2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #37142

WIP: Toward a Free-Body Diagram Mobile Application

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WIP Toward a Free-Body Diagram Mobile Application

Abstract

No skill is more important for a student of mechanics than the ability to draw a complete and accurate free-body diagram (FBD). A good FBD facilitates proper accounting of forces when writing the balances that lead to governing equations in statics, solid mechanics, and dynamics. Because this skill is essential, educational approaches that improve the ability of students to draw correct FBDs are critical for maximizing the potential of the next generation of engineers.

Traditionally, learning to draw FBDs involves classroom instruction followed by homework practice consisting of problems drawn from a textbook. Homework as practice does not serve all students well, because it does not scaffold the process of drawing FBDs in terms of distinct tasks (e.g., isolating the body, considering support reactions) nor does it offer immediate feedback, which students often need to avoid falling into the same error repeatedly.

To address these shortcomings, we embarked on the design, implementation, and testing of a mobile application (app) that offers an alternative venue for FBD practice. The app provides students with asynchronous opportunities for training, varied tasks that target specific FBD issues, and several levels of immediate feedback. We hypothesize that the gamified environment and puzzle-based gameplay will improve student skill and self-efficacy in drawing FBDs, particularly for women, who may feel less confident in their spatial skills. Data collected to describe student experiences may also provide additional insight into how to improve FBD instruction generally.

In this paper, we detail the process for designing and implementing the app and provide initial data regarding student impressions and use. The app was piloted in Fall 2022 in a large *Introduction to Statics* course as a non-graded study activity; all students except one (n=97) participated in an evaluation of its design features and user experiences. Approximately half (54%) of students indicated they had played half or more of the available games.

When commenting about how the FBD app did, or did not, help their learning, 49% of respondents appreciated that the app allowed additional opportunities for practice. Students used these opportunities to further develop several skills, such as visualizing the system and setting up accurate diagrams, which strengthened their confidence and reviewed key concepts. While describing the value of practicing through the app, 21% of students called out how the app provided feedback. They specifically mentioned the positive experiences of receiving feedback that is immediate, that explains boundary connections, and that deepens learning after mistakes are made. These and other findings from the pilot study are discussed with corresponding next steps for development.

Introduction

No skill is more important for a student of mechanics than the ability to draw a complete and accurate free-body diagram (FBD). FBDs are foundational to all mechanics courses in civil, mechanical, and biomedical engineering programs. Together, these courses enroll a significant portion of the over 600,000 students who enter engineering programs in the United States each year [1]. Thus, educational approaches that improve the ability of students to draw correct FBDs are critical for maximizing the potential of the next generation of engineers.

Traditionally, learning to draw FBDs involves classroom instruction followed by homework practice consisting of problems drawn from a textbook. Homework as practice does not serve all students well, because it does not scaffold the process of drawing FBDs in terms of distinct tasks (e.g., isolating the body, considering support reactions) nor does it offer immediate feedback, which students often need to avoid falling into the same error repeatedly.

To address these shortcomings, we embarked on the design, implementation, and testing of a mobile application (app) that offers an alternative venue for FBD practice. Successfully developing such an app that students enjoy using could improve the learning of a large number of students [2]. As designed, the app provides students with asynchronous opportunities for training, varied tasks that target specific FBD issues, and several levels of immediate feedback. Our hypothesis is that the gamified environment and puzzle-based gameplay will help all students improve FBD skills and self-efficacy, and will particularly help women and underrepresented students, who lack confidence with spatial skills [3]. Self-efficacy is particularly important for helping these students thrive in engineering [4], and educational apps can provide mastery experiences that help build self-efficacy [5]. Additionally, our app will provide faculty with detailed data on student progress and errors. This data may offer additional insights into the process students use when drawing FBDs and highlight commonly made errors, allowing for tailored instruction or new approaches to teaching. In this paper, we detail our process for designing and implementing the app and provide initial data regarding student impressions and use.

Why an FBD App?

The proliferation of smartphones has transformed how people communicate and carry out tasks. Because smartphones are computationally powerful and constantly connected to the internet, mobile apps allow people to work and play in new ways. Some tasks that once required physical proximity, such as cashing a check, can now be performed quickly and easily anywhere and anytime. Other tasks that previously required separate objects, such as calling someone (via a telephone) or navigating to a new location (via a map), now only require a smartphone. Most people – faculty and students included – always have a smartphone with them and carry out significant parts of their lives on these devices.

Because of the power and ubiquity of the smartphone, apps to aid learning are increasingly being developed for these and other portable electronic devices. Language learning apps, which began to appear over a decade ago, are a rapidly growing way to start learning a new language

[6]. Likewise, students in elementary school are now learning and practicing math using gamified apps on tablets. But engineering education has been slower to adapt to the use of smartphones, and over a decade after Apple trademarked the phrase “there’s an app for that” there are very few apps dedicated to teaching students engineering concepts.

A smartphone-based learning environment offers certain advantages over a traditional learning environment. First, an app can be designed to isolate skills with which students have difficulty, allowing them to practice those skills repeatedly until they have gained competence. This type of tailored instruction is difficult in the classroom setting. Second, an app can provide a student immediate feedback, catching mistakes and correcting them as they happen. In a traditional classroom setting, the feedback loop may be a week or more for mistakes made on homework or other assessments. Third, an app enables asynchronous, location-independent practice, allowing students to make learning gains even when committing small amounts of time or when practicing in unconventional situations, like during a morning commute. Finally, an app can also be gamified – structured in such a way to make the learning fun – which can increase user engagement and learning.

Apps have successfully improved spatial visualization of engineering students. An app that allows users to practice drawing shapes and visualizing 2D and 3D rotations developed by eGroveEducation increased student persistence, as measured by the number of times they tried a sketch again without asking for help, and more than doubled the number of students with significant learning gains [7,8]. But an app for drawing FBDs has not yet been created. Thus, we have begun developing an app designed to assist students in mastering the skills necessary to draw complete and accurate FBDs.

Previous Efforts at FBD Software

A large body of research has developed around FBD instruction and assessment [9]. Recent innovations include hand-drawn FBD instruction, such as the exploded-view technique [10], and the use of hands-on exercises that allow students to feel forces and moments as they construct FBDs [11-13]. These improvements to FBD instruction have undoubtedly improved the undergraduate learning experience, but students still struggle. Classroom activities in a course are typically accompanied by homework, which provides a way for students to practice drawing FBDs and receive feedback on their work. It is the process of practice, in addition to initial instruction, that helps students catch mistakes, internalize methods, and build habits that lead to content mastery [14]. Because homework, as the dominant means of providing practice, often fails to isolate discrete skills and lacks immediate feedback, several efforts have been made to develop computer-based tools to aid students by personalizing feedback.

Some tools in this area include an FBD Assistant developed at Vanderbilt University [15] and *Andes* [16], a physics tutoring system resulting from collaboration between the University of Pittsburgh and the US Naval Academy. Both of these programs are effective in generating student learning gains related to drawing FBDs, but both are limited to computers and require working within non-intuitive interfaces or learning management systems. Another effective tool is

Mechanix [17,18] which allows students to draw FBDs freehand via a computer interface and incorporates automatic grading; however, this program is intended for classroom use and is not freely available to the general public.

Our FBD app differs from these past efforts in several significant ways. First, our app is intended to run on mobile devices, making it portable. Second, our app will be publicly available, meaning it can be used not just by students, but by anyone looking to learn or review FBDs. Finally, our app offers exercises that target particular FBD pitfalls, making it possible for the user to customize their practice and focus on issues with which they struggle.

Overview of the App Development Process

The design and development process was organized into three phases: design and prototype (complete), deployment and refinement (underway), and research study (future work). More details of each of these stages are supplied in the sections below, and an overview is provided in Figure 1. Within each phase, iterative cycles of testing and refinement based on design-based research methods [19,20] were employed. Early undergraduate students, advanced undergraduate students, early career engineers, and faculty members were identified as key stakeholders and consulted during the development process.

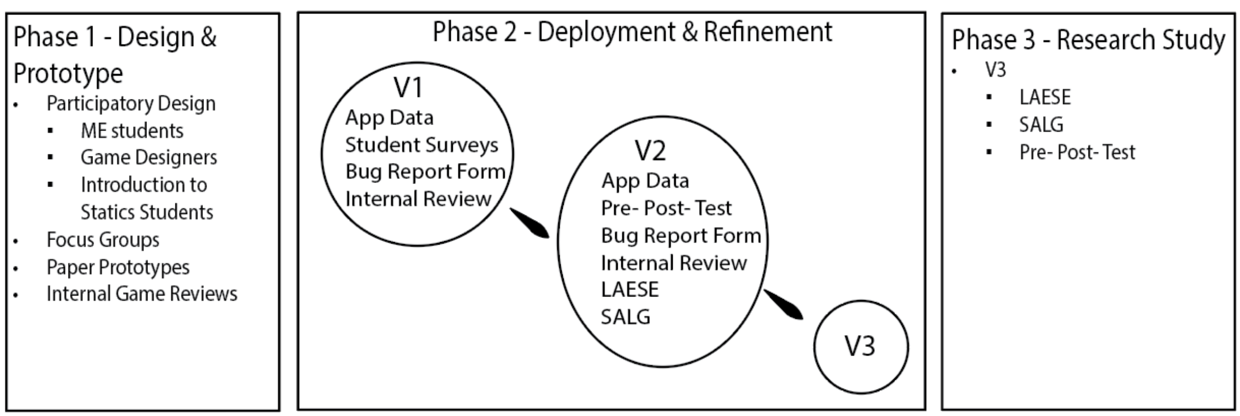

Figure 1: An overview of the development process for the FBD app.

Phase 1: Design and Prototype (complete)

The goal of this phase was to design an app that scaffolds the learning process associated with drawing FBDs. This was accomplished by segmenting typical problems into small tasks with which students typically struggle and associating each task with a “mini game” in the app. Mini games were designed to be inclusive and feature feminized gameplay in order to appeal to the widest possible audience.

In this phase, participatory design was used because it allows all stakeholders to be part of the design process so that the final product reflects the entire community’s values [21]. There is a strong tradition of participatory design in interactive media, especially for projects with a marginalized audience [22]. Semi-structured interviews and focus groups were used to capture learner perspectives, prioritize features for prototyping, ensure helpful app feedback, and gain clarity about how the app was used.

Phase 2: Deployment and Refinement (underway)

The goal of this phase is to test the app and use feedback to refine usability and gameplay. In Fall 2022, approximately 100 early undergraduate students enrolled in an introductory statics course at Worcester Polytechnic Institute (WPI) were surveyed regarding their use of the app. Data from this round of testing was used to revise the prototype gameplay to be more user-friendly and to rework the tutorials. In Spring 2023, approximately 57 early undergraduate students enrolled in an introductory statics class at Bucknell University and 26 advanced undergraduate students enrolled in a rehabilitation engineering class at WPI are being surveyed regarding their use of the app. Data from this round of testing will be used to further revise the app and determine additional features during Summer 2023.

Phase 3: Research Study (future work)

The goal of this phase will be to answer three questions:

- How do students engage with the app in learning FBD skills?
- Does the app promote mastery of FBD skills, particularly for women and underrepresented minorities?
- Does the app promote increased self-efficacy, particularly for women and underrepresented minorities?

Once improvements from the first two phases of app development are integrated into an updated version, the app will be re-deployed in multiple courses. The app will then be assessed to gauge its impact on students' improvements in technical competency as well as self-efficacy.

Current State of the App

In its current state, the FBD app is structured around three "mini games" related to drawing rigid body FBDs: a tracing game designed to provide practice in isolating the correct body to "free" to start an FBD, a falling game designed to provide practice in quickly identifying supports that provide particular support reactions, and a place and orient game designed to provide practice in drawing complete FBDs. Each mini game has a tutorial that introduces gameplay mechanics and associated critical skill(s) and a number of instances or "levels" on which to practice. Further mini games will be added in the coming year that address additional FBD skills (e.g., identifying two-force members) or provide different types of practice (e.g. identifying mistakes on pre-drawn FBDs). Care has been taken to have each mini-game target a particular pitfall area for students (with the exception of the place and orient game for drawing complete FBDs), allowing focused practice via repetition on a particular mini game. Below, each mini game is described in additional detail.

Tracing Game for Isolating Bodies

The first step in drawing an accurate FBD is isolating the correct body. When several bodies are joined together to form a system, students can struggle to isolate the best body or subsystem to start their FBD. To build skill in this area, we developed a mini game in which students must trace around the correct body or sets of bodies based on a prompt indicating a goal for the FBD. With one of their fingers, students trace the outline of the body or bodies they want to isolate. Levels involve images composed of several bodies and subsequent levels will often replicate the same images with different goal prompts in order to emphasize how the best body to isolate depends on both the system and the goal for the FBD. This content variation is shown in the tracing game tutorial in Figure 2 and in two paired levels shown in Figure 3.

Figure 2: The first tutorial for the tracing game for isolating bodies.

Figure 3: Level 03-1 shows car A isolated to find the force between the two bodies (left), and Level 03-2 shows both cars, A and B, included in the system (right).

Falling Game for Identifying Support Reactions

Another important skill when drawing a FBD is replacing environmental connections with equivalent forces and moments. Students often struggle to recall the appropriate substitution for typical supports, such as pins, rollers, fixed connections, etc., in 2D and 3D. To give students practice recalling support reactions, we developed a mini game in which students are given a support reaction goal they need to match such as “connections with at least one moment reaction”. In the mini game itself, small drawings of different supports then fall down the screen. Supports that match the goal must be swiped to the left, while supports that don’t match the goal are swiped to the right. This helps students to quickly learn and internalize the various common support reactions. An image of one level in the falling game is shown in Figure 4. Correctly identified connections reward the user with stars, while supports identified incorrectly fill the screen with smoke.

Figure 4: A roller correctly identified as having no moment reaction (left), a pin misidentified as having a moment reaction (center), and connections before and after swiping (right).

Place and Orient Game for Complete FBDs

To give students practice creating complete FBDs, we created a two-part pick and place game. The first screen of this game, shown in Figure 5, presents students with a scenario for which they need to draw the FBD. On this screen, students can elect to interact with the system by removing various supports and seeing how the system will respond via a physics engine simulation. Once students are ready to create their FBD, they move to a second screen, shown in Figure 6 (left), where they use a drop-down menu to select which body to isolate for their drawing. They then use buttons to select and drag coordinates, forces, and moments to various locations on the body, tapping these loads to change their orientation, until they have a complete FBD, as shown in Figure 6 (right).

Figure 5: A weightless link and smooth contact support beam BD (left). Upon clicking the link, the system simulates the swinging of beam BD when supported by only the selected link (right).

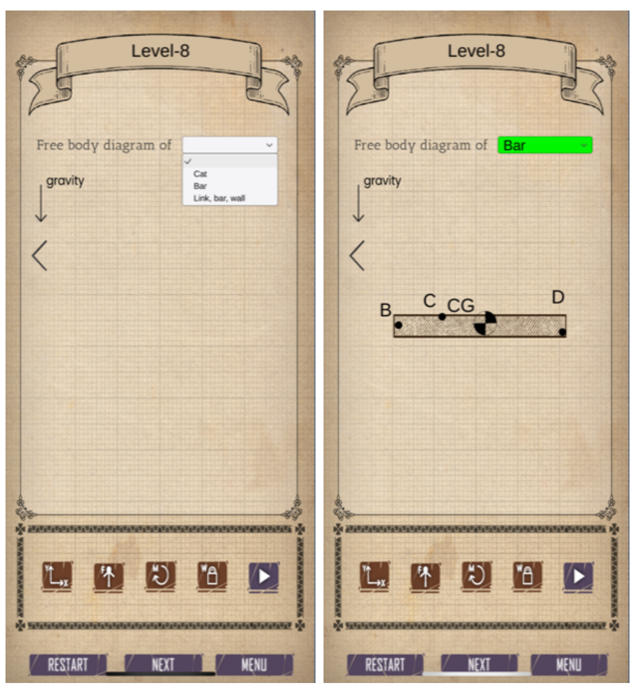

Figure 6: Three system options “Cat”, “Bar”, and “Link, bar, wall” are available for selection (left). Once selected, the correct system “Bar” is shown (right).

This mini game incorporates multiple forms of user feedback. An initial feedback system provides the students with the number of components that are correct, incorrect, or missing as shown in Figure 7 (left). A multi-level hint system allows students to gradually reveal the solution if they have difficulty. The first hint level reveals which components on the screen are correct and incorrect, as shown in Figure 7 (center). The second hint level draws missing components on the diagram, fully completing the solution, as shown in Figure 7 (right). This allows students to get assistance if they need it, but in a way that is appropriate to their level of expertise.

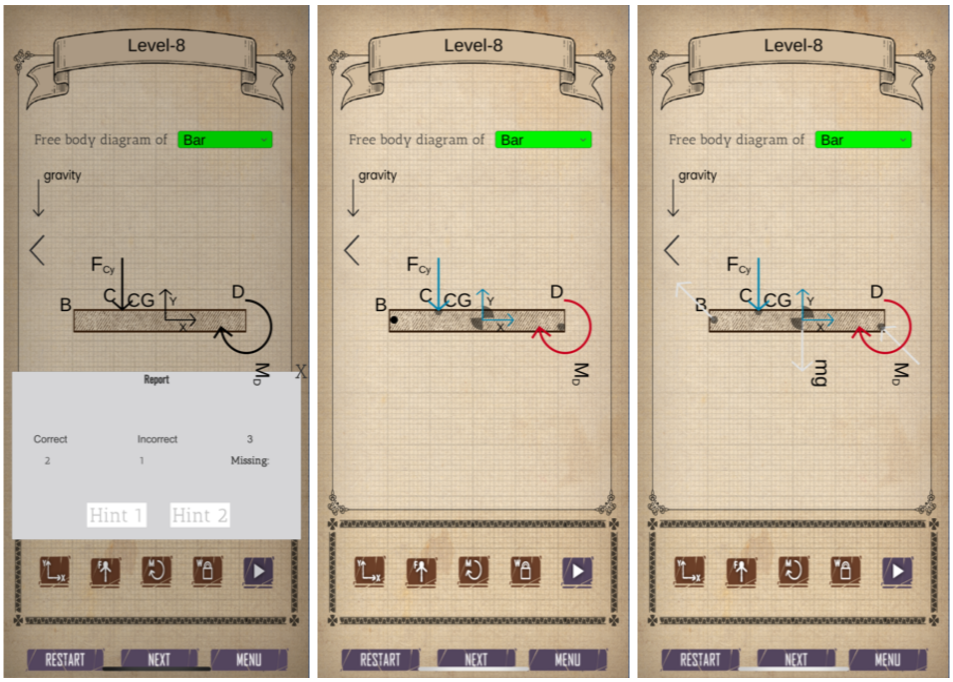

Figure 7: General user feedback indicates that there are 2 correct, 1 incorrect, and 3 missing elements (left). Hint 1 shows the correct elements in blue and incorrect elements in red (center). Hint 2 shows the missing elements in white (right).

Student Testing and Feedback

The app was piloted in Fall 2022 with students enrolled in a large introductory statics course as a non-graded study activity. Students were enrolled at WPI primarily as sophomores. All students except one (n=97) participated in an evaluation of its design features and reported their experiences. Within this sample, 41% of students identify as women, 56% identify as men, and 3% identify as non-binary or gender fluid. Students also self-identified their racial/ethnic identity, with 33% indicating a BIPOC identity. Approximately half (54%) of students indicated they had played half or more of the available games.

Data were collected using a survey deployed via Qualtrics. The Student Assessment of their Learning Gains survey (SALG) [24 - DUE 0920801] asks students the extent to which they made gains in specific aspects of their learning (e.g., “identifying what type of problem you are asked to solve,” “developing a logical argument to defend a proposed solution”) using a five-point scale from “no gains” to “great gains.” The survey also asks students how much specific aspects of the class (e.g., attending lecture) helped their learning, allowing us to isolate student experiences with the FBD app. The SALG has been used by more than 22,000 instructors to assess nearly half a million students. Open response questions were embedded in the SALG survey to collect contextual data regarding students’ experiences of why they engaged (or did not engage) with the mobile learning tool and how they found it more or less useful than other learning activities.

Design Fidelity

The first set of findings helped us to consider whether the app was constructed in alignment with the goals for creating it. One of the app’s primary design goals is to provide a gamified environment, in contrast with the typical practice offered by homework assignments. Students were asked “What did the FBD app environment feel like?” Response options ranged from “it felt like a gamified environment” and “it felt somewhat like a gamified environment” to “it felt closer to a homework environment” and “it felt like a homework environment.” Two thirds of responding students indicated that the app feels at least somewhat like a gamified environment as shown in Figure 8. This suggests that there is work to be done revising the design to ensure that the elements required to gamify learning are adequate.

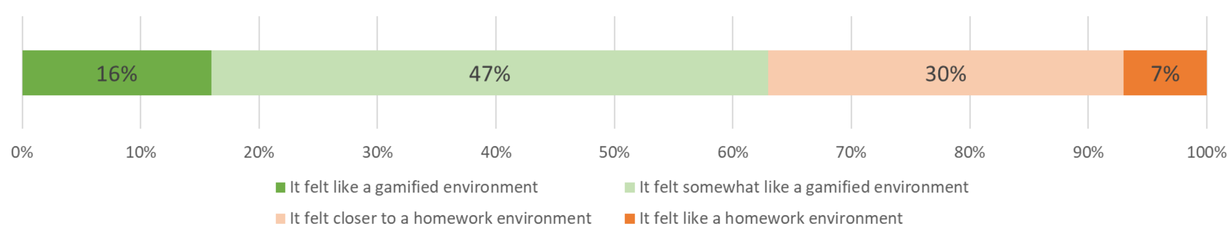

Figure 8: Student description of the app environment.

A second design goal is to modernize how students learn and practice FBDs. When commenting about how the FBD app did, or did not, help their learning, 49% of respondents appreciated that the app allowed additional opportunities for practice. Students used these opportunities to further develop several skills, such as visualizing the system and setting up accurate diagrams, which strengthened their confidence and reviewed key concepts. As one student shared, “The FBD app helped me with remembering all the components. I often miss one or two when I am rushing through, but the app made sure I included everything before moving on.” Other students shared similar reactions, such as “There was a kind of FBD checklist I had to go through in my head to make sure everything was done right” and “The FBD app helped me have a better understanding on what needs to be included in FBDs.” Identifying each step and alerting students to distinct steps is not possible because of the time delay involved when homework is the primary mode of practicing FBD skills.

While describing the value of practicing with the app, 21% of students specifically called out valuable aspects of how the app provided feedback. Students appreciated that feedback through the app is immediate: “The FBD app was very helpful because it gave me examples and immediate feedback on my mistakes, which we had less of in this course.” Other students emphasized the benefits of receiving feedback that explained the system’s support reactions. “The FBD part helped since you could click the points holding the object up to see what was happening. Also the arrow hints helped a lot too.” As another student explained, “I liked the visuals on the FBD part that you could tap to see how the support impacted the system.” The app has been successful in providing feedback that is immediate and that scaffolds conceptual learning in that immediate moment.

Several students also pointed out the benefits when the app helped them correct mistakes. “It was fun to problem solve. If I get it wrong, I can try it again,” was one student’s response. “I liked how it helped you visualize FBDs, and helped you understand how to correct whatever mistakes you might have made” shared another. Feedback that deepens learning after mistakes are made is a design feature of the app that distinguishes it from homework; student response to this design feature was positive along with requests for additional improvements in this area.

Initial Evidence of Student Learning

An item in the SALG survey asked students to report how much the FBD mobile app helped their learning. On average, students reported the FBD mobile app was of moderate help to their learning ($M=2.98$, $SD=1.09$) with an even distribution of learning experiences reported (see Figure 9). There were no gender-based differences in learning gains from the app, with $t(90)=-.68$, $p=.50$. As other studies have resulted in women rating their STEM learning lower than men [23], we interpret this initial parity with cautious optimism.

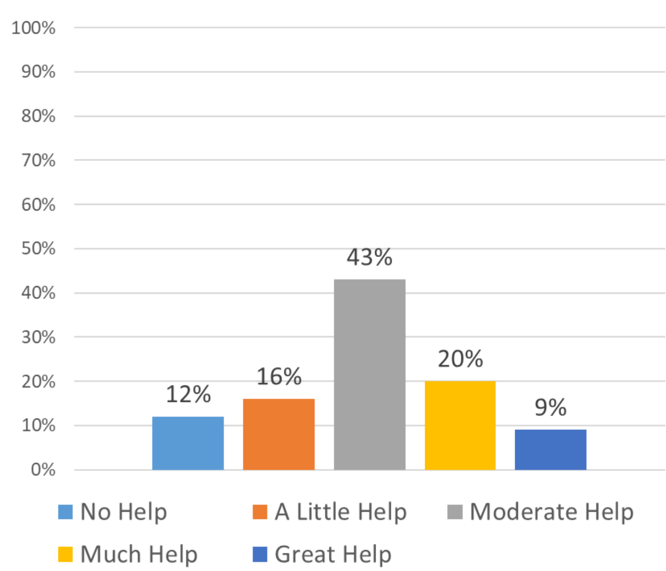

Figure 9: Learning attributed to the FBD app.

As students used the app with varying frequency, we can also explore whether there are any dosage effects. The 41 students who completed less than half of the FBD mobile app games reported less learning ($M=2.63$, $SD=1.09$) than the 52 students who completed half or more of the games ($M=3.27$, $SD=1.01$). This is statistically significant with $t(91)=2.90$, $p<.01$. This lends additional support to the interpretation that the app is positively affecting student learning; however, this does not imply causation between the app and learning, as those who did not find themselves learning early in their use may have stopped before completing half or more of the games. This is an area we intend to explore further with the aid of additional data in the next phase of the study.

Suggestions for Further Improvement

Students were asked to provide formative feedback to determine which aspects of the app needed additional revisions to be fully usable as a learning support. Students were given two opportunities to indicate which aspects of the app were not helpful to their learning. The first open-response item asked, “What is one thing you would change about the mobile app?” The second open-response item, appearing later in the survey, asked, “What is one thing you would remove/eliminate from the app?” Most commonly, 43% of students requested changes to improve the user interface and fix known bugs; these requests were almost all generally stated and reflected the current stage of app development.

More specifically, 32% of students pointed out the need to adjust the sensitivity of the app’s accuracy to better reflect user intentions. As one student shared, “I would make the buttons less sensitive because the arrows and such flipped too easily. Also sometimes the arrows would not fully line up with the correct solution so it would say it was wrong even if it wasn’t.” Another student summarized, “the accuracy of the FBD drawing, size of the FBD diagram, circling the FBD and the loading speed.” These useability issues were prioritized for refinement in late Fall 2022/Winter 2023.

The next most frequent request, made by 21% of students, was improvements to the feedback provided through the app. Many of these comments provided insights into how students would expect feedback to function within a gamified environment. For example, one student suggested “One thing I think I would change would be to add your previous score in a viewable place.” Another student requested that the designers, “Add more explanations, for example in the falling game if you get a couple wrong maybe after you finish the game you could see which you got wrong with an explanation as to why it’s wrong.” A few students requested additional scaffolding, such as “Having the drawing/circling section have a hint system or ability to display the answer like the other 2 sections.” These requests are integrated into the team's interval review process.

A few students indicated they would change the app to include more elaborate tutorials. This may be a longer-term development activity but is not directly necessary for testing the app and was thus prioritized lower than other formative feedback.

Discussion

Initial findings from students suggest that the app is on track to engage students in learning and practicing key FBD skills. The app is intended to provide opportunities to receive more structured, immediate feedback during practice than traditional homework; current feedback suggests that students are using the app in this way. This serves as initial proof of concept and is encouraging for faculty who may want to adopt similar tools.

The initial findings also provide some evidence that women are performing as well as men with the practice sets. We look forward to further examining how self-report and performance on a concept inventory tool compare after using the app. This is particularly interesting as we know that women tend to under-rate their technical abilities. The potential for the app to tell us more about the interplay between building skills, improving self-efficacy, and with that confidence, increasing performance, will allow us to delve deeper into the benefits of this new way of scaffolding FBD learning.

Next steps for the project include streamlining the process of adding users to the app, incorporating student feedback, developing back-end analytics, and adding new games and levels. These improvements are designed to reduce barriers for student interaction with the app by targeting challenge areas and developing further exercises to improve skills in those targeted areas.

Conclusion

Data collected during the deployment and refinement phase of this project suggests the FBD app has a positive impact on student learning. Associated student comments indicate that the immediate feedback generated by the app is particularly valuable. This early data also shows that a majority of students consider the app environment to be gamified and therefore more engaging than a typical academic exercise. Taken together, these results suggest the app is a valuable and fun new way for students to practice and build skills related to drawing FBDs, and further development of the app is warranted.

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