A Qualitative Investigation of Students' Problem Solving Strategies in a Spatial Visualization Course

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Abstract

This Complete Research Paper describes a research study aimed at understanding strategies engineering students use in solving spatially-related problems. The participants in our study are first year engineering (FYE) students in an Introduction to Spatial Visualization course at a Southeastern university. This course is recommended for FYE students who score below the required threshold on the Purdue Rotation Visualization Test (PSVT:R) on entry into the engineering program, to help them improve their spatial visualization skills. Seventeen students enrolled in the course in Fall 2018 participated in this qualitative study.

Spatial abilities are important in many scientific fields including engineering. People can develop their spatial abilities through practice and training. This possibility highlights the usefulness of strategies that can be used for solving spatial tasks. There are several spatial ability measures including paper cutting tests, mental rotation tests, cross section tests and mental cutting tests. The current study examines strategies that students used while performing spatial tasks that require the use of mental cutting and rotation techniques.

In this qualitative study, we are interested in students' descriptions of the use of strategies on mental cutting and rotation tests. Data was collected via interviews, involving a think-aloud protocol. The analysis of interview data was guided by a-priori codes from our coding rubric developed in a previous study. The findings from this study provide further understanding on the kinds of strategies students use in tackling spatial tasks. Importantly, the study findings provide confirmation for the codes in our rubric and suggest that some of these strategies are relevant across tests and could be used more broadly.

Keywords: spatial visualization, spatial abilities, first-year engineering, spatial strategies, think-aloud protocol

Background

Spatial visualization ability is essential for success in many academic fields including in medicine (Cohen & Hegarty, 2007; Wanzel, Hamstra, Anastakis, Matsumoto, & Cusimano, 2002), dentistry (Schwibbe, Kothe, Hampe, & Konradt, 2016) and engineering (Ha & Brown, 2017). Two categories of spatial reasoning, as defined by Linn and Petersen (1985), are mental rotation and spatial visualization. Mental rotation involves the ability to manipulate three-dimensional (3D) objects in one's mind by rotation, and spatial visualization involves the ability to manipulate three-dimensional (3D) objects in one's mind through mental cutting and unfolding. A number of tests are routinely used to assess spatial skills. They include Vandenberg-Kuse's Mental Rotation Test (MRT) (Vandenberg & Kuse, 1978) and the Purdue Spatial Visualization Test: Rotations (PSVT: R) (Guay, 1977; Yoon, 2011) for mental rotation skills and the Mental Cutting Test (MCT)(CEEB, 1939) and Santa Barbara Solids Test (SBST) (Cohen, 2015; Cohen & Hegarty, 2012) for mental cutting skills. Several studies have demonstrated the ability to improve spatial ability through training. Uttal et al. (2013) reported a meta-analysis of training studies and concluded that spatial skills are malleable and that spatial training programs may play an important role in the education of STEM professionals. Several engineering programs working with one of such training programs, the ENGAGE Engineering Project (Veurink et al., 2009) have offered courses in spatial visualization. These courses have been shown to positively impact participant spatial skills and retention in engineering programs (Boersma, Hamlin, & Sorby, 2004; Srivasavan, Smith, & Bairaktarova, 2016; Veurink & Sorby, 2011). Studies also show that problem solving strategies play a role in performance in spatial ability tasks. Thus, we find value in investigating solution strategies that students use in solving spatial visualization related problems. Knowing these strategies could provide some help on how to design interventions for training students to develop in their spatial visualization skills.

The Current Study

Methods

This complete research paper describes a follow up study on qualitatively investigating the strategies that engineering students utilize in approaching spatial visualization problems. The research method for this study involves the use of a think aloud protocol, also known as verbal protocol analysis (Adams, Punnakanta, Atman, & Lewis, 2002; Adams, Turns, & Atman, 2003).Think aloud protocols have been used by researchers in different fields including engineering, technology, and the social sciences, to investigate design processes and to understand cognitive processes of readers while reading in a foreign language (Ericsson & Simon, 1996; Gregory, Mentzer, & Becker, 2014; Katalin, 2013). Charters (2003) suggests that the use of think-aloud protocols should be accompanied by additional triangulating data. Our current study examines participants' responses within a think-aloud protocol session. At the end of the semester, students in the spatial visualization course were invited to participate in a spatial visualization exercise session. At each session, the investigator introduced the study to students, discussed consent information with the participants including letting them know the session would be audio recorded and that they were free to withdraw from participation if they chose to.

After signing consent to participation, students were given a problem set comprising of 10 questions. The first four questions were from the Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R) (Guay, 1976; Maeda & Yoon, 2013) and the last six questions were from the Santa Barbara Solids Test (SBST) (Cohen & Hegarty, 2012). The PSVT:R involved questions that required students to indicate what an object would look like after it has been rotated. Conversely, the SBST requires knowledge of cross-sections, in which students determine the shape of an object after it had been cut at a plane. Figures 1 and 2 below show sample problems from each of these two tests. Participants were asked to think aloud, that is, verbally express their process of approaching each problem and coming up with an answer. These think-aloud sessions were audio recorded. After the participants were done with the problems, the investigator asked if they could briefly describe or name the strategies they used as they solved the problems.

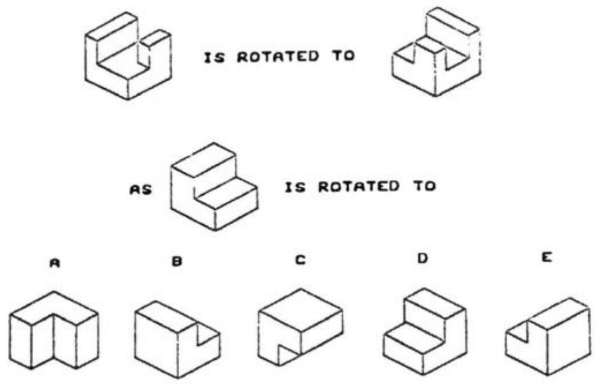

Figure 1: The PSVT:R Sample Problem (Guay, 1977)

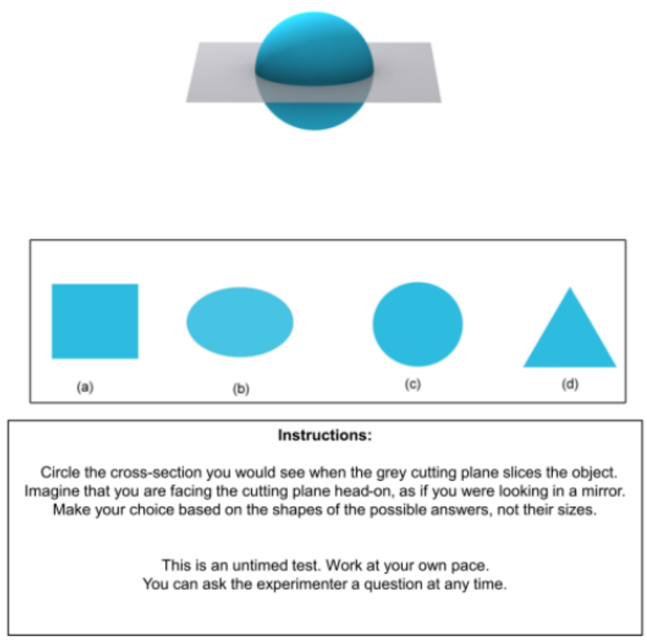

Figure 2: SBST sample problem (Cohen & Hegarty, 2012)

To ensure triangulation as suggested by Charters (2003), we used the think aloud protocol data and referred to the exit survey that all students were asked to fill out at the end of the semester. This helped us corroborate the participant descriptions of how they approached the rotation test (PSVT:R) from the think-aloud sessions with written responses they provided on the survey. In consulting this exit survey data, we only analyzed the responses of the students who participated in the think-aloud exercise. The question on the survey of relevance to this study is, *What strategies did you use to solve the rotation test problems?* This data allowed us to see if participants described the same strategies on the exit survey as they used in answering the rotation questions during the think-aloud sessions. It also allowed us to see if these written answers were similar to strategies they reported using when they were asked to name or explain them at the end of each think-aloud session. We would like to note that our codes described in the previous study were originally generated through analysis of similar written responses on the SBST. Consequently, our overall analyses incorporated data from both written and verbal responses on the SBST and PSVT:R.

Participants and Sampling

The participants in our study are first-year engineering students, enrolled in an Introduction to Spatial Visualization course at a large land grant university. This course is recommended for first-year students who score below the threshold of 60% on the PSVT:R prior to entry into the engineering program. The goal of the course is to help students improve their spatial visualization skills. Participants in this study were among a cohort of 231 students divided up into three sections of the course. Seventeen students across all three sections participated in an interview session involving a think aloud protocol at the end of the semester. Students were invited to participate in the exercise at the end of the semester voluntarily. They were informed their process in arriving at the answers was the important piece in the exercise rather than answering questions correctly. We think this information helped alleviate some pressure that could limit their ability to freely discuss the strategies they were using during the sessions.

Analysis

Analysis of the data involves verbatim transcription of audio recordings from the interview sessions. In addition to transcripts, the researcher also made note of key strategies used or mentioned by the participants as well as any other notable information at the end of each think-aloud session. Some of these notes were comments about gestures or actions of participants that were only observable visually and would not be captured in the audio recordings. Participants responses were analyzed using the coding rubric that was developed in our previous study (Yeaman, Bairaktarova, & Knott, 2018). In that study, we identified six categories of strategies that students used in answering questions on the Santa Barbara Solids Test (SBST), a cross-sections test. The six categories developed are *mental action, guessing, guiding rule, intuition, process of elimination and thinking*. Each of these categories described in our former study are reiterated in the following paragraph.

Mental action implies that the student visualized, imagined, created a mental picture or did some level of mental manipulation of the object to get the answer. *Guessing* categorizes responses that used the word ‘guess’ or explained that the student arrived at a conclusion by chance or without showing evidence of deliberate reasoning. *Guiding rule* describes when the student(s) used a standard or criterion to judge which option is likely to be the answer, for example, student responses that involved the use of if-then logic (“if…then…”) or stating a specific criterion that led to the answer (“whatever is…is the answer”). *Intuition* describes students’ responses in which the word “intuition” was used or the response showed that the student came to an understanding of the answer immediately without the need of conscious reasoning. *Process of elimination* categorizes when the participants recognized which options were not likely to be the answer and narrowed their options by setting the unlikely choices aside. *Thinking* implies an expression of some level of thinking, typically by using the word thinking, thought or another derivative of the word ‘think’ explicitly. Although we understand that some level of thinking may occur before most students decide on an answer choice, this category is unique in the sense that it is based on students’ use of words that imply thinking only.

As in the previous study, in this current study some participants reported using strategies that were a combination of more than one of these six categories. It should be noted that these categories were solely based on the SBST. Here, we paid attention to where students’ strategies were in alignment with the aforementioned categories and where they deviated. We also thought it would be useful to apply the same codes to the PSVT:R as this investigation could show whether they could be relevant across more that one type of spatial visualization test.

Results and Discussion

In the following discussion, original names have been replaced with pseudonyms to protect our participants’ identities.

Santa Barbara Solids Test: This section touches on the strategies that participants used in solving the SBST questions. As previously mentioned, these questions were the latter six of the ten questions participants were given during the think-aloud sessions. The strategies that came up from this portion of the study were *process of elimination, thinking, intuition, guiding rule* and *mental action*. The one that recurred the most was *process of elimination*.

Process of elimination. Sometimes participants explicitly mentioned that they were not choosing an answer because it could not be right. For instance, Nikki says:

> This one, let's see. Okay, so it can't be this one because it's like squared off here, it's not at a point. So that eliminates that one...I think it would be this one because this part’s here, wouldn't look like this [inaudible] here.

Another participant, Thomas explained:

> For figure seven, I see that the cone is being cut by the cutting plane in the center. So, the top will be pointed so we can eliminate C, we can't take A though it has pointed one, because, the figure which is inside of, let's say the pink figure is one and blue is two…

In Thomas’ discussion, he explicitly eliminates two options and explains his process, even beyond the quote we have highlighted. Another participant, Aaron while working on one of the problems said:

> For this one I know it's not D because the triangles point wouldn't be facing like outward.

He gave specific reasons why he was eliminating option D related to the features of the object and his expectation of what the surface should look like after it had been cut. A couple of times during the session, he also crossed out the options that he did not expect to be correct, with his pen, as he was speaking. He eventually settled on an answer and circled it. Some other participants, even though they did not audibly express that they were applying the process of elimination, cancelled answers in a manner similar to Aaron while working on their problems.

Thinking. Some participants expressed that their strategy involved thinking. Nikki for instance said:

> I just, try to think of it just a face and not what's going on with the rest of the object itself.

When asked to describe the strategies she used for the cross-sections test, Leah, another participant said:

> I don't know, I just thought about it. For the cross-sections test, I just kind of think about it…

From her description, we can surmise that where relevant, she spends some time *thinking* about the object before choosing an answer.

Intuition. Andre seemed to use intuition in answering some of the questions, as he arrived at some answers quickly and without much deliberation. This is something that could only be captured watching him.

When asked about the strategies he used, Tim responded:

> I think slicing is purely observation…There's no need to imagination. Imagining there's a cut...you can just...I kind of just see it.

Based his response, it appears that in solving cross-sections tests he tends to get a sense of the answer without having to do much deliberation. Speaking to him further revealed that he has some prior experience with taking similar tests even before taking the course. This repeated practice could explain why he would approach solving problems in this manner.

Mental action. A few participants applied mental action, which involves imagining, creating a mental picture or some level of mental manipulation. Sometimes these mental processes were also revealed physically through hand gestures. Andre was one of the participants who applied this strategy. When asked what strategy he used, he responded:

> …how I see the picture in my head, and where I think the line is cutting. So, this one obviously 'cause it's a cross section, even if it's cut on a circle. It's gonna cut a straight line, so you're not gonna see the curvature.

Leah also alluded to using *mental action* as one of the strategies for solving the cross-sections tests, in addition to *thinking*. In her response, she mentioned,

> …and sometimes I like, I like tracing like the exact line where it cuts through. In my mind where I go, okay so this is cutting through like that so that'd be a straight line, and then that would be a straight line and then that would be a straight line, and then just looking at it like that.

Essentially, she would imaginatively trace a line where the cross-section cuts through the object and envision what she was likely to see. The tracing that she did in her mind resembles what we have described as *mental action*.

Combination of strategies. Some students combined multiple strategies in the process of answering a question on the cross-sections test. Hanna explained,

> For this one, because the cut from here and at here we will not have the same size so it will, and it is not a triangle because it does not meet at any part in the blue one… so, it's not B and I think the upper here is smaller than the cut at the base.

She seemed to have a particular criterion or expectation of what the correct answer should look like based on the cut. This fits into the strategy we have classified as, *guiding rule*. Then, based on this criterion, she could eliminate the unlikely answer choice, thereby demonstrating a *process of elimination*.

Purdue Spatial Visualization Test: Rotations (PSVT:R): In this section, we discuss strategies students used in solving PSVT: R problems. We compare data from two sources, data from the first four problems in the think-aloud session and data taken from an exit survey administered in the Spatial Visualization class. At the end of the semester, students in the Spatial Visualization class were asked to complete an exit survey. One of the survey questions was, *what strategies did you use to solve the rotation test problems*? In Table 1 below, we report the strategies participants reported using in the exit survey as well as whether those strategies were mentioned during the think-aloud session. We used these two data sets to ensure triangulation as suggested by Charters (2003).

The majority of participants used the same strategies in the think-aloud sessions as they reported that they used in tackling rotation problems. However, in the cases of Thomas and Carlos, we could not tell from the transcripts from the think-aloud sessions that they used the strategies mentioned in the exit survey. In addition, there were no notes on whether these participants displayed actions that were not captured in their words. Additionally, Mike did not fill out the exit survey so we could not make a comparison between how he approached rotation problems during the think-aloud session and at the time of the exit survey.

Table 1: Comparing participant data from exit reports and think-aloud sessions

Index	Pseudonym	Gender	What strategies did you use to solve the rotation test problems?	Use or discuss using strategy (ies) during think-aloud session
1	Nikki	F	I would look at the top picture and recognize that it is spun to the left twice and then I would do that to the picture on the bottom. I would use the L shape on the picture as a reference when rotating the object.	Yes
2	Hanna	F	Use hand as a (sic) example then apply to the subject below	Yes
3	Leah	F	Trying to use my hands to figure out how the original object is rotated, and repeating those motions with the object I need to figure out.	Yes
4	Sophia	F	visualize the objects using my mind and hand [mental action]	Yes
5	Thomas	M	I used my hands to visually rotate the objects and also thought about what sides would be visible and where they would be on the other object. [mental action; thinking]	Not clear
6	Carlos	M	It is good to try to use your hands to visualize the transformations the question is asking you to preform (sic). The ninety-degree rule should also be used. If allowed, trying to sketch the object would be very helpful.	Not clear
7	Chris	M	First I observe how the original object being rotated. Then applying the same rotation order to the object asked to be rotated. Finally pick up the answer choice that goes with what I get from last step.	Yes
8	Mike	M	N/A	N/A

9	Aaron	M	The primary strategy I used on this test was the use of my hands to mimic rotation. This helps because it allows you to imagine an object in front of you. Once you have this imaginary object before you then you are able to rotate it in your head anyway you like. It leads you to match the movements of the given object with the one your are supposed to be rotating. [mental action; hand gestures]	Yes
10	Grant	M	I used my hands to help my mind rotate the object, and used pen and paper to organize my thoughts. [hand gestures; mental action; writing/drawing]	Yes
11	Andre	M	I used my hands to make a 3D visual representation of the object to that I could manipulate it in a real space. Along with this I used the different views we learned about in class to help me understand what the image is supposed to look like all the way around. [hand gestures]	Yes
12	Shane	M	I would imagine an axis and then treat the angle of the first image as a reference point to see which direction it turned [mental action; reference key feature]	Yes
13	Tim	M	Find the spot that are different than other part and locate the move it did. Do the same thing to the problem object. You first find the detail of the example part. Check the movement it did. Check if its correct. do the same movement to the problem in your mind. You need to have a module in your mind to move it. I t can be a blur as long as its a blur with details. [reference key feature]	Yes
14	Forest	M	I envisioned it with my mind and used my hands to try to help me see how it moves. [mental action]	Yes
15	Valerie	F	I tried to rotate the object with my hand to show how the object would rotate. [hand gestures]	Yes
16	Martha	F	To do this problem I imagine how the sample object changes. It gets rotated first through -z axis then -x axis. I also imagine how the side facing me changes. Through this I can come to the conclusion that E is correct answer. [mental action]	Yes
17	Francis	M	See how the example turns, then use the same steps to get the sample.	Yes

In the process of solving problems in the PSVT:R section, a number of participants applied some of the same strategies used in solving SBST problems. Notably, Tim was going through *mental action* in the process of solving the rotation problems. At some point, he said:

> …and when they rotate, it's like this and this. This must be showing to like, something over here…which I believe is B.

And at another point, he explained:

> Yeah, because if you want to rotate to this, you need to first do that and then do that.

In these quotes, by “this” and “that”, he was referring to hand gestures in which he seemed to move the object and turn it in specific directions. When Andre was asked what strategies, he used in addressing the rotation questions he replied:

> mental movements I guess…Because I gotta see, like with the first one. What I do is I line up this corner because they're all squares, because they're all squares…

We also noted that he used hand motions while he was working on the questions.

It is interesting that despite the difference in the nature of PSVT:R and SBST problems, some of the strategies we had previously identified were applicable in tackling both types of problems. Notably, *process of elimination* and *mental action*. A major difference in the use of mental action between the two spatial visualization tests is how students apply their cognitive processes. In SBST, students can imagine the object in their minds without showing much of the process physically. In PSVT:R on the other hand, more participants tended towards expressing what they were picturing by demonstrating the process using hand motions or drawings on paper.

Thinking also came up in this part of the study. For example, Leah in her response about what strategies she used said:

> For the rotation test I do a lot of backwards thinking too, about how like, instead of looking, sometimes it's easier to look at how, like, not one shape goes to the other but how like the second shape goes back to the first, and looking at the options and seeing which shape would like go back to the one shown.

In some cases, participants applied *guessing* as a strategy even though, they did not explicitly report that this was one of the strategies they used when asked. For instance, Carlos explained:

> For question two, it's easy to identify this big block being flipped and turned so it's facing me instead of facing to the left, but for the object in question [inaudible] to recognize that because of the triangles, but the back of this object should look something like either C or A. So, I'm going to guess C. Wait, no. I'm going to guess A because of this triangle back here.

In this particular case, he had an idea of what the answer could be but he was not sure so he resorted to guessing. Similarly, Chris expresses his difficulty in solving a problem:

> I just couldn't understand the shape of this thing. Like, I couldn't read the ... I'll just pick one.

Basically, he ends up just picking an answer as a guess.

It should be noted that in our former study, we did not capture if students drew or wrote on piece of paper while they were engaged in spatially-related problem-solving exercises. In the current study we observed that a number of participants drew on paper while attempting to answer their questions for both the PSVT:R and SBST portions. For example, Shane drew on paper while solving all PSVT:R problems. He specifically drew arrows to show directions of rotation. He also drew some lines while trying to answer on of the SBST questions. He still explained his process out loud throughout the process of solving all the problems. Notably, in the beginning of the session he had expressed that he did not feel confident explaining his process in words, particularly in relation to confidence in speaking English. The investigator reassured him that she could understand him and that he should express himself however he saw fit. The student’s confidence played a role, however he seemed to process better by including drawing in his process. Similarly, Tim also drew on paper in answering one of the PSVT:R questions. In this case, he drew angles on the objects in the multiple-choice options on the path to deciding which of them was the correct option.

Another notable finding from both cross-sections and rotations questions is that participants were looking for unique features or parts of objects in the process of solving a problem. Many of the participants identified a key feature to focus on, which helped them determine how an object should look after it had been rotated or a colored part of an object to look for when a piece of the object has been cut. However, this focus on key features was more common on the rotations test. Forest exemplifies this strategy in his description:

> This one just flipped on this side pretty much because you can see all the features pointing out. You just gotta flip this one block on too it's top so it's gonna be standing on here and so it'll be on E.

Conclusions

In conclusion, our study confirms that the codes from our previous study are valid as the strategies they represent were used by a different set of students. The strategies participants applied in tackling cross-section problems include *process of elimination*, *thinking, mental action, intuition* and *guiding rule*. When solving rotation problems participants used *process of elimination*, *thinking, mental action* and *guessing*. Guessing was not prominent among the participants on either test except in cases where participants were unsure or had little confidence in addressing a problem. This could be because students had gotten more familiar with the problems as they were seeing them again at the end of the semester. To clarify, all the participants took the PSVT:R before entry into their first year in the engineering program. Upon taking the spatial visualization course, they also took both the PSVT:R and SBST towards the beginning and end of their semester in the course. In addition to these exposures, they were seeing a few questions from each test in the sample problems we used during the think-aloud sessions. And since the focus of the sessions was not to get a right answer, the participants were more likely to figure out how best to answer the questions and feeling less inclined to guess. The few cases in which *guessing* was used were on the PSVT:R. It could be due to participants finding the SBST easier to solve as they seemed to spend less time these problems than they did on the PSVT:R.

It is interesting to note that while some strategies are applicable across spatial visualization ability tests such as the cross-sections and rotation tests, others including *guiding rule* and *intuition* were only used in one type of problem. Another notable finding from this study is that in some cases, students were drawing on paper what they imagined or were using drawing to direct their cognitive processes in solving a problem. Finally, this study reveals that in addition to self-reporting of solution strategies, having students think-aloud is another way to better understand their cognitive processes during problem solving, especially related to spatial tasks. It was helpful to be able to watch the students while they were working because some students were quietly processing or said things out loud that would not be ordinarily understood, but were in reference to gestures they were making with their hands. These understandings could be used in developing interventions for helping students develop in their spatial abilities.

Limitations and Future Studies

Participants in our study completed a one-semester spatial visualization course and some of the strategies they applied are based on their prior experiences before the course while others are informed by techniques they learned during the course. Therefore, we cannot assume that all students are using the same strategies especially if such strategies are effective and happen to be based on prior experiences. Furthermore, some students mentioned aspects of the course that they found helpful in tackling the spatial visualization problems presented to them during the think-aloud sessions. These include repeated exposure to spatial tasks and creating and manipulating objects using a computer aided design (CAD) software during the course. While this was not a focus of the investigation, we think it is useful to highlight these course components as they seem to have influenced participants' approaches. These aspects could also be useful to include in interventions introduced to students for supporting their development of spatial visualization competency.

This research study is only a step towards understanding approaches to better support students in a remedial spatial visualization course improve on their spatial skills. Our future work will involve considering students' pre- and post SBST and PRVT:R test scores to further understand how students' strategies may be related to improvement in score performance and development in spatial skills over the course of the semester. The latter can help make informed decisions about which of these strategies to reinforce in future iterations of the course.

References

Adams, R., Punnakanta, P., Atman, C. J., & Lewis, C. D. (2002). Comparing Design Team Self-Reports with Actual Performance: Cross-Validating Assessment Instruments. *American Society for Engineering Education Annual Conference & Exposition*.

Adams, R. S., Turns, J., & Atman, C. J. (2003). Educating effective engineering designers: The role of reflective practice. *Design Studies*, *24*(3), 275–294. https://doi.org/10.1016/S0142-694X(02)00056-X

Boersma, N., Hamlin, A., & Sorby, S. (2004). Work in progress - impact of a remedial 3-d visualization course on student performance and retention. In *34th Annual Frontiers in Education, 2004. FIE 2004.* (pp. 600–601). https://doi.org/10.1109/FIE.2004.1408587

CEEB. (1939). CEEB Special aptitude test in spatial relations. College Entrance Examination Board, U.S.A.

Charters, E. (2003). The Use of Think-aloud Methods in Qualitative Research An Introduction to Think-aloud Methods. *Brock Education*, *12*(2), 773. https://doi.org/10.1093/ije/29.4.773

Cohen, C. A. (2015). Spatial Intelligence Learning Center (SILC). Retrieved from http://www.spatiallearning.org/

Cohen, C. A., & Hegarty, M. (2007). Sources of Difficulty in Imagining Cross Sections of 3D Objects. In *29th Annual Conference of the Cognitive Science Society (CogSci 2007)* (pp. 179–184).

Cohen, C. A., & Hegarty, M. (2012). Inferring cross sections of 3D objects: A new spatial thinking test. *Learning and Individual Differences*, *22*(6), 868–874. https://doi.org/10.1016/j.lindif.2012.05.007

Ericsson, K. A., & Simon, H. A. (1996). *Thinking-aloud processes*. *Protocol Analysis* (2nd ed.). Cambridge, Massachusetts: MIT Press.

Gregory, S. L., Mentzer, N., & Becker, K. H. (2014). African American high school students' human-centered approach in design. *ASEE Annual Conference and Exposition, Conference Proceedings*.

Guay, R. B. (1977). *Purdue Spatial Visualization Test*. West Layafette, Indiana: Purdue Research Foundation.

Ha, O., & Brown, S. A. (2017). Spatial Reasoning Difference between Civil and Mechanical Engineering Students in Learning Mechanics of Materials Course : A Case of Cross-sectional Inference. In *ASEE Annual Conference & Exposition*. Columbus, OH.

Katalin, E. (2013). "Please, keep talking": The 'think-aloud' method in second language reading research. *NovELTy*, *7*(3), 1–7.

Linn, M. C., & Petersen, A. C. (1985). Emergence and Characterization of Sex Differences in Spatial Ability: A Meta-Analysis. *Child Development*, *56*(6), 1479–1498. Retrieved from http://www.jstor.org/stable/1130467

Maeda, Y., & Yoon, S. Y. (2013). A Meta-Analysis on Gender Differences in Mental Rotation Ability Measured by the Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R). *Educational Psychology Review Educ Psychol Rev*, *25*(1), 69–94. https://doi.org/10.1007/s

Schwibbe, A., Kothe, C., Hampe, W., & Konradt, U. (2016). Acquisition of dental skills in preclinical technique courses: influence of spatial and manual abilities. *Advances in Health Sciences Education*, *21*(4), 841–857. https://doi.org/10.1007/s10459-016-9670-0

Srivasavan, A., Smith, J., & Bairaktarova, D. (2016). Identifying Freehand Sectional View Technical Drawing Activities in Engineering Design Graphics Course to Enhance Spatial Skills of Engineering Students. In *Proceedings of the ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE August 21-24*. Charlotte, NC, USA.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The Malleability of Spatial Skills: A Meta-Analysis of Training Studies. *Psychological Bulletin*, *139*(2), 352–402. https://doi.org/10.1037/a0028446

Vandenberg, S. G., & Kuse, A. R. (1978). Mental Rotations, A Group Test of Three-Dimensional Spatial Visualization. *Perceptual and Motor Skills*, *47*, 599–604.

Veurink, N. L., Hamlin, A. J., Kampe, J. C. M., Sorby, S. A., Blasko, D. G., Holliday-Darr, K. A., … Knott, T. W. (2009). Enhancing visualization skills-improving options and success (EnViSIONS) of engineering and technology students. *Engineering Design Graphics Journal*, *73*(2), 1–17.

Veurink, N. L., & Sorby, S. A. (2011). Raising the bar? Longitudinal study to determine which students would most benefit from spatial training. In *American Society for Engineering Education*. Vancouver, BC. Retrieved from https://peer.asee.org/18592

Wanzel, K. R., Hamstra, S. J., Anastakis, D. J., Matsumoto, E. D., & Cusimano, M. D. (2002). Effect of visual-spatial ability on learning of spatially-complex surgical skills. *Lancet*, *359*(9302), 230–231. https://doi.org/10.1016/S0140-6736(02)07441-X

Yeaman, A. O., Bairaktarova, D., & Knott, T. (2018). Developing a Coding Rubric for Students ' Spatial Visualization Strategies Developing a Coding Rubric for Students Visualization Strategies. In *ASEE Annual Conference and Exposition*. Salt Lake City, Utah.

Yoon, S. Y. (2011). Psychometric Properties of the Revised Purdue Spatial Visualization Tests: Visual Rotations (The Revised PSVT:R).