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Students' Perception of Using 3D Digital Models to Solve 3D Statics Problems

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Students' Perception of Using 3D Digital Models to Solve 3D Statics Problems

Abstract

Graphical representation of forces and moments acting on a structure, and understanding their spatial significance, are two of the biggest challenges students encounter in a statics course. The complexity of the issue increases for 3D problems, which require students to visualize the directions of force projections and the moments or rotation they cause about 3D cartesian axes. This study investigates students' perception when using 3D digital models to solve common 3D statics problems. The 3D digital models were created using TinkerCAD software to help students visualize 3D statics problems along with their corresponding forces. Students were able to translate and rotate these 3D digital models within a web browser. A think-aloud protocol followed by semi-structured interviews was used to gather students' cognitive process and perceptions of solving 3D statics problems both with and without the 3D digital models. Four interviews were conducted, and each interviewee solved two 3D statics problems under two different conditions while voicing their thought processes. In the first condition, the interviewee was provided with the problem statement and a perspective drawing of the problem. In the second situation, the interviewee was given both the problem statement and the perspective drawing, along with the 3D digital models. The transcript of the interview data was coded and analyzed by focusing on students' cognitive processes and perceptions. Data gathered from this analysis were compared between the two conditions, collectively and individually, by examining how the interviewees gathered information, identified its significance, made decisions, and explained their rationale. The results suggest that students perceive 3D digital models as helpful and may assist in reducing the cognitive load for visualization and in increasing their confidence when solving the problems.

Keywords

Statics, Spatial reasoning, 3D visualization, 3D problem-solving, Think-aloud, Student perception

Introduction

Spatial visualization skills are important for success in STEM fields, especially engineering. Many engineering problems require students to visualize a system in different orientations, including rotating, translating, and section-cutting the system. Many researchers have shown a strong correlation between success in the STEM field and spatial reasoning skills [1-3]. Wai et al. [3] analyzed data from longitudinal studies conducted over 11 years and confirmed that spatial visualization strongly influences success in many STEM field. In addition, Hsi et al. [2] also conducted longitudinal studies showing spatial reasoning ability significantly predicted students' success in engineering graphics course exams.

Engineering statics is one of the gateway courses for students interested in mechanical, civil, and aerospace engineering majors. Therefore, successful completion of this course is crucial for students' retention in these majors. From the past five years of data at the University of Georgia

(Fall 2019 – Spring 2024), 23.1% of students fail statics (D, F, W grade) [4]. This number is significant considering the importance of this course in a student's academic path.

Statics is based on fundamental mathematics and physics concepts, including algebra, geometry, vector operations, and Newton's laws of motion. In this course, students are required to synthesize these fundamental concepts into their problem-solving process to successfully complete a mechanical analysis of a static system. The first step in this process requires students to understand the system described in the problem and sketch free-body diagrams (FBDs) representing the system. Based on these diagrams, students apply mechanics and mathematics to write and solve equilibrium equations for forces acting on the system. Studies have shown that common statics errors are related to how forces acting on a system of rigid bodies are represented and treated in calculations [5-7]. This includes interpreting interaction characteristics between objects (e.g., supports and connections) into forces, and calculating force components or moments of forces about certain axes. The complexity of this issue increases when students must solve 3D problems instead of 2D [8].

Much of the recent literature on the development of 3D models to facilitate Statics instruction has focused on virtual and augmented reality applications. Hagenberger et al. [9] and Ha [8] conducted studies on the usage of virtual reality (VR) technology in helping students solve 3D Statics problems. These studies found that this exposure does help students understand some 3D problems better than just seeing 2D images. Dunmoye et al. [10] conducted a study to investigate modes of cognitive engagement of students working together to solve statics problems in a VR learning environment. Their work-in-progress study identifies that active and constructive modes dominate over the interactive mode of cognitive engagement when involved in the activity. Giancaspro et al.[11] and Miner et al. [12] developed augmented reality (AR) applications to help students understand 3D vectors and their application in 3D statics problems. While the implications of the tools to the students' performance in solving 3D Statics problems are still unclear, some students involved in the study shared positive experience using the apps. Despite its promising benefits, the implementation of VR and AR tools can still be a barrier for many students considering accessibility and efforts needing to learn the tools. Thus, we focus on the study of 3D models for use on standard computer monitors or smartphones through web browser.

This study is conducted to: 1) identify students' cognitive process when solving 3D statics problems without and with accessible 3D digital models, and 2) investigate students' perception of accessible 3D digital models to solve 3D statics problems. In this study, the models were developed in the TinkerCAD platform and accessible via web browser platforms through a computer or smartphone. It should be noted that these models can be developed in other platforms, such as GeoGebra, that allow certain types of interactions (translating and rotating) between the users and the models. This study does not focus on the developed models but on the students' cognitive process and perception when using digital models to help them solve 3D statics problems. Moreover, this study was conducted to familiarize the first author with the engineering education research field, specifically qualitative methods, and was supported by the innovation grant provided by the Engineering Education Transformations Institute at the University of Georgia.

Theoretical Framework

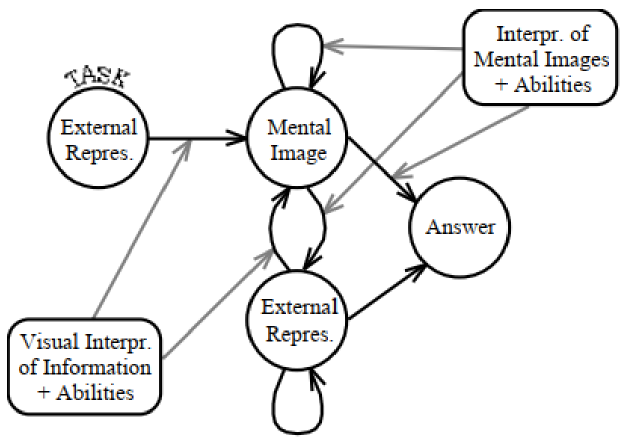


Figure 1. A model describing the problem-solving process involving 3D geometry visualizations.[13]

Two theoretical frameworks: constructivist theory of perception and cognitive load theory can be integrated into a problem-solving process model proposed by Gutiérrez [13] (see Figure 1). The constructivist theory of perception suggests that (visual) perception is an active cognitive process where individuals interpret sensory data based on prior knowledge [14]. On the other hand, the cognitive load theory states that learning efficiency depends on how much working memory is occupied during problem-solving [15]. The model proposed by Gutiérrez [13] describes a problem-solving process in mathematics involving 3D geometry visualizations. The problem statement (*task)* is interpreted as external representation to generate the first mental image that is used to process the information and solve the problem. Depending on one's visualization and cognition abilities, different processes, including generating other mental images and/or external representations, may be needed before delivering the solutions.

In the context of the 2D-drawing problem-solving in this study, the problem statement and 2D perspective drawing serve as the initial external representation. Interviewees will use this information together with their prior knowledge to actively generate and reconstruct mental images that they perceive to be useful and manipulate (e.g., mental rotation) them to solve the problem. This process may require higher cognitive effort than when 3D digital models are introduced as an additional external representation. The 3D digital models may make visualization easier for students to perceive the information and actions needed to deliver the solution. Hence, it reduces cognitive load and allows more efficient problem-solving.

Methodology

The think-aloud method is selected as the research method for this study because it is suitable to investigate the thought process of participants in problem-solving [16]. In this method, interviewees will be given a problem to be solved, and they will speak out their thought process while solving the problem. The interviewer will act as a facilitator to remind the interviewees to keep speaking out their thoughts. Fonteyn et al. [16] recommended conducting a follow-up interview process to fully obtain the description of the reasoning used during a particular problem-solving task.

Selection of Participants

Interview participants were recruited from statics classes near the end of the semester, and the interviews were conducted after the semester concluded. An email was sent out to students. Four students responded to the email and voluntarily participated in this study. This voluntary participation can create some bias to the results since the participants are not randomly selected. Hence, this should be noted as a limitation in this study. We believe this limitation is acceptable, as the goal of this study is to develop an initial, exploratory understanding of how our 3D models influence Statics problem-solving, rather than to generalize to broader populations.

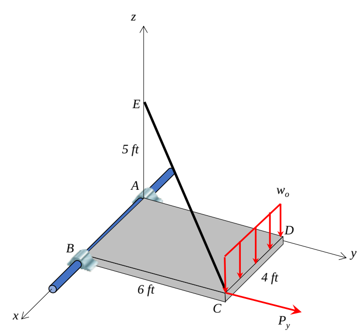
Materials

Two similar 3D statics problems were developed for this study. Figure 2 shows the 2D isometric images of the system and their problem statements. These problems share similar components such as supported by journal and thrust bearings, a cable or a strut, distributed forces, and one concentrated force.

A plate *ABCD* is rigidly connected to a cylindrical rod. This rod-plate structure is then supported by a journal bearing at *A,* a thrust bearing at *B,* and a cable tied between point *C* to *E*. It is assumed that the cable is pinned to something rigid at joint *E* (no movement). A force in the *y* direction is applied at point *C* and a uniform distributed force in the negative *z* direction is applied on the plate along the edge *CD*. Assume that $P_y = 100\ lb$ and $w_o = 50\ lb/ft$.

Write the equilibrium equations needed to solve for the reactions and cable force CE

Note: ignore the thickness of the plate, diameter of the rod and dimensions of the bearings in your calculation.
<u>Journal bearing *A* restricts translational motions in the *z* and *y* directions. Thrust bearing *B* restricts translational motions in the *x, y* and *z* directions.</u>

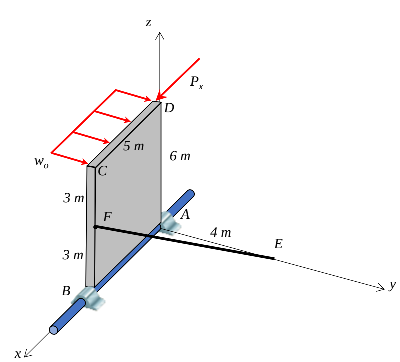


(a) Problem A

A plate *ABCD* is rigidly connected to a cylindrical rod. This rod-plate structure is then supported by a journal bearing at *A,* a thrust bearing at *B,* and a strut connecting point *E* and *F*. It is assumed that the strut is pinned to something rigid at joint *E* (no movement) and pinned to the plate at joint *F*. A force in the *x* direction is applied at point *D* and a uniform distributed force is applied on the plate along the edge *CD*. Assume that $P_x = 1000\ N$ and $w_o = 50\ N/m$.

Write the equilibrium equations needed to solve for the reactions and strut force FE

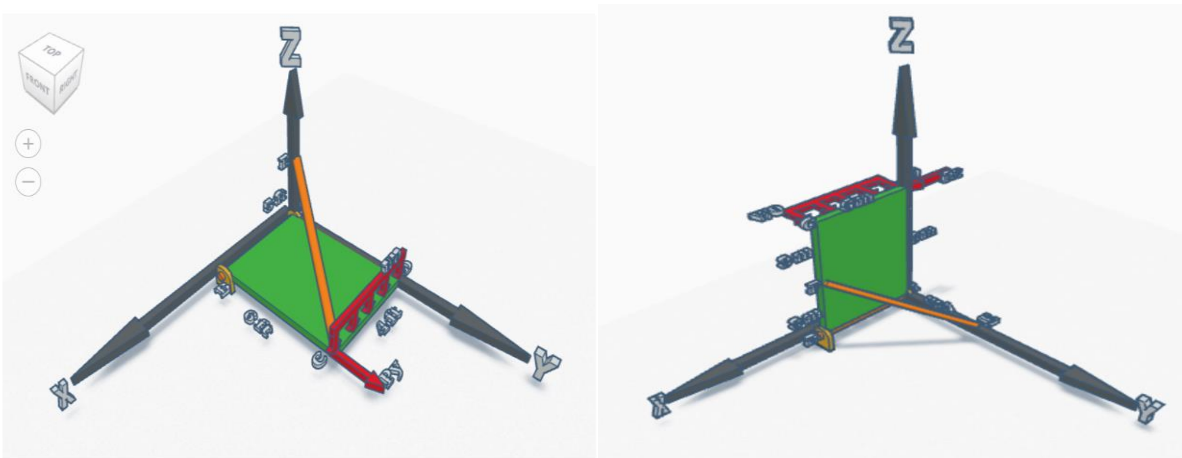
Note: ignore the thickness of the plate, diameter of the rod and dimensions of the bearings in your calculation.
<u>Journal bearing *A* restricts translational motions in the *z* and *y* directions. Thrust bearing *B* restricts translational motions in the *x, y* and *z* directions.</u>



(b) Problem B

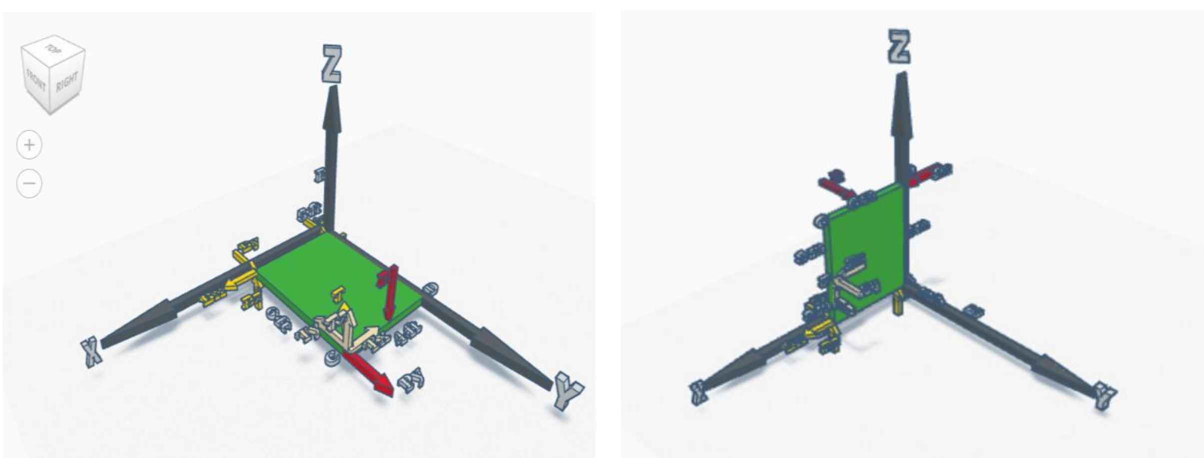
Figure 2. 2D isometric images and problem statements for the problems developed for this study

For each problem, two sets of TinkerCAD models were developed. Figure 3 shows the first set of the 3D digital models showing exactly the same components (bearings, plate, cable or strut, forces) as in the 2D isometric images. Figure 4 shows the second set of 3D digital models showing the FBDs of the problems. In using these digital models, students were able to rotate and translate the models, however they could not move each component of the object independently from the others.



(a) Problem A **(b) Problem B**

Figure 3. 3D digital models for the problems developed for this study



(a) Problem A **(b) Problem B**

Figure 4. 3D digital models showing the free-body diagrams for the problems developed for this study

Data Collection

Each interview consisted of two distinct problem-solving sessions: solving a 3D statics problem using only a 2D perspective drawing (2D-drawing) or solving a 3D statics problem using the 2D perspective drawings and their corresponding 3D interactive models (3D-model). To capture the potential impact of problem order, two interviewees were given Problem A as the 2D-drawing followed by Problem B as the 3D-model. The remaining two interviewees were given Problem B as the 2D-drawing followed by Problem A as the 3D-model. Both the 2D-drawing and 3D-model interview sessions were split into three phases: 1) describing the static system given in the problem, 2) deriving the equilibrium equations for the system, and 3) a semi-structured interview. The first two phases were conducted using the think-aloud method, while the semi-structured interviews were conducted based on the following set of referenced questions:

1. What are the difficulties in relating the given information (2D-drawings, 3D-models, and problem statements) to deriving equilibrium equations?
2. What do you like about the 3D digital models?
3. What aspects of the 3D digital models that helped you writing the equilibrium equations?
4. What kind of changes you wish to see from the current 3D digital models? What features that you expect to be here?

Students' on-paper problem-solving was recorded using a document camera. Interaction with the TinkerCAD model was documented using screen-recording software during the interview. The audio collected from the voice recorder was transcribed using Otter.ai and edited as needed. The transcripts were coded in MAXQDA for detail analysis.

Transcript Analysis

The analysis of the transcript data can be divided into two components: 1) script and referring phrase analyses [16], and 2) thematic analysis. The script and referring phrase analyses involve labeling transcripts of collected data with specific codes and find patterns in the data to ease the analysis and document writing. Meanwhile, the thematic analysis involves labeling the transcripts data in an open-ended manner extracting meaningful themes that emerge from the data itself.

Script analysis is conducted to provide a general description of the cognitive processes that interviewees used during a problem-solving task. Fonteyn et al. [16] proposed four themes for coding the interview data for instances where the interviewees: 1) attentively considered the information (*Study*), 2) made a decision on the significance of information (*Conclude*), 3) verbalized their choice (*Choose*), and 4) explained their rationale for their action or decision (*Explain*). Table 1 below provides examples of how the interview data were coded using these themes.

Table 1. Example of script analysis

Examples of interview data	Theme
"Over here, we have the distributed force going along this entire side CD, pushing down on the object, we also have a force Py, pushing the object in the positive y direction, or pulling in the positive y direction. And then you also have a tension force going from E to C."	*Study*
"We have our force B of x not acting on it. B of zed is acting on it. B of y of course is not acting on it. In terms of our tension, let's see. F of y won't be act-ing on it or T of y. T of x would be rotating around and also T of zed would be rotating around."	*Conclude*
"First start off with the <u>moment around the x axis"</u>	*Choose*
"So Py wouldn't act to it <u>because it's parallel with it.</u> But-- and then also, since <u>the bearing A is also on that axis</u> it won't act on it either."	*Explain*

In the referring phrase analysis, interview data were coded with respect to various common phrases used when solving a problem in statics. The codes used included instances of drawing free-body diagrams (*FBD*), performing sum of moments (*SoM*), performing sum of forces (*SoF*), and describing the physical and geometric aspects of the problem (*PnG*).

In the thematic analysis, additional themes were identified based on any notable instances in the transcript data from the 2D-drawing and 3D-model problem-solving sessions verbalized by students, including difficulties and specific problem-solving strategies. Any specific feedback on the 3D models was also coded and used to highlight their positive aspects and identify potential areas for improvement.

After the interviews were completely coded, the occurrence of the themes was quantified for the 2D-drawing and 3D-model problem solving conditions to identify patterns found in problem-solving. The frequency of each theme in the interview was used to compare the 2D-drawing and the 3D-model problem-solving processes.

Results and Discussion

Table 2 presents the frequency of script analysis themes found in the coded transcripts when interviewees solved 3D statics problems without (2D-drawing) or with (3D-model) 3D models. According to Fonteyn, et al. [16], the themes used in this script analysis describe the reasoning process of the interviewees used during problem-solving tasks. All of these themes have consistently appeared more frequent when interviewees solved the problems without the 3D models (2D-drawing). The reduction in the *choose* was less pronounced than the others. We believe this is because the actions associated with writing equilibrium equations were coded under this theme, and both 2D-drawing and 3D-model problem-solving tasks require the same number of equilibrium equations to be written.

Table 2. Frequency of the script analysis themes found in the coded transcripts for 2D-drawing and 3D-model problem solving

Script Analysis	2D-drawing	3D-model	% Reduction
Study	22	13	41%
Conclude	96	61	36%
Choose	39	33	15%
Explain	37	20	46%

In the referring phrase analysis, statics themes (*FBD, SoM, SoF, and PnG*) also appeared slightly more frequently when interviewees solved the problem without 3D models (2D-drawing) (See Table 3). In general, the difference in code frequencies between 2D-drawing and 3D-model problem solving task, although decreased, is not as drastic as the difference in the frequency of the script analysis codes in Table 2. This smaller difference is expected because both problem-solving tasks required interviewees to describe their freebody diagrams and write the same number of equilibrium equations.

Table 3. Frequency of the referring phase analysis themes found in the coded transcripts of 2D-drawing and 3D-model problem solving

Referring Phrase Analysis	2D-drawing	3D-model	% Reduction
FBD	17	14	18%
SoM	33	26	21%
SoF	14	11	21%
PnG	10	9	10%

There are several possible explanations for the lower frequency observed in 3D-model problem-solving tasks compared to the 2D-drawing problem-solving tasks:

1) The 2D-drawing tasks were conducted before the 3D-model tasks. Therefore, interviewees may have felt they had already talked the problems sufficiently during the 2D-drawing tasks and spoke less during the 3D model tasks, particularly for repetitive processes such as writing the equilibrium equations and describing the system. This should be noted as a limitation of this study and a point of improvement for future studies.
2) Some interviewees may have struggled to understand the 3D models, which limited their ability to describe their actions. This explanation is possible because one interviewee initially avoided using the 3D models when writing the equilibrium equations since the interviewee thought the 3D models could distract his or her focus in solving the problem. This observation is similar to results reported by Giancaspro et al. [11] that some students faced challenges in learning the digital tools. However, a more detailed data analysis presented in the next paragraphs indicates that all interviewees were able to interact with the models and gain benefits from using them in problem-solving tasks.
3) Interviewees may have required less cognitive effort to study and understand the problem and decide on the significance of value or information when 3D-models were provided. Based on the theoretical framework, this is an ideal explanation. From a constructivist perception perspective, introducing relevant 3D models externalizes some spatial visualizations needed to solve the problem. Hence, the models minimize the need for interviewees to reconstruct mental images. Therefore, their cognitive load is reduced as suggested by the cognitive load theory. Although the theoretical framework and further analyses on the data in this study tends to support this reasoning (as discussed in the subsequent paragraphs), the authors of this paper agree that further studies are needed to confirm this reasoning.

Open-ended thematic analysis of the interview data provides valuable insights into interviewees' perceptions of the 3D models and support the reasoning that 3D models can be beneficial in solving 3D statics problems. When solving problems without 3D models, interviewees reported challenges with 3D visualizations, particularly in determining the direction of moments caused by forces. These challenges could lead to more cognitive effort needed to study the information and make decisions based on the information as evidenced by the higher frequency of script analysis results for the 2D-drawing condition presented in Table 2. The following quotes describe interviewees' difficulties in visualizing the rotational direction of a force about certain axes.

"Okay. So, first when I thought about it, I thought that it would go. Like, doesn't make sense, but it kind of goes like this... Also, like, the orientation of each force also, are a bit tricky on this

problem because I don't know how to-- like, which direction it goes. Like this. I thought about it. This is going clockwise..."

"And the thing that I find hardest is usually when I'm trying to find the direction of moment, because I have to think about the force, like in terms of this diagram, but if I have, if I am taking the moment about like the x axis here, but then my resultant is about like, or is in the direction of the y axis, I have to like, in my head, I always reorient it so that I can see it in like where it would be the zy-axis…"

"*I would say the most difficulty comes with the force going from E to F. How that acts with respect to the axes, when we're taking a moment equation, or whether it's about z, x, or y*."

All interviewees noted that the 3D models helped them visualize the problem better, especially the 3D models that already include the force diagrams. This emphasizes the benefits of 3D models and the importance of drawing the force diagrams correctly. Specifically, students noted that breaking up the diagonal force into cartesian components improved their understanding of how the force acted on the system. This finding supports the third possible reasoning above that interviewees may have required less cognitive effort to solve the statics problems when 3D digital models were provided. This finding also shows instructors that emphasizing how to draw the components of a 3D diagonal force is beneficial to students' understanding of deriving equilibrium equations. Students have reported that they can visualize the moment implication of a diagonal force better once they have drawn its components. The following quotes indicate how the 3D models helped students visualize how a force can rotate about a certain axis.

"Yeah. When the forces are being drawn, and like, I can see what direction it rotates, I think that will be a lot helpful, because in the two-dimension, I can't really see that, clearly. So, I think the 3D model helps in that way."

"The biggest thing is, of course, visualization because I can physically spin saying this one's going around this way. So, it's acting like that. And I can basically see exactly how these are going to change the moment around certain axes, which helps a lot in terms of direction because just remember, the right-hand rule is supposed to be spinning around that way."

"… And I can physically see what forces are gonna be acting on it. So, let's just take this point F of here, I will see this one's not going to act in the-- around the z axis, but we have the F of y acting in the z direction, but the F of z won't be acting in that direction..."

"So definitely having the force drawn out are really helpful in writing the equilibrium equation, while this model over here just helped you kind of like visualizing..."

The 3D models also helped the interviewees' problem-solving confidence by confirming how the forces are positioned or located in 3D space. Direct quotes related to problem-solving confidence are shown below.

"The second part is also verifying the results I have, because I can go back and say, okay, basically double checking, I can verify that this force is the only one acting in this direction, this one's acting in this direction, so on and so forth."

"I don't have any doubt that there's-- it's a three dimensional but if I were looking like I guess however this is drawn, if I were to go out, I could easily confuse or I would say in the previous one you could confuse it for being only acting in 2D"

In relation to problem-solving strategies, this study confirms the research results obtained by Litzinger et al. [5] on how students often rely on memory and their prior knowledge when solving statics problems. For example, some interviewees had doubts on what forces are implied by the thrust and journal bearings. In addition, interviewees referred to the right-hand rule to determine the direction of moments when solving the problems. This observation can be found in problem-solving conditions with and without 3D interactive models.

"Yeah, first looking at the w_0 *trying to figure out if it's negative or positive going around the x axis. So based on my right-hand rule, it should be negative."*

"What was the difference between the journal bearing and thrust bearing because they look similar?"

Despite commonalities in the problem-solving process for both experimental conditions, introducing the 3D interactive model appears to have reduced the reliance on significant memorization when performing a static analysis. The best example of this is a quote from one interviewee explaining how, although they understand the right-hand rule, with the 3D model they found they could correctly assign the direction of the moment caused by individual forces acting on the object.

"But that would help in terms of figuring out your moment saying, even if you don't remember the right-hand rule, you could say, okay, this one's gonna be acting in this capacity and this one will be acting in the opposite direction, that sort."

Identifying the direction of a moment in 3D space is a common challenge for statics students. From the analyzed interviews, introducing 3D interactive models to students may help build an intuition for moment direction rather than students' relying on memorization of processes like the right-hand rule.

On a personal note, this study not only helps in improving how the first author assists his students to be more successful when solving 3D statics problems but also allows him to step into a new research field in engineering education. Performing this study helped the first author identify a possible need to investigate the relation of students' spatial cognition and problem-solving skills to better understand the reasons students often struggle with 3D problems. In addition, this study also provides feedback on how 3D models can be developed to help students learning this topic. Some of these features include the ability to toggle the forces on and off allowing students to be more focused on those specific forces and the use of color to help identify the different forces acting on the system.

Conclusion

This study investigated students' cognitive process and perception of using 3D digital models to solve 3D statics problems by employing a think-aloud method. This study suggests that interviewees perceive 3D digital models to be helpful in visualizing force components and moment implication of a force about certain axes in 3D space that may contribute to less cognitive effort when interviewees solving problems with 3D digital models. In addition, interviewees were able to use the 3D digital models to confirm their understanding of the problems. Hence, the models increase their confidence in solving the problem. Furthermore, the interview data also indicates that drawing components of diagonal forces can help students visualize the moment implication of the forces better. Therefore, it is crucial that statics instructors convey to students how to properly split a complex 3D force vector into its cartesian components. Reminding students to draw the components of the force on their FBDs may also improve students' comprehension of 3D systems and their success in solving 3D statics problems.

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