sheets can be thought to be a form of planning coping actions. In preparing his reference sheets, he re-grouped references and bolded the ones related to his previous mistakes. He stated:

"I kind of narrow down my references to be more specific to my common mistakes. . . I have them segregated into different sections. So, if I'm working on a problem, I know what problem that section is or which fundamental it is. I go to my reference sheet, see my common mistakes, in a way. So, I kind of bold things." [Interview 2]

Andres lamented failing learning objectives due to making several minor and careless mistakes. Nevertheless, he learned from these experiences and said they led him to use the metacognitive strategy of searching for minor mistakes in subsequent exams.

Mastery learning encouraged him to learn from his mistakes and to take action to prepare himself to pass the learning objective on subsequent exams. In a traditional course, he did not feel like he had to learn from his mistakes because subsequent exams did not test previous material. He said:

". . . the only difference is that mastery may put some importance on [learning from mistakes]. So, you have to know it. While [in a] traditional class, it's like, 'Well, if you could make up for it by knowing the current material [being tested], then you could just forget about [previous material].'" [Interview 2]

In the last half of the mastery learning course, Andres described feeling a lot of pressure to pass the learning objectives. At this point, he was aiming for a "C" grade, the minimum grade needed to pass the class, but he only had a few opportunities. He felt stress and anger but was committed to studying and remedying the reasons behind his mistakes. He said:

". . . the last couple of exams? That's just added a lot of stress. So, it was pressure you could feel inside you that it's like, 'Okay, you need to get this done.' It made me want to just abandon the other classes; I had to catch up in a way. . . . You have to constantly calm yourself down because when it starts getting towards the final exams, the teacher starts mentioning like, 'Hey, you only got five exams left and you guys need to catch up if you're trying to get a C in a class,' which is where I was. I was borderline getting a C at that time so I was like, 'Okay, I really got to pick it up.'" [Interview 3]

Andres' reactions to mistakes in a traditional course were calculated evaluations of whether he needed to learn the material for future exams. He did not try to learn from his mistakes if he thought he did not need to know the material for future

exams. In the first half of the mastery learning course, Andres' reactions were varied; he described investigating the reasons for his mistakes and actively preparing to do better in future exams by modifying his reference sheet. While in the last half of the mastery learning course, Andres felt heightened pressure to pass the learning objectives to get the desired grade. He experienced a lot of stress and anger toward small mistakes. In the end, Andres achieved a "C+" in the course, which signified that he passed ten out of 16 learning objectives.

3.1.4 Nicole: Moved from depressed and having self-doubt in a traditional course to having contrasting feelings of hopefulness and frustration in the mastery learning course.

Reactions to mistakes in a traditional course

When Nicole was asked to reflect on her reactions to mistakes in a traditional course, she acknowledged having feelings of depression and self-doubt about her abilities to accomplish her goal of graduating. However, she had an unwavering resolve to work harder. Specifically, when she was asked about what her reactions were after receiving a low grade in a major assignment or exam, she said:

"It made me feel really down. Maybe I couldn't do this engineering field or major . . . maybe I picked the wrong one. Maybe I'm not cut out for this. But I'm very stubborn, so I felt so much like a failure, but I was like, 'No, I need to get it the next time. I need to get it the next time.'" [Interview 1]

Nicole's self-doubt pertained to not being capable of achieving her goal. She experienced a diminished sense of belonging, thinking, "Maybe this isn't for me" or that she was "not cut out to do it" [Interview 1]. She felt that she was incapable of completing her degree. However, she described having a mentality of perseverance, stating:

"I would always think the worst in the very beginning [after getting a low grade]. But then once I got home I was like, 'No, . . . What can I do now to not get [an] F.'" [Interview 1]

After realizing she had made a mistake that led her to a low grade, Nicole experienced feelings of depression and self-doubt. However, later, she evaluated her options for not getting an "F" grade and used positive self-talk to tell herself that she needed to do better next time.

Reactions to mistakes during the mastery learning experience

In the beginning, Nicole's reactions to mistakes in a mastery learning course were similar to her reactions in a traditional course. Making mistakes in the mastery learning course gave Nicole a "sinking feeling" in her heart, accompanied by the thought

that she didn't do enough to get a good grade. She felt frustrated because she thought she was not "smart enough" to answer the problems correctly. After the "sinking feeling," self-blaming, and frustration subsided, Nicole acknowledged that she had other opportunities to pass the class and that she could "redeem herself" [Interview 3]. She stated, "... there's always that sinking feeling at first, but then that afterthought that like, 'Oh, I can do it again. I have another chance to redeem myself'" [Interview 3].

Once Nicole realized that she had multiple opportunities to demonstrate mastery (i.e., positive future expectancy), she described feeling more hopeful and greater peace of mind, stating, "... maybe it brings my hopes up again that I can do it again. It just gives me a little bit of peace of mind that I have another chance" [Interview 3]. She also described that learning from her mistakes made her feel a sense of belonging in engineering, thinking that engineering was the "right major."

While Nicole experienced a sense of relief, she also felt frustrated that she needed to work harder and invest more time studying the course material, saying, "I'm going to have to spend another weekend. I'm going to have to spend another week. And that's taking time away from the other topic" [Interview 3]. When Nicole did not pass a learning objective, she described working harder to pass it in the next attempt. On those occasions, she typically achieved a mastery grade and felt proud of not giving up.

When making mistakes in a mastery learning course, the knowledge that she had more retake opportunities led Nicole to feel contrasting emotions: hope and frustration. While Nicole felt hopeful and had peace of mind knowing she had multiple opportunities to correct her mistakes, she also felt frustrated about spending more time studying to pass a learning objective. The retake opportunities engendered positive emotions, but she also lamented the extra work that they took. Ultimately, Nicole received a "B-" in the course, which affirmed that she likely followed up and corrected some of her mistakes, which resulted in the mastery of several learning objectives.

3.1.5 Rafael: From feeling upset in a traditional course to feeling more motivated and hopeful in the mastery learning course

Reactions to mistakes in a traditional course

Rafael described how when he made a mistake in a traditional course, he felt "upset" [Interview 2] because he knew he would receive a low score for the exam or homework, and there was no way to change it. Saying:

"Usually, in other classes, I think for everybody if they get a bad score on something, they would feel upset because that's the score they're going to get, they don't have another chance." [Interview 2]

As part of his reactions to mistakes in a traditional course, Rafael described plans to take corrective action (i.e., coping actions) to improve his mistakes. Additionally, after a mistake, Rafael discussed engaging with the following learning strategies: "working harder," "ask[ing] more questions" [Interview 1], and understanding the reasons behind the mistake.

Reactions to mistakes during the mastery learning experience

Rafael described that his emotional reactions to mistakes in the first half of the mastery learning course were, first, getting "a little bit upset" [Interview 2], but later, he experienced increased task-related motivation and a feeling of hopefulness. Specifically stating,

"... you would feel a little bit of upset but overall, you'll still be hopeful in the end because you'll have another shot at getting a better score on it, so it makes you feel motivated and hopeful still because you know you'll be able to... If you look at the problem one more time and focus on it and try it again, you may get the answer right, and then the you'll get a better score in the end." [Interview 2]

Rafael explained that mastery learning's promise of retake opportunities motivated him because he could get a better score and better understanding by applying effort. The increase in task-related motivation originated from knowing he had more opportunities to succeed. He also experienced a feeling of hopefulness because he knew there was the possibility of obtaining better results in the future – a positive future expectancy. Additionally, Rafael also planned coping actions by preparing to ask the professor or friends for help and planning to try to understand what he did wrong.

Rafael's reactions to mistakes in the last half of the mastery learning course were similar to his reactions in the first half of the mastery learning course. In the last half of the mastery learning course, after a mistake, Rafael experienced some degree of frustration but then reminded himself that he could mitigate his mistake by trying again, stating:

"So when I didn't pass it, I was annoyed at first 'cause I wanted to pass the first time, but I wasn't upset or anything because I knew I could try again and get a better score this time." [Interview 3]

In the latter half of the semester, after a mistake, Rafael described being able to learn from his mistakes through feedback and gaining a better score. Rafael also likely followed and implemented

his plans to learn from his mistakes in the first half of the mastery learning course since he received an “A” in the course, passing at least 17 out of 18 learning objectives.

Overall, Rafael’s reactions to mistakes in the mastery learning course encompassed high task-related motivation and an emotional response of hopefulness. Rafael experienced higher task motivation and hope because he knew he had more opportunities to fix a mistake and get a better score. Knowing he had multiple chances motivated him and gave him hope to have the grades and knowledge he desired in the future. Rafael’s frustration in the mastery learning course was lower than in a traditional course because he knew that one failed exam would not impact his chances of earning a high grade. While Rafael planned coping actions to help him mitigate errors in both a traditional and mastery learning course, in a traditional course, the amount of time he invested in learning from his mistakes was much smaller than in the mastery learning course.

3.2 Recurrent Cross-sectional Theme (RQ1): Students’ Positive Future Expectancy resulted in more Positive Emotional Reactions

Amy, Diego, Jack, Nicole, and Rafael described how knowing they can fix their mistakes through retake opportunities (i.e., positive future expectancy) produced a variety of desirable emotional reactions. Having a positive future expectancy after a mistake increased their motivation, hope, and calmness and decreased their anxiety and stress compared to their reactions in traditional courses. Specifically, Jack and Rafael described feeling more motivated by knowing they could fix their mistakes using retake opportunities. After a mistake, Jack considered that he had more opportunities and felt more “eager to ask for help” [Interview 2]. Jack was motivated by the chance to succeed that additional retake opportunities afforded to him. Rafael described feeling more motivated and hopeful at the knowledge that he could correct his mistakes with effort and achieve a mastery grade on the learning objectives. Nicole and Amy also described feeling more hopeful after a mistake, knowing they had multiple opportunities. Having additional opportunities to attain a mastery grade on the learning objectives removed the sense of finality that was experienced in a traditional course. Amy stated: “You feel like you have another chance, that pretty much you’ll get them next time, and if not, next time after that, but there’s still hope.” [Interview 2]. A positive future expectancy after a mistake induced feelings of calmness in Rafael and Nicole. They felt calm, knowing their mistakes were not final and they could try again.

A positive future expectancy after a mistake also reduced Jack and Diego’s negative emotional reactions. In traditional courses, not knowing how to answer a question would make Diego very stressed. However, Diego described that in mastery learning exams, he felt less stressed than in traditional exams when he didn’t know how to complete a learning objective. Jack said that a positive future expectancy reduced his anxiety, stating:

“... multiple opportunities ... I think it eases the anxiety of me as a student because I get to have basically more opportunities to get [the learning objective] cleared; whereas, a traditional class, you just get opportunity once and then you won’t get to do those again.” [Interview 3]

The availability of retake opportunities likely led students to feel that after a mistake, there was a good chance that they would be able to correct it and achieve a mastery grade on the learning objective. This positive future expectancy led students to have desirable emotional reactions or reduced their negative emotions compared to their reactions in traditional courses.

3.3 Recurrent Cross-sectional Theme (RQ1): Mastery Learning Improved Students’ Sense of belonging in Engineering

For Amy and Nicole, mistakes in traditional courses resulted in thoughts that tended to contest their sense of belonging in engineering. After a mistake, Amy thought she wasn’t “good enough, ... not smart enough, that [she didn’t] have what it takes” and that “she didn’t know the material.” She also felt, “I can’t do this. I’m not cut out for this” [Amy, Interview 1]. Similarly, following a mistake, Nicole had thoughts that challenged her sense of belonging. She thought that maybe engineering wasn’t for her, that perhaps she wasn’t “cut out” to do engineering, wasn’t “smart enough,” or that because of her mistake, maybe she “couldn’t do this engineering field or major” [Nicole, Interview 1]. After making a mistake in traditional courses, Amy and Nicole had thoughts that put in doubt their ability to do engineering and that was, at least in part, a reason why they had thoughts that challenged their belonging in engineering.

In contrast, for Amy, mistakes in the mastery learning experience did not contest her sense of belonging. When she made a mistake in a mastery learning course, she did not feel like she “kn[e]w nothing” [Amy, Interview 2] as she felt in the traditional course. She did not think that she lacked knowledge or ability. Instead, upon making a mistake, the retake opportunities gave her hope that she could learn the material and pass the learning objective. After a mistake in mastery

learning, she described feeling hopeful that she could improve her understanding.

Like Amy, Nicole's belonging in engineering wasn't challenged by mistakes in the mastery learning course. More significantly, Nicole learned more from her mistakes in the mastery learning course, supporting her sense of belonging in engineering. Learning from her mistakes and passing the learning objectives after a failure in the mastery learning course made her feel empowered and that her ability was sufficient to do engineering. She thought, "[I am] capable of learning these topics," and "I was smart enough to stick with engineering, that this is the right major I picked for myself" [Nicole, Interview 3].

In traditional courses, after a mistake, both Amy and Nicole's thoughts contested their sense of belonging in engineering by putting in doubt their abilities. In contrast, after a mistake in the mastery learning course, Amy did not experience doubts about her belonging. Instead, Amy felt hopeful that she could learn from her mistakes and get a better grade. Similarly, in the mastery learning course, Nicole's sense of belonging was not contested; mastery learning supported her sense of belonging in engineering. She learned more from her mistakes, leading her to think that her ability was sufficient to do engineering.

3.4 Recurrent Cross-sectional Theme (RQ1): The Last Half of the Mastery Learning Course Evoked Strong Negative Emotions for Students

In the last half of the mastery learning course, three students (i.e., Alexander, Andres, and Jack) were in danger of not passing enough learning objectives to attain their desired grade. The situation of not knowing if they would be able to get their desired grade made them react to mistakes with anxiety, heightened stress, or fear. Jack said that he needed to pass two learning objectives in the final exam to get a "B" course grade; failing to achieve mastery of those learning objectives would have resulted in a "C" grade, making him anxious. Andres felt a lot of pressure in the last two exams to pass all the learning objectives he desired, stating, "It was pressure you could feel inside you that it's like, 'Okay, you need to get this done'" [Andres, Interview 3]. He contemplated abandoning his other classes to catch up and to master the needed learning objectives. Ultimately, Andres persevered in juggling all his coursework responsibilities. Alexander described experiencing a "do or die mindset" where he had to perform well at all costs to get the desired "good grade" [Alexander, Interview 1]. Alexander said the "do or die" mindset he experienced at the end of the mastery learning course was the same mentality he experienced in traditional

courses, "if you fail the exam, well, you fail the class" [Alexander, Interview 3]. This mindset of urgency induced feelings of worry and fear in Alexander. These students' heightened emotional responses resulted from reduced opportunities to pass enough learning objectives to attain the desired grade. For any mastery learning student who still had a few learning objectives to pass in the final exam, negative emotions were likely present as their chances to attain their desired grade were diminished.

Despite experiencing elevated emotional reactions in the last half of the mastery learning course, these students' overall impression of the intervention was positive. Specifically, Alexander stated that he preferred mastery learning because it allowed him to learn more than a traditional course and helped him pass the course. While Jack would have preferred more retake opportunities *after* the final exam, he stated that he thought mastery learning was good when students needed to master fundamental concepts, like in a Statics course. Andres liked the mastery learning course even though he felt heightened stress at the end of it. He appreciated the opportunities that mastery learning gave him to achieve the learning objectives in the middle and end of the course that he hadn't achieved initially. He also appreciated how his instructor "helped everyone along" with the learning objectives [Andres, Interview 3].

3.5 Recurrent Cross-sectional Theme (RQ2): Retake Opportunities and a Focus on Mastering the Learning Objectives Facilitated Students' Learning

Six students (Alexander, Andres, Diego, Jack, Nicole, Rafael)¹ stated that they learned more from their mistakes in the mastery learning course than in their traditional courses. These students described they learned more from their mistakes in the mastery learning course because of the advantages of the retake opportunities and the focus on achieving a mastery grade. Their statements pointed to different reasons why retake opportunities were beneficial for learning from mistakes. Jack learned from his mistakes more in the mastery learning course because when he failed a learning objective, he saw a similar problem in subsequent exams and could try his luck again. Nicole took advantage of retake opportunities to learn from her mistakes because she could take all the time she needed to understand the learning objectives properly. In mastery learning, the deadline students experienced was the need to master a certain number of learning objectives by the end of

¹ Amy did not consent to participate in the third interview and was not asked this question.

the class to attain a certain grade. Nicole benefitted from this structure as she could take extra time to understand the learning objectives. When Andres made a mistake on a learning objective, he attempted to learn from it and could test his knowledge rapidly in subsequent exams.

Alexander highlighted the advantage of a focus on mastering the learning objectives as the reason he learned from his mistakes more in the mastery learning course, stating, “. . . in master[y] learning, you’re trying to actually learn the section each at a time, make sure you actually mastered it” [Alexander, Interview 3]. Diego and Rafael attributed their learning from mistakes in the mastery learning course to the availability of retake opportunities and the focus on mastering the learning objectives. Diego and Rafael had the mindset of mastering all learning objectives in the course. Mastery learning encouraged them to review failed learning objectives and find mistakes so they could achieve a mastery grade in subsequent exams.

The structure of mastery learning, which provided retake opportunities and a focus on mastering the learning objectives, led these students to learn more from their mistakes than in a traditional course. Additionally, most of these students revealed that they were motivated to attain a certain course grade and learn the material. It is likely that the grading structure of needing to master a certain number of learning objectives to attain a certain grade was an important underlying motivation for students to learn from mistakes.

4. Discussion

The individual descriptions showed nuanced and diverse ways students reacted to mistakes in traditional courses in the first half and in the second half of the mastery learning course. These reactions-to-mistakes arcs could help instructors and researchers of mastery learning courses better understand how their students respond to mistakes. Most reactions to mistakes in traditional courses had a negative undertone (e.g., guilt, hopelessness, anxiety). The negative emotional reactions in traditional courses were related to students’ inability to improve their grades after they made a mistake. More significantly, the individual descriptions show how students modified their reactions when they experienced a mastery learning course. In the mastery learning course, participants reacted with positive emotional reactions after mistakes. The positive emotional reactions enhanced students’ hope, calmness, and task-related motivation and reduced anxiety and stress. These positive emotional reactions were spurred by students’ understanding that, with effort, they were likely to fix

their mistakes, learn, and pass the learning objective. Some students likely benefitted from mastery learning’s effect of producing positive emotional reactions after a mistake to reduce, or bypass entirely, the amount of emotional and motivational management they would have to do to begin learning from their mistakes. In Tulis et al.’s [20] framework, this means bypassing the phase of “Managing One’s Motivations or Emotions” and reaching the state of “Learning Strategies” faster (see Fig. 1). Students who reported positive emotional reactions after a mistake in their mastery learning course also said they learned more from mistakes in that course structure, thus bolstering the idea that having positive emotional responses facilitated their learning. Studies show that positive reactions are positively related to persistence and engagement [18] and facilitate learning following mistakes [19].

In the last half of the mastery learning course, some students experienced increased anxiety, stress, or fear after making mistakes. These emotions were elicited by the knowledge that students had few opportunities to pass learning objectives and achieve their desired grades. It is likely that these negative emotional reactions did not help students learn from their mistakes. After experiencing an adverse emotional reaction, studies show that students need to engage in emotional and motivational management to prepare them to engage with the process of learning from their mistakes [20, 24–26]. Specifically, when students have predominantly negative emotional reactions to mistakes, they need to put effort into improving their motivation and change their emotions to engage with adaptive learning processes [20]. In the Learning from Mistakes theoretical framework, this means moving from the “Secondary Reaction” (i.e., beginning to cope) to “Managing One’s Motivations or Emotions.” Positively managing motivations or emotions allows students to engage with helpful learning strategies and achieve learning, while negative reactions to mistakes have been associated with a lack of student effort and performance [18].

In examining participants’ reactions to mistakes, we also found that mastery learning positively influenced participants’ sense of belonging brought about by their ability to correct mistakes; this was only observed for the two women in our sample. When questioning participants about their learning from mistakes, we found that students credited their ability to learn from mistakes to the architectural features of the mastery learning course. Below, we discuss students’ improvement in learning from mistakes, improvement in women’s sense of belonging, and the effect of mastery learning on students’ mental health and wellbeing.

4.1 Improvement in Learning from Mistakes

Nearly all students reported learning more from mistakes in the mastery learning course than in a typical traditional course. Students attributed their abilities to learn from mistakes to the availability of retake opportunities and the emphasis on mastering learning objectives. The architectural components of a typical mastery learning course allowed students multiple opportunities to try problems again and learn from their mistakes. Mastery learning's focus on mastery also incentivized students to try to better understand the concepts related to the learning objectives. Our results suggest that students in mastery learning will take advantage of the opportunities to learn from mistakes. Research shows that students do demonstrate a desire to participate in rectifying mistakes [50, 51]. Andres, Amy, Jack, and Rafael described engaging more in learning strategies, such as help-seeking and reviewing faulty logic after a mistake, in their mastery learning course than in traditional courses. Self-regulated learning strategies, such as seeking help, have been attributed to higher academic performance in an engineering course that used a type of mastery learning approach, i.e., standards-based grading [52]. We believe that the components of ample instructor feedback and a course grade based on how many learning objectives students master are also important in helping students learn from mistakes. Beyond learning from mistakes, it is likely that mastery learning's architecture provides an incentive for students to learn how to learn – which has been described as a meta-competency needed in the current and future climate of engineering practice [53].

Compared to traditional engineering courses, the mastery learning structure more closely achieves the goal of making mistakes a natural part of the process of inquiry and is a structure more aligned with the goal of developing talent [1]. Our students stated they learned more from their mistakes in a mastery learning course because mistakes were allowed, and they were given opportunities to correct them. Students in a mastery learning course can take advantage of the beneficial aspects that mistakes have on learning, like greater reasoning processes to achieve the correct answer and focusing on the right direction [16]. Additionally, students in mastery learning courses have the opportunity to follow a mistake-correction process that educational theory has suggested is the natural way of learning [17]. The focus on mastery rather than simply passing or failing reinforces the idea that learning is a continuous process. This educational strategy not only boosts students' confidence and resilience but also fosters a growth mindset,

where they are more willing to take risks, explore new concepts, and ultimately achieve a deeper understanding of the material. From the results presented, we ascertain that mastery learning's structure of retake opportunities and a focus on mastering learning objectives generates a positive mistake climate. We recommend mastery learning instructors supplement mastery learning's positive mistake climate with short interventions throughout the semester to reinforce constructive attitudes toward mistakes and support students in managing them effectively. The mistake-climate or mistake-management interventions could consist of short 10–15 minute discussions a few times at the beginning of the semester where the instructor goes over the importance of a positive perspective toward mistakes, beneficial aspects of learning from mistakes, the benefits of cultivating a growth mindset [54], and methods to learn from mistakes. This should help more students take advantage of the opportunities to learn from mistakes that mastery learning offers.

4.2 Improving Women's Sense of Belonging

Our study showed that treating mistakes as final in traditional courses contributed to some students' diminished sense of belonging. Specifically, the two women we interviewed described how mistakes made in traditional courses challenged their sense of belonging, a reaction not observed among their male counterparts. Studies have shown that women feel a lower sense of belonging in STEM than men [55, 56], while robust self-efficacy beliefs can help mitigate feelings of not belongingness [57] and support persistence [58]. Additionally, a study found that fields where students believe that achievement depends on high innate ability also have a lower representation of women [59]. In a traditional course structure, Amy and Nicole uniquely described having a diminished sense of belonging, feeling that their ability was insufficient for success. Conversely, the opportunity to learn from mistakes without major penalties led Nicole to feel her ability was sufficient to do engineering and prompted Amy to reject the perception that she was incapable. Thus, through offering opportunities for academic growth, this alternative educational approach enhanced Amy's and Nicole's sense of belonging in engineering. In contrast to a traditional course, mistakes were not final in a mastery learning course; students did not receive a grade that led them to make a definitive evaluation of their ability. Instead, they were in an environment focused on academic growth that gave them opportunities to eventually achieve mastery, and their sense of belonging was improved as a result.

While the effect of mistakes on students' sense of

belonging was not part of the theoretical framework utilized in this study [20], the Learning from Mistakes framework could be modified to include students' experiences with thoughts and emotions that challenge or support their belonging in their professional community. Incorporating reactions related to a sense of belonging could provide researchers with a more holistic context for analyzing students' reactions to mistakes and could create a more comprehensive framework that captures the spectrum of students' reactions.

4.3 Mastery Learning's Possible Effect on Mental Health and Wellbeing

We observed that five students in the first half of a mastery learning course experienced positive emotional reactions (i.e., hope and calmness) and a reduction in negative emotional reactions (i.e., anxiety and stress), which are indications of betterment in mental health and wellbeing. Still, three students experienced adverse emotional reactions (i.e., anxiety, stress, or fear) in the last half of the mastery learning course. However, those students also had a positive overall impression of mastery learning. Taken together, the available evidence suggests that mastery learning has a net positive effect on students' mental health and well-being. In support of this view, Bloom [3] stated, "Mastery learning . . . can be one of the more powerful sources of mental health" [pg. 61]. Asghar et al.'s [60] argued for the need for an improvement in undergraduate engineering students' mental health and wellbeing. Their systematic literature review concluded that "the current condition of . . . [mental health and wellbeing] is unsatisfactory for supporting academic performance and retention in undergraduate engineering programs" [pg. 14]. Collectively, the studies in the systematic literature review show that participants were twice as likely to present anxiety or depression when compared to the general public, and for undergraduate engineering students, stress was found to be pervasive [60]. We have presented data demonstrating that students experience more positive emotions and a reduction of negative emotions when they make mistakes in mastery learning courses. Thus, a mastery learning implementation may positively contribute to the betterment of undergraduate engineering students' mental health and wellbeing.

The Learning from Mistakes theoretical framework [20] describes positive and negative emotional reactions to mistakes. Students' experience of positive emotions corresponds to an enhancement of their wellbeing and their experience of more negative emotions corresponds to a decrease in their wellbeing [60]. The framework's exploration of positive and negative emotional reactions indirectly

initiates a conversation about students' mental health and wellbeing. There is potential to expand the theoretical framework to include references to students' wellbeing.

4.4 Mastery Learning as an Element of HSI Servingness

We have discussed some of the positive effects that mastery learning can have on HSI students. These include increased learning from mistakes, encouraging positive emotional reactions and reducing negative emotional reactions to mistakes, improving women's sense of belonging, and potentially improving students' mental health and wellbeing. This evidence supports the argument that mastery learning can lead to greater academic development and be beneficial for students' affective states above what students experience in traditional courses.

In parallel, the recent discussions of how HSIs can best serve their predominantly minoritized student population do not include the utilization of alternative educational strategies like mastery learning [15]. However, mastery learning would be a beneficial element of HSI servingness based on the evidence presented in this article and in the systematic literature review [4]. Our data shows that HSI students may benefit from mastery learning's positive mistake climate, which, in contrast to traditional courses, encourages the natural learning process of making and correcting mistakes [17]. HSI students may also benefit from improvements to mental health and wellbeing that come from increased positive emotional reactions and reduced negative reactions to mistakes. Women HSI students may see improvements in their sense of belonging coming from an environment that encourages academic growth and does not encourage negative self-evaluations of their abilities. Future discussions on HSI servingness should consider including mastery learning as an educational strategy given its positive effects on students' learning and affective states.

4.5 Future Work

Due to mastery learning's key role in the discussion of the transformation of undergraduate engineering education and its potential to support HSI's servingness, future work should be conducted to understand in more detail mastery learning's diverse effects (i.e., sense of belonging, learning from mistakes, negative emotional reactions, improvements on mental health and wellbeing) on engineering students. Research on mastery learning's effects on engineering students can be used to improve mastery learning's positive contributions to engineering education and diminish its unintended negative effects. For example, we presented evi-

dence that mastery learning improved women's sense of belonging. Future research should delve more deeply into identifying those individuals whose sense of belonging is most affected by this pedagogical intervention and study, more specifically, the aspects of mastery learning that foster a sense of belonging. We also showed that some students experienced negative emotions at the end of the course due to reduced opportunities to correct mistakes. Future work should investigate ways to improve these negative reactions to mistakes – perhaps by emphasizing the benefits of focusing on passing learning objectives early in the course. Finally, we indicated that positive emotional reactions to mistakes could enhance students' mental health and well-being. Future investigations could test this hypothesis through quantitative surveys and evaluate the effect of a mastery learning course on the mental health and wellbeing of students.

5. Conclusion

This study presented a longitudinal qualitative investigation of seven undergraduate engineering students who experienced a mastery learning engineering course at an HSI. The purpose of the study was to gain insight into how participants' reactions to mistakes changed as they experienced their mastery learning course and the factors that facilitated their learning from mistakes. Students' individual descriptions highlighted the diversity of ways one can react to mistakes in traditional courses and how those reactions changed in a mastery learning course. Our participants' emotional reactions in traditional courses tended to be negative and

stemmed from their inability to correct their mistakes. In the cross-participant themes, we found that a majority of participants experienced positive emotional reactions after making mistakes in the mastery learning course. Positive emotional reactions were related to students' knowledge that their mistakes could be corrected by taking advantage of the retake opportunities. Mastery learning helped improve women's sense of belonging because their environment allowed them to grow from their mistakes. Additionally, we also found that in the last half of the mastery learning course, some students experienced enhanced negative emotions. These negative emotions stemmed from students' lack of opportunities to correct their mistakes and achieve their desired grades. Most students described they learned more from their mistakes in the mastery learning course than in traditional courses. They attributed their enhanced learning to mastery learning's architectural features of retake opportunities and the focus on mastering learning objectives. This study increases our understanding of the ways mastery learning leads students to learn from mistakes, which can help improve the implementation of mastery learning and develop engineering student talent more effectively. This investigation also highlights the potential beneficial effects of mastery learning on undergraduate engineering students' mental health and wellbeing thereby contributing to the field's efforts to improve their experience.

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