A systematic literature review of educational spatial visualization software and implementations for computing education

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***Abstract*—Spatial visualization has been proven to be an important indicator of students' success in STEM related disciplines and is useful for all engineers. Studies have analyzed the importance of spatial visualization and its relation to technical creativity, problem-solving, and engineering design. Spatial visualization skills aid in developing core competencies expected of students in a STEM field. Recently, the focus of spatial visualization and its impact on computer science education have gained traction, as preliminary results correlate spatial skills with improved competencies and academic outcomes in computing science courses. With increased adoption of technology in academic environments, technology can be leveraged to make it more accessible for instructors to implement spatial visualization training. To explore if these software(s) are being utilized, this paper will explore two questions: What software(s) are being utilized in current research to improve spatial visualization skills of engineering students and are they being used to specifically improve computing skills of students? If software(s) are being implemented, are they readily accessible for instructors to use, or are there paywalls or institutional barriers to implementing these software(s)? A systematic literature review of spatial visualization training in higher-education contexts was conducted to answer these two research questions. Results indicated that the majority of prior spatial visualization training in higher-education contexts utilized hybrid approaches with paper-and-pencil training while using learning management systems (ie: Blackboard, Canvas) to host the material. Specific technologies found for training included SpatialVis™, CogSketch, and PerSketchTivity. From these tools, SpatialVis™ had the most accessible website, implementation protocol, and information. Further research is needed to explore differences in training outcomes based on paper-and-pencil training as opposed to software training, however development of an easily accessible suite of spatial visualization training will be needed as future research is conducted, particularly if spatial visualization training is to be broadly adopted by the computing education community.**

Keywords—spatial visualization, computing education, educational technology, educational tools.

I. Introduction

In the 1950's spatial visualization skills were established as a reliable indicator of success in the field of engineering [1]. Recent research has empirically validated this claim and has linked spatial skills to success in engineering and engineering careers [2-5]. While spatial skills are important, differences in spatial skills have been linked to gender [6] and socioeconomic status [7]. However, research has shown that spatial skills are malleable and trainable [8], which has enabled the development of interventions to train these skills. This helps in improving the success of underrepresented populations in engineering and STEM. These interventions and trainings of spatial skills have seen marked improvement in students' performance in coursework, such as calculus [5]. More recent developments have shown the importance of spatial visualization skills for computing education success [9-11], which has prompted some universities that provide computer science or engineering degrees to implement spatial visualization interventions. With further adoption of spatial visualization training in computer science courses, and recent calls for computer scientists' educators to implement unique technologies to train spatial visualization skills [12], a systematic literature review of current technologies implemented can be beneficial. These technologies are beneficial, as prior studies have experienced fewer positive results in training spatial skills if the delivery is done in a relatively short period of time and in ways that do not align with students' schedules [29]. The systematic literature review can provide information on modality, distribution, and aspects spatial visualization training software should utilize to be effective. To perform a systematic literature review, a systematic literature review protocol adopted from the medical field for software engineering domains was used [13].

II. Review of Literature

A. Literature review protocol and search strategy

The aim of this literature review was to thoroughly identify ways spatial visualization skills are being trained for engineering students, and if they are being trained in a way to improve computing skills. The database libraries of Elsevier, Compendex, IEEE, ERIC(EBSCOHost), Web of Science, were used to find literature. All five databases were explored using the combination of the following keywords: ("spatial visualization", "spatial abilities" OR "mental rotation test" OR "mental cutting test") AND (compu* AND educa*) AND (software OR program* OR application) AND NOT (med*). If the paper explicitly stated it belonged to the medical domain or medical area, it would be excluded from the search.

B. Literature review exclusion and inclusion criteria

Exclusion criteria consisted of the following: literature that was found in the medical field or non-engineering majors were excluded; literature that explored the usage of virtual reality, or AR, was excluded as a recent systematic literature review explored implementations of AR to train spatial visualization skills over the past decade [14]; literature that was in non-higher education contexts (adult learners, K-12 students); literature targeted unique populations such as learners with disabilities. Inclusion criteria included the following: the study had taken place in the past 23 years (2000 - 2023), study had taken place in higher-education

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contexts, the study explicitly stated an intervention, training, tool, or assessment for spatial visualization had occurred. These inclusion criteria were developed to make the studies applicable to other higher-institution contexts.

C. Literature review gathering process

The first round of searching using the keywords generated 406 results by searching the five databases using a combination of the following keywords: spatial visualization, spatial modeling, spatial abilities, intervention, training, program, assessment, and development. The title was read and if it included one or more of these keywords it was kept. In the next round, the exclusion criteria were utilized on the n=406 pieces of literature, which reduced the number of publications to n=155. Following this, the inclusion criteria was applied, reducing the amount of literature to n = 14 publications.

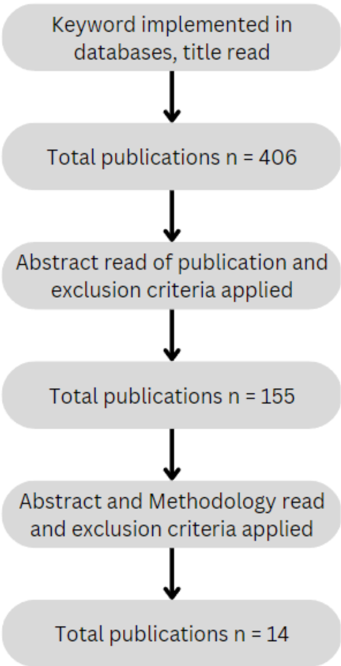

Fig 1. Literature review process

III. ANALYSIS OF LITERATURE

The following section will detail literature discovered that satisfied the inclusion and exclusion criteria in an attempt to answer the first research question: "*What software(s) are being utilized in current research to improve spatial visualization skills of engineering students and are they being used to specifically improve computing skills of students?*".

The authors discovered three broad themes that software from the literature belonged to. The first approach was hybrid software training, where an instructor would post material on a learning management system and then use built-in quizzes via the learning management system or paper quizzes. The second approach is in-house software training, where instructors used software designed for sketching or modeling purposes to implement training material or build an application specific to their class needs. The third approach was focused software training, where applications that were created directly for spatial visualization training were utilized by the study.

A. Hybrid Software Training

A study between three US universities targeted an introductory computer science course at each university and distributed eight modules of spatial visualization training material to be taught asynchronously across the 16-week long semester, which created a hybrid approach to spatial training [17]. Each module would take an hour to complete, with videos, extra printable worksheets, and physical snap-cubes to help train the skills. Pre/posts tests of the Purdue Spatial Visualization Test: Revised (PSVT:R) and a validated computer science 1 exam were distributed to the students. A total of 274 introductory Computer Science (CS) students in the control group and 71 CS introductory students in the treatment group were examined. Two interesting results were found. There is a correlation between students' spatial skills and their success in learning to program, and the hybrid implementation improved students' spatial skills and programming abilities. However, participation bias could have impacted the positive gains. The lack of mandatory participation in the training, implementation of videos and resources via a learning management system introduced more novel approaches [17].

In an engineering graphics course, students used AutoCAD 2-D and Inventor (a 3-D Modeling Program) with a unique intervention of visualizations of unfinished walls made of Lego-bricks [18]. These walls were presented in a training period using slides in-class and were taken from a repository of potential images from a 3-d visualization textbook the author of the paper had created. Students would complete a test bank of questions in 10 minutes. It was not stated which format the test was distributed, via an online tool or in person using a worksheet (pen and paper). Students reported positive results for the students. However, it is noted that this course specialized in engineering graphics and was not a general engineering course.

In [19], two first-semester chemistry sections in a US university were tasked with completing spatial ability tasks for credits part of the course. The goal of this study was to examine if the modality of the test, online or in-class, are equivalent. A sample size of 457 students were examined for both online and in-person students. A lecture was administered followed by a testing period for the spatial tests. Students that took the test in-person had 50-minutes to take the spatial test during a class session followed by watching a 50-minute lecture. The online section had to watch the 50-minute lecture then select a timeslot of three days to be administered the test, which could not be started or stopped on demand. These times aligned with the in-person sections. With two sub-tests dropped due to administration errors, students in the online test had greater scores in a mental rotations test, whereas students that completed the paper folding test in-person had slightly better scores. This study analyzed cognitive skills as well, but for our purposes of spatial visualization technology they were not discussed. The authors found that in-person and online administration of cognitive and spatial tests are valid. The drawbacks of scrolling and computer limitations (screen-size) on test distribution must be considered. The authors conclude that either form is valid. The learning management system was not discussed and no unique technology outside of the learning management system was discussed.

B. In-House Software Training

A 2010 study introduced a novel approach to teaching 3D spatial visualization via a mobile game application on touch screen phones [15]. Students were able to compete based on the times and difficulty of the problem and all participants (n=16) found the experience satisfiable. Recommendations for the touch screen game included a concise explanation of the program at the start, intermediate feedback during task completion, and a scalable difficulty of problems based on user heuristics (such as time spent, or errors made). [15]

In a chemical engineering course, 30 students were trained using software called 3D-MIM. [16] This software created an environment of a 3-Dimensional representation of a chemical bond and allowed it to be rotated, alongside a 2D view of the chemical bond [16]. While modification to the bond was not possible, students commented that the visualization of a 3D bond was easier than their mental visualizations. A pre and post test that used 18-multiple choice questions with a moderate or above gain to visual, relational, and orientation spatial skills. [16].

In [21], the authors discuss 9 different visuo-spatial tests and their implementations using computer supported technology. The 9 tests discussed in [21] were virtual card rotations task, Corsi tapping test of spatial working memory, visual patterns task of visual working memory, dual memory and processing tasks, a spatial n-back task, rotated patterns task, colored bars task, a coordinative complexity task, and a four-square ordering task. Each of these tasks are runnable inside of a GUI through a website repository attached to the article. While these tasks are different from the distributed PSVT:R task distributed, the implementations of these tasks could be used to supplement training material done asynchronously or using a hybrid approach. Instructors or students would be able to navigate to where these tasks live and attempt to run the tasks for further training.

A 4-week, 36-hour course designed to teach 3D modeling implemented a visualization program called 3D Max alongside 3D printer modeling [22]. These forms were implemented using a paradigm called CDIO (conceive, design, implement, operate). A total of n = 13 students participated in the course. Students were given a pretest, midtest, and posttest of the PSVT:R and Mental Rotations Test. For each lecture, the first section of the course provided lectures, illustration of samples, and 3D MAX exercises. The second portion required the development of a project concept and a finalization of a complete 3D modelled project. Learners were able to explore a combination of 3D models alongside the 3D Max program to help develop their spatial visualization skills. The implementation of a midtest (provided halfway through the course) allowed richer comparison on higher scoring spatial visualization students. The impact of solid models (3D printed objects) implied that for subjects with stronger spatial ability, the effect of solid models improves their spatial visualization for more difficult spatial visualization aspects. Results of the program allowed for improvements for the majority of students in the course.

C. Focused Software Training

Graduate students in a higher-education institution in Asia were randomly selected and were given spatial visualization training using four categories, Virtual 3D (SketchUp pre-made model), Physical 3D (scaled/wooden architectural objects, such as bricks, cubes) [20]. A total of n=72 participants joined the study. Through training, the authors found that while the participants pre-test score of spatial skills were similar, the group that utilized virtual 3D technology, which was SketchUp using a pre-rendered object, had significantly higher gains in their visualization scores as opposed to groups that only used physical 3D objects [20]. The authors posit that spatial training must incorporate spatial cues and situated environments to ensure that cognitive processes during training can help learners with lower spatial abilities.

Researchers have explored the implementation of randomized creation of 2D and 3D assets that can be utilized for mental rotation tests. In [23], researchers have explored the implementation of Python and Blender packages that can utilize JSON files to create permutations of unique mental rotation questions. This article discusses the use case of the package but does not explore the implementation inside a higher-education course. The same authors have applied the resources they developed in [23] to a browser-based quiz system that utilized the package generation. In this application, a browser-based system is designed to implement advanced mental rotation test tools [24]. The browser allows users to swap between 2D and 3D views of permutated mental rotation question. This program allows the quizzes to be taken quickly and has survey integration, so users and instructors that distributed the survey can have faster access to results of students. These forms have integrated Google Forms or similar surveys utilizing APIs, which can automate feedback, organize layouts of tests. In a preliminary study, 263 CS, 129 CS Engineering, and 109 Business Informatics students utilized the browser-based application. In this controlled experiment, specific questions allowed for 2D and 3D viewing of an object, whereas others only allowed for 2D viewing of the object. This resulted in a higher-than-average score for students that had access to the 3D viewer for the first set of questions, but for later questions the usage of a 3D viewer did not have significant impact [24]. The authors dictate that future research of the tool must examine if the usage of the 3D tool changes the outcomes of assignments significantly.

Other research has implemented a tool that trains spatial visualization skills using a tablet application [30]. This software was grounded in Vygotsky's Zone of Proximal Development, where a knowledgeable other ascertains a learners' current understanding and provides scaffolding to assist their learning [31]. In [30], the authors developed Spatial Vis^tm, an application that provides spatial visualization tasks that students must complete using sketching on a tablet screen. Students can ask for hints while completing tasks on the application, and portions of their current sketch that were correct would be highlighted in green, which would show them where they went wrong if lines drawn were not in green, as presented in [30, Fig 2.]. There are also small, highlighted areas that provide a hint on where to sketch next. To dissuade constantly using hints, the authors of the software implemented a form of gamification, where students would get stars based on performance and number of hints used, with more stars granted for less hints used. This software can be used asynchronously as part of a class, remotely, or in-person. An application like this provides a low-cost implementation of the spatial training intervention and would streamline the process of training instructors to distribute the intervention as the application both provides the material and acts as a knowledgeable other to train the students. However, the authors still recommend that instructors facilitate monitor students while they use the app, and provide appropriate help if students get stuck.

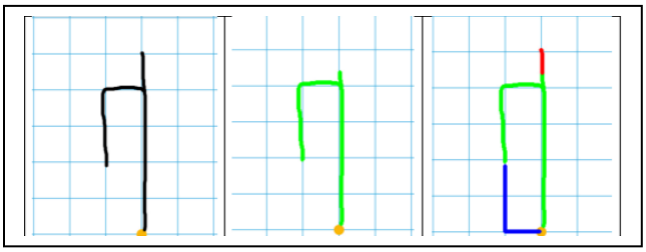

Fig 2. Example of hints for spatial visualization task [30]

Authors of [32] used a sketching technology called "PerSketchTivity". This technology was created using JavaScript's Paper framework and HTML5 Canvas, which allows the application to work on a variety of platforms and have accurate stylus input. Spatial visualization tests were not specifically employed, but exercises of straight line, square, and circle drawing and more advanced geometric shapes were given to students. A total of n=8 undergraduate students from a variety of engineering backgrounds tested the background. The application would provide an introductory video to students, followed by a mixture of geometric drawing tasks. These would be scored based on time and line deviations from the expected drawing, which were automatically graded by the application after completion by the user. Users responded positively to the application, although they did voice confusion on where to proceed when they completed a specific exercise.

Other researchers have found students may experience anxiety when sketching and had implemented a Design Coach to be part of a pre-built sketching software called CogSketch [33]. Students explain their design to Design Coach when using CogSketch through a combination of textual and sketch designs. The Design Coach utilized algorithms developed in previous work by the authors to provide feedback on textual input (if it makes sense) and sketching input (if sketches are appropriate). CogSketch software, used via desktop or tablets, can then be used to generate sketches. In the researchers' university, a design and technical communication engineering course administered homework assignments to n = 32 students. Pre/post surveys that measured sketching anxiety were administered to the selected students. Overall, the combination of Design Coach alongside CogSketch resulted in reduced anxiety levels for the students that utilized the two technologies [33].

Researchers in a first year engineering design course tested two courses the SpatialVis application, developed by eGrove education [35] and experimented on by previously mentioned authors [30], to two sections of an introductory engineering course [34]. In this study, n=23 students were assigned to use the SpatialVis application as homework (experimental group), while n=22 students received normal spatial visualization training and no usage of the app (control group). All students took a pre/posttest of the PSVT:R assessment using the university's blackboard system. The researchers found that while there were no statistically significant differences between the experimental and control groups, students that were low performing visualizers in the experimental group showed substantial progress. From the experimental groups' 23 students, 13 were found to be low performing spatial visualizers by scoring under 70% on the PVST:R tests. From these 13, 8 students were able to raise their post-test score above the threshold of 70%. The researchers attributed these substantial gains to the interactivity, automated grading, and hints provided by the spatial visualization application [34].

Similar to prior work that has explored teaching sketching using industrial design methodologies. Researchers in a first-year engineering course implemented a new pedagogy, termed Perspective teaching, which adopted pedagogies from industrial design, and compared it to Traditional teaching, which traditional methods of training spatial visualization skills in students were used [36]. Additionally, a subset of students taking the Perspective version of the engineering course utilized an application called SketchTivity. This application that has automated feedback systems for students and used tablets for drawing [36]. A random sampling of students (n=20) took the Perspective version of the engineering course and used SketchTivity. The authors found that students that used SketchTivity had improved development in sketching skills in comparison to students in the Traditional teaching style of the engineering course. However, there students taught using the Perspective pedagogy without the application had slightly better results than those that used the Perspective pedagogy and the application. The researchers conclude that usage of SketchTivity does improve spatial visualization ability of students with less instructor feedback and automated feedback from the application.

IV. Analysis of Barriers to Implementation and Implications for Computing Education

The literature review provided a variety of unique pedagogical tools that have been implemented in engineering courses at higher-education institutions. The following section discusses the accessibility of these tools for practitioners or researchers interested in applying these tools to engineering courses, alongside any implications that the literature could make for computing education. This section aims to answer the remaining two research questions: "*If software(s) are being implemented, are they readily accessible for instructors to use? Are there paywalls or institutional barriers to implementing these software(s)?*"

A. Hybrid Software Barriers

In [17], the learning management system that was used for the online section of students was not explicitly stated. This is due to three different universities that needed to implement the intervention simultaneously. Instead of needing to utilize a 3rd party directory, each respective university could add an assignment or quiz to their learning management system to distribute to students. Instructors that would need a proctor service could implement services such as LockDown [25] or Respondus [26] which can be used to improve security of the test. The overhead of this implementation may not require too many resources or time investment from instructors, as they can utilize a learning management system, they are familiar with and would just need to test the quizzes before distribution. In relation to computing education, if a computer science course is hosted on a learning management system, spatial visualization trainings can be added into the system easily, and it can be up to the instructor's discretion to provide it as assignments, quizzes, or extracurricular material.

Research that utilized unfinished Lego-brick walls and brick formats on PowerPoint slides resulted in improved gains for the students [18]. The resources provided by the authors of [18] are available via textbook and online repositories. However, a specific application to use these resources was not mentioned, and it is more likely an instructor could use the slides or examples from text to enhance lessons for students training spatial abilities. Similar to the work conducted in [17], this can be done using a learning management system or slides.

Similar to [17], researchers in [19] found that the distribution of the spatial visualization test, whether in person or virtual, did not have a large impact on outcomes for students. However, the researchers did caution to ensure the layout of the spatial visualization test has been checked and the functionality works as intended. The authors found that as online students scrolled during a specific question, the example figure provided disappeared [19]. While the learning management system is a useful tool to act as a repository for the spatial visualization tools, it must have quality control to ensure no errors occur. Resources such as short videos and printable worksheets, which the authors used in [19], would improve learning for this asynchronous approach while not requiring a large time and resource commitment from the instructors. In [17-19], the courses targeted were first-year engineering courses or technical drawing courses, and the application to computing education was not evidenced. However, as mentioned earlier, the resources and implementation styles can be implemented in any engineering course for a relatively low-cost, as it was just uploading material to slides or learning management systems.

B. *In-House Software Barriers*

In [15], the 3D mobile game application was developed in-house with no public accessibility. However, similar forms of applications could be developed using their groundwork and feedback of user heuristics. For example, a virtual tutorial of the application, and ensure the information users must know is concise and easily accessible. With greater access to mobile phones and interactive, touch screen technology, the application could be integrated into courses quickly. This course was a normal engineering course, and no specific relations to computing education was stated.

The chemical engineering course that implemented 3D-MIM did not cite an online repository one could use to access the tool [16]. While useful for chemical students, it is not readily accessible of a tool to access. Online searches for "3D-MIM chemical tool", "3D-MIM visualizer tool" resulted in just the article itself. For instructors to implement this tool, a similar tool must be found or need to be developed. As this was a chemical engineering course that specifically enhanced visualization abilities of chemical bonds, it is not applicable to computing education contexts.

Unfortunately, while the authors of [21] provided a great breadth of resources and tools to implement spatial skill training via online tools, the repositories provided in the paper are no longer accessible as the domain is no longer hosted. The author searched for similar tools mentioned in the paper, such as "Corsi tapping test online," which resulted in some tools that could be implemented [28]. However not all of the tools could be found online, but the tools discussed in the paper could provide a foundation for future iterations and research. These tools have individual websites that an instructor could point students toward, however management of scores, timing, and an explicit relation to spatial skills could be difficult for an instructor to develop.

C. *Focused Software Barriers*

In [20], results indicated that the 3D Virtual tools provided a higher gain in spatial skill ability for students as opposed to 3D Physical tools. The program utilized, called SketchUp [27], offers a free-trial period of 30 days and a free web-based modeler. An account is required to use the tool, but it provides a suite and tutorial that new users can follow. There is also a save feature to distribute projects. Instructors could create a repository of 3D models based on the mental rotation test or similar validated tests and distribute them to students. However, this tool may not be beneficial if instructors want to reduce outside resources and account creation students must utilize. The environment for new students, in particular undergraduate students, may be intimidating if students are not familiar with 3D modeling software. For computing education, where students must manage new systems such as new text-based editors and coding environments, the time and resource cost to implement even more modelling systems could impact motivation. Also, there were no provided materials to use in SketchUp by the authors of [20], which would require the instructor to create the materials from scratch.

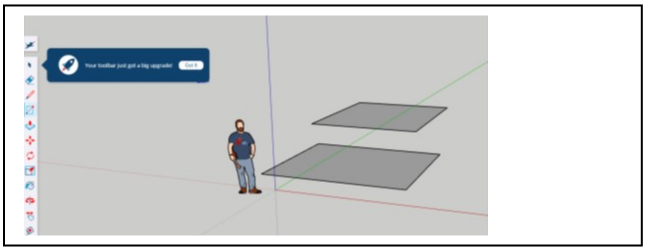

Fig 3. Example starter SketchUp file

The authors of [23] provide an overview of a mixture of Python, a text-based programming language, and Blender, a 3D modeling software, and how they can be utilized together to generate assets for mental rotation tests. For an educator to utilize this software based on this paper, a solid grasp of both languages, including an understanding of GitHub would be required. For engineering educators that wanted a low-cost implementation for spatial visualization software, this may be too time consuming to implement. For computing education, it could be more feasible as educators may be familiar with the languages and GitHub's process. Fortunately, the authors of [24], some that were part of the authorship of [23], provided a website in their article that packaged the developed software of Python and Blender. This packaged software simply needs an internet connection to run and is hosted on a website. Notably, the authors of [24] discuss that students can take pre-set quizzes and results can be linked to Google Forms or similar survey polls. This automates grading and provides a fast analysis of students' spatial visualization skills. The randomization algorithm of mental rotation tests developed in [23] are also implemented, alongside 2D and 3D views of spatial tools. This tool is available by searching for "vis-skill browser" and is still hosted at the time of this paper [37].

The application developed by authors in [30] provided gamification, automatic feedback, and stylus-based input to the spatial visualization training software. By searching online for "SpatialVis software," users can find the website where it is hosted by eGrove education [35]. Users can navigate to the eGrove website and create an account for free, alongside request a SpatialVis account for personal evaluation [35]. There are also teaching resources which break down spatial visualization lessons into accessible modules, training videos, and additional engineering design activities accessible for free. This tool works on mobile devices, Windows, and Mac devices. While the assessment of the product is free, a quote would need to be placed to be implemented into a classroom. In application to computing education, the pre-packaged nature of this product, alongside the ability to have specific lessons could provide a smoother implementation for instructors that wish to implement this technology.

The authors of PerSketchTivity [32] developed a similar application to [30] in terms of automated feedback and tablet construction, however it focused more on perspectives of primitive and advanced blocks (spheres/cones). To utilize the software, a google search of "PerSketchTivity" was conducted. While the website of the software is accessible, an account cannot be registered without a registration code. There is also no trial period accessible through the website. In terms of implementation styles, while this software can be used to help train spatial visualization skills, it is geared to in-depth sketching courses, rather than more general engineering or computing courses that would utilize the PSVT:R test or Mental Rotations Test.

The usage of CogSketch and a personalized tutor by the authors of [33] seems to be reproducible in other courses. The CogSketch software is available for download through the Northwestern University Qualitative Reasoning Group through a search of "CogSketch" [38]. On the webpage, there are also tutorials, manuals, and resources available for user download. For implementation in engineering or computing classrooms, an instructor can download the software, examine the instructional guides, and create your questions. The research group does recommend utilizing the software on a tablet or similar device, as sketch creation via a pen is easier than a mouse. While the set-up could require more resources and time from the instructor's end, the software is free to use with a wealth of resources to help in the implementation of the software. Communication with the research group is possible and can establish a way to utilize the software to train spatial visualization skills in engineering courses.

Notably, researchers in [34] implemented the SpatialVis app in a use-case to a higher-education context [35]. The ease of implementation, data collected, and experiences they discussed help reaffirm the production quality and implementation possibility of the SpatialVis software. This study can be reproduced in both engineering and computing contexts, with a modified participant selection methodology to explore other outcomes. For purposes of this literature review, the implementation of this software is practical.

Researchers of [36] discussed the tool "SketchTivity", with a search of the tool that results in a Texas A&M university lab group [39]. Publications and information of the group was accessible via the website, however, a link to download the tool was not discovered by the authors. A contact form is accessible which could provide a start to discuss usage of the tool in classrooms. As the application was not accessible for download, the author could not ascertain the implementation capability of the tool.

This section was a discussion of the applications examined and their potential capability to be implemented. Future work and conclusions will now be discussed.

V. Future work

This literature review examined spatial visualization technology utilized in engineering courses at higher-education institutions. For resource, cost, and accessibility reasons, spatial technologies that utilized AR (virtual reality), were not included due to a prior systematic literature review that specifically targeted AR technologies in spatial training [14]. The goal of this literature review was to establish existing applications that could be used in engineering and computing courses to assist in the delivery of spatial visualization training material.

There was a breadth of details to cover from these tools, but three main implementation approaches for spatial visualization training using software were discovered. The first approach involved a hybrid and instructor focused style. This means that either a learning management system (ie: Blackboard, Canvas) was used to host spatial visualization training material, and students would either take the quiz on paper or through a quiz generated by the students. This approach was used by the authors of [17-19]. A second approach involved in-house software or modifying existing software to fit the needs of spatial visualization training. The authors of [15], [16], [21], [22] developed this in-house software which resulted in varying impacts of their course. Finally, the authors of [20], [23-24], [32], [33] all utilized software that was built explicitly for training spatial visualization skills. From these three approaches, the authors recommend following the third approach to training spatial visualization skills, in particular the application discussed in [30]. Future work will include a graph that details the author's ratings of each of the tools based on defined accessibility criteria (ie: ease of access, instructional access, distribution modality).

Aforementioned research explored the usage of virtual reality, or AR technology, to train spatial visualization skills [14]. While beneficial, it may not be realistic that these technologies can be easily implemented in other higher-institutions and be built into an engineering curriculum with an already dense amount of courses to undertake. To this end, the authors sought out alternative technologies that can be implemented outside of AR technology. Future work can consider AR technology and apply the previously mentioned accessibility criteria to these tools as well.

VI. Conclusion

While the body of evidence for spatial skill ability being important for success in STEM is accepted, the ways to implement the interventions that train these skills is not as well discussed. It may not be ideal to assume that paper-and-pencil approaches to training spatial skills is the most effective way, although that may be what the majority of prior interventions have done. The authors determined three broad themes surrounding spatial visualization training tools from the review. The first approach uses hybrid software training, which utilizes instructors posting material on a learning management system and the usage of built-in quizzes or paper quizzes. The second approach is in-house software training, where instructors use software designed for sketching or modeling purposes to implement training material or build an application specific to their class needs. The third approach is focused software training, where applications created directly for spatial visualization training are utilized. Institutional and instructor resources and commitments vary, but from these approaches, the third approach appears the most accessible way to implement spatial visualization training. From the applications of the focused software training, SpatialVis™, CogSketch, and PerSketchTivity are all useful applications, however SpatialVis™ has the most accessible website, implementation protocol, and information out of the three tools.

It is critical that technologies to train spatial skills continue to be developed, tested, and enhanced as the fields of engineering and computing education develop. There are risks that while institutions or instructors understand and subscribe to the importance of spatial skills, they may have to drop or modify the training of these skills due to an overloaded curriculum. To help dissuade this from happening and ensure that spatial skills are being trained, a low-cost, easily accessible, and reputable suite of tools can be implemented across various institutions. Furthermore, the training process would be streamlined, which can lead to further research about differences in spatial skills through the training medium and explore how technology interacts with these skills. A streamlined application would reduce the stress, resource, and time commitment on instructors to implement these spatial interventions, alongside ensure our engineering students are benefitting from training their spatial visualization skills. While reaffirming the importance of spatial skills in engineering is crucial, it is equally important to ensure the training material and approaches are modern, effective, and replicable for all our engineering students.

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