Considering Spatial Skills Training Methods for Computer Science Students

Miranda C. Parker
Department of Software and Information Systems
University of North Carolina at Charlotte
Charlotte, NC, USA
miranda.parker@charlotte.edu

Jack Parkinson
Centre for Computing Science Education
University of Glasgow
Glasgow, Scotland UK
jack.parkinson@glasgow.ac.uk

Abstract

Students' spatial skills are correlated with performance in STEM disciplines, including computer science. Fortunately, these skills can be trained, consequently improving computing course outcomes. The typical spatial skills training in computing education utilizes a workbook that helps students visualize and sketch the rotation of 3-D shapes. However, more methods have been tested in other STEM fields, including video games and spatial-related toys. In this position paper, we discuss these methods from adjacent fields and present a case of how to pilot them with our computer science students. We argue for the need for more flexible, but still impactful, spatial skills training methods to support our students. These methods could also provide a lower barrier to entry to teaching spatial skills, leading to more computing instructors adopting these methods and more computing students having spatial skills training opportunities. Further, broadening our spatial skills training methods can help us better understand the connections between spatial skills and computer science, which is especially obscure given the abstract nature of our field.

CCS Concepts

• **Social and professional topics → Computing education**.

Keywords

spatial skills, training, intervention

ACM Reference Format:
Miranda C. Parker and Jack Parkinson. 2025. Considering Spatial Skills Training Methods for Computer Science Students. In *Proceedings of the 30th ACM Conference on Innovation and Technology in Computer Science Education V. 1 (ITiCSE 2025), June 27-July 2, 2025, Nijmegen, Netherlands.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3724363.3729043

1 Introduction

Spatial skills include the ability to imagine, remember, and mentally transform symbols or objects [13]. There is an abundance of evidence that spatial skills are strongly correlated with Science, Technology, Engineering, and Math (STEM) achievement [29]. Spatial skills tend to differ along spectra of gender and socioeconomic status, with women and low socioeconomic status students tending to under-perform in spatial tests [25]. However, spatial skills can be trained so as to improve outcomes for all students, both in terms of greater spatial skills and also in terms of achievement in the classroom [30].

There are a myriad of spatial skills training methods that have been shown to be effective in improving outcomes in other STEM education fields, including video games, courses, and specific spatial task training [30]. To date, a vast majority of the work in computer science (CS) education has focused on a ten-week course that involves workbooks developed by Sheryl Sorby [19, 27]. Little to no work has been done in CS education with the other training methods. Finding a variety of effective ways to train spatial skills is critical to encourage and allow instructors to integrate these training methods into their diverse educational settings with minimal interruption or time away from content learning. Additionally, different training methods may work better for different students.

A growing body of research – discussed throughout this paper – demonstrates that spatial skills training is valuable for CS students. We also have good theories for why this is the case, based on the works of Parkinson et al. and Margulieux [13, 23]. However, our theories for this relationship are largely untested and we may be advocating training in the common fashion without considering the greater potential of other methods. How can we maximize student improvement – in multiple dimensions – with the most effective kind of skill development? Perhaps Sorby's program *is* the best way for CS students to develop spatial skills. But, in this position paper, we argue that we will not know the full power of that training method until we investigate the alternatives.

It is our position that spatial skills training is valuable but we have not yet explored possibilities for spatial skills training beyond a single route. Thus, additional methods of training these skills should be considered. We begin by summarizing spatial skills training in computing education to date, followed by an overview of the primary method used: sketching workbooks. We discuss the challenges that are often faced when implementing this method of spatial skills training in computing classrooms. Then, we present alternative methods of spatial skills training based on the STEM education literature. We describe a case study that uses one of these alternative methods, Tetris, with mixed preliminary results. Finally, we provide our perspectives on the future of spatial skills training in computing education.

ITiCSE 2025, Nijmegen, Netherlands

ACM ISBN 979-8-4007-1567-9/2025/06
https://doi.org/10.1145/3724363.3729043

2 A History of Spatial Skills Training in Computer Science Education

Spatial skills research is traditionally based in math and the sciences. However, the CS education research community is actively replicating findings from STEM education and finding similar results. Here, we detail the background of spatial skills training studies in CS education research in order to provide context and motivation for exploring different methods of training.

In 2015, Cooper et al. used spatial skills training during a 10-day CS summer school [4]. Half of the participants completed 45 minutes of spatial skills sketching exercises each day, while the other half completed additional programming activities. The spatial group showed slightly higher gains in a subset of AP CS exam questions than the students with extra programming time, though the differences in gains were only significant when examining questions with the highest item discrimination.

Following this, Bockmon et al. published a study in 2020 involving voluntary spatial skills training – consisting of paper sketching and online quizzes – for students in the CS1 cohorts at three institutions [1]. Similar to Cooper et al., they found that students taking part in spatial skills training improved significantly more in a CS post-test than the control group.

This was closely followed by Parkinson and Cutts, who incorporated a mandatory paper-based spatial skills program for CS0 and CS1 students who scored 60% or below in a spatial skills test [21]. Prior to training, students who slightly outperformed the training cohort in spatial skills (60–70% in the test) also outperformed them in CS assessments, but the training cohort showed substantially higher gains in their CS assessments after training.

Ly et al. conducted online mandatory spatial skills training for their entire cohort of CS1 students, which was met with mixed attitudes and showed variable gains, but at least appeared to close a gender gap in spatial skills that was initially observed [12].[1]

Finally, Parker et al. conducted a spatial skills training with the intent to improve course outcomes for mid-major students (rather than introductory students, as all previous studies have involved) [18]. In this instance, although a correlation was observed between spatial skills and a standardized programming test, spatial skills training did not impact gains in the programming test and curiously did not improve spatial skills either.

2.1 Spatial Skills and CS Success

Although there is an abundance of evidence that there are relationships between spatial skills, spatial skills training, and CS ability, it remains unclear why these connections exist at all. Unlike other STEM fields, CS is based in a virtual realm, with few physical – and obviously spatial – representations present compared to other sciences. The current theory that explains these connections is Spatial Encoding Strategy (SpES), proposed by Margulieux [13]. SpES is the theory that spatial skills help students encode non-verbal mental representations and identify landmarks to orient representations. These two elements would aid computing students who are actively engaged in code comprehension and debugging tasks [13]. The SpES theory has been supported by further research which found that students with higher spatial skills were more able to demonstrate advanced chunking (information storing) and encoding (orientation) techniques when solving programming problems; students with lower spatial skills were less likely to demonstrate these skills [22].

Margulieux's theory indicates that spatial skills are valuable for learning and understanding any and all forms of non-verbal information and representations. Although CS does not include many *physical* examples of these kinds of representations, *abstract* representations abound and are crucial for understanding CS at any level.

Reflecting on all this work involving spatial skills and CS learning, the authors believe that spatial skills training for CS students is valuable. We are not claiming that spatial skills is the *most* valuable single addition an instructor might make to a program (although, it could be, depending on the context) or that it should be considered in place of any other specific additions or reforms. In fact, work by Endres et al. demonstrated that while spatial skills development *was* valuable for programming outcomes, students in a parallel technical reading intervention showed slightly higher gains in a standardized programming assessment [5]. However, they also acknowledged that both spatial skills and reading skills had distinct correlations with computing outcomes, indicating that developing either of these skills would probably be valuable for students in different ways. As such, we do not aim to advocate for spatial skills training *above* any other particular interventions or curricula changes. Rather, we propose that it is an important piece of the puzzle for learners' success in CS, and many methods of developing spatial skills should be considered.

3 Sorby's Sketching Workbook

Although the various training studies mentioned in Section 2 had differences in the students involved and the delivery methods employed, they have a crucial similarity: each used Sorby's Introduction to Spatial Visualization program [26]. The program appears to be the *only* method of deliberately developing spatial skills that has been used in CS education in the literature to date.

In 1993, Sorby and Baartmans developed a spatial visualization course for Mechanical Engineering students with low spatial skills test scores [27]. The course used paper-and-pencil tasks (often referred to as the 'workbook') as well as multimedia activities. Each week, students engaged in practice to increase their 3-D spatial skills. Over six years, the spatial skills training course consistently resulted in gains in spatial skills among students [27]. The workbook now consists of ten modules, broadly covering isometric and orthographic projections, combinations of 3-D objects, reflections and symmetry.

Sorby's program is tried, tested, and self-contained, making it relatively easy to implement. However, given that there are so many ways to improve spatial skills, as can be seen by Uttal et al.'s meta-analysis of the field [30], it is a failing of the current research that such a narrow perspective of spatial skill development has been used in computing practice. In the next section, we outline some challenges with implementing the workbook program to prompt a discussion about possible alternatives.

[1] Most of the studies mentioned here – and some additional studies – were written up and compared in an ACM Inroads article [19].

4 Challenges in Delivering Spatial Skills Training with Workbooks

While Sorby's workbook training program has been broadly successful in CS at several institutions, there are challenges associated with its implementation. This section is predominantly based on the experiences of one of the authors, whose institution has been conducting spatial skills training with CS students for over five years.

The first concern with the workbook-based spatial skills training method is cost. The ten-week spatial skill development program site license and online resources for learning can be purchased for $2,000 for three years. Costs are substantially higher when student workbooks are factored in, priced at $21 per student, quickly increasing the expenditures for large cohorts. The physical workbooks themselves must then be handed in and marked by instructors, with automated methods proving to be difficult to implement and frustrating for students to use [12, 19]. In the overall budget of an institution or department, these costs may not be prohibitively high, but convincing management that *any* additional expenditure is worth the cost can be difficult.

This leads to a second major challenge in implementing the training: internal push-back. As previously mentioned, the connections between spatial skills and computing are not immediately obvious, so a strong case must be made to faculty and administrators involved in deciding program content. Such an intervention must be consistently and convincingly championed. It takes considerable persuading for CS faculty to decide that it is worthwhile to dedicate classroom space, student timetabling, and instructor support for them to – as some might summarily judge Sorby's workbooks from a distance – draw some pictures.

Beyond financial and administrative costs, there are challenges related to experience and the hidden curriculum involved in spatial skills development. One of the authors has been training spatial skills alone at their institution for several years, and leadership of the program has recently been handed to a new team. Even though sessions were held with five new teaching assistants (TAs) to share the original instructor's knowledge, the program has been notably less effective, with substantially higher drop-outs and fewer participants completing the whole program.

The TAs reflected on their experience of teaching the program with the original instructor to try to identify where they faced challenges and why these may have led to reduced student engagement and success. Two main reasons arose: they could not support students who were struggling and they did not really understand why the program was being delivered.

It is easy to see how both of these challenges would have impacted student engagement. If students cannot get support from their TAs when they are struggling, they have little reason to continue attending sessions. The TAs reflected that often they felt that they could just *see* the solution and did not have the vocabulary or practice to guide the struggling students to the answer. In many cases, the task is "simple": just visualize the answer; simply *see* a rotation take place in your head. Yet, some students will struggle to do exactly this, so there is no clear route for those who struggle with elements of the spatial skills training itself.

There *is* a way forward, but one which the author has developed with students over several years of practice delivering the course. One solution is to take the student several steps back to visualizing much simpler objects, particularly ones that can be embodied and seen in the real world (like a pencil or an eraser), and work hard to create a mental representation of it. Then, closing their eyes, the student should rotate the object 90 degrees on their desk slowly – physically – while copying the motion in their head. When they have completed the rotation, they should open their eyes and see if the orientation of the object matches their imagination. In most cases it should, but they can keep practicing if not. The student can then move on to more complex objects and sequences, gradually building up their ability to work with their head. This process gradually trains visualization, and should help to prepare students for the sketching exercises.

This sequence of activities is challenging to describe to a TA and difficult to know when to apply. Indeed, some students who are struggling are simply facing mindset issues. Sometimes all they need to motivate them is to turn back to the beginning of the workbooks – to the easier activities – and remind them how challenging they originally found them, but can now complete them easily. In short, while it appears straightforward, the workbook method is not always easy to teach and involves creative, out-of-the box thinking from instructors, often shaped by experience.

The second challenge – TAs not understanding the need for the training – is mostly related to *transfer*. The same challenge can be seen from students' perspectives in Ly et al.'s work, where they indicated that "they did not see how spatial skills helped them program" [12, p. 7]. Even if students and TAs understand the underlying reasons why spatial skills are valuable to them, there is still a disconnect between sketching shapes and writing programs. The reasons for *why* the relationship exists are rooted in psychology and neuroscience [13], which are unfamiliar and inaccessible to many students beginning a CS program.

It seems, then, that in order for a sketching spatial skills development program to be successful in a CS context, it requires an expert in the field to be present and prepared to fight for the program's existence. Removing the expert can lead to declines in student engagement due to TAs not being as experienced in the subject. This makes the apparently lightweight and easy-to-deliver program appear less so in practice, with a level of expertise possibly required to deliver it effectively. As seen in the differences in outcomes of studies in Section 2, this may be the underlying reason why training is not always effective.

5 Alternative methods for developing spatial skills

Given the challenges inherent in the delivery of workbook training, we will now explore some alternative methods of developing spatial skills. Some of these are described by Uttal et al., though additional relevant work has been conducted in this area since their 2013 meta-analysis [30] which are included in our discussion here. This list is not exhaustive, but is considered by the authors to be three potential routes which are most likely to be effective alternatives to Sorby's workbook.

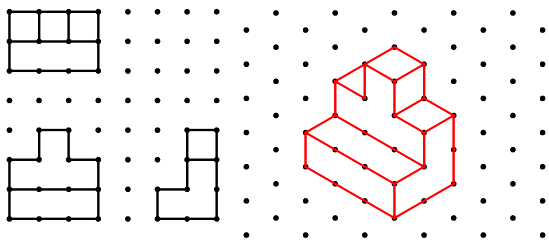

Figure 1: A sample from Sorby's workbook prompting the student to sketch the isometric projection from the orthographic projections provided (the correct sketch is in red)

5.1 Block Play

Block play and construction activities have been used in research to explore spatial skills development in several different ways [3, 14, 15]. As far as we can determine, *all* research involving construction toys and spatial skills to date have been geared towards children, usually in primary school. They also rarely explicitly involve dynamic spatial tasks, like rotation or visualization (which in this case could arise from needing to build a structure where not all angles or parts of an object are visible).

One route to spatial development for CS undergraduates – or adults in any discipline – could be through complex spatial LEGO activities. These could use activities like Sorby's as a template, except that instead of *sketching* a result, the participant must *build* it. This might make spatial skills activities more engaging and reduce the need for expert support in completing activities.

To provide a concrete example, consider one of Sorby's sketching exercises, which requires the student to draw a 3-D isometric perspective of an object given three 2-D orthographic projections (of the top, front and side of the object). An example is shown in Figure 1. Now consider a diagram of a LEGO object with the orthographic projections given, as seen in Figure 2, and the task is to build the 3-D version out of LEGO provided. This will require very similar skills to those required for Sorby's activities, but gives a more tactile context.

One of the authors has trialed spatial LEGO activities at public engagement events at their institution, attracting an audience of children and adults. This has not permitted formal testing of the activities for their relationship with spatial skills, but it has given the opportunity for a wide range of perspectives to be collected about the activity.

Parkinson and Cutts explain that spatial tests are a good way to describe spatial skills to avoid ambiguity and to demonstrate just what skills are being examined [20]. It appears that the LEGO activities achieve this too, with participants grasping within seconds the complex visualization task required and needing little prompting to begin coming up with a solution.

When spatial skills and their relationship with STEM are explained to participants, this is usually not met with doubt, as has been observed in previous studies [12]. Instead, most participants indicate that they can see how this kind of thinking would be useful, and go on to give non-physical examples of how complex spatial thinking could support STEM activities. For example, one participant said that when they are trying to develop a proof in math, they need to hold a lot of complex information in their head at once, and it felt a little like trying to line up the three views of the LEGO structure in their head. Another participant, who self-reported as being an epidemiologist, described the "hidden" routes of contagious diseases as being multi-layered and multi-faceted, and indicated that they often wished they were better at this kind of thinking in order to understand interconnected disease vectors more intuitively.

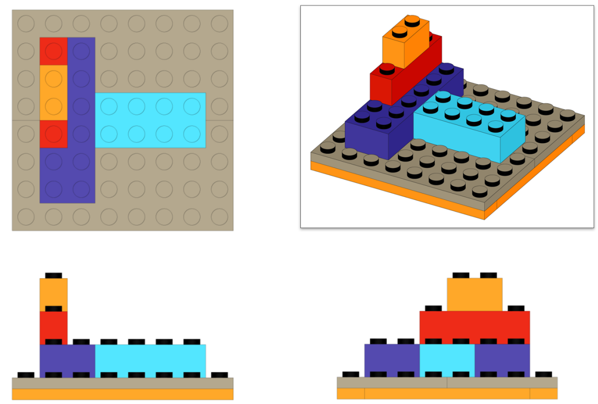

Figure 2: An example of a LEGO activity developed to construct a LEGO object using orthographic views and a representation of the resulting construction

Therefore, block-based practice could be an alternative to sketching activities. It is effective at developing the skills required in some experimental contexts, does not attract the same level of skepticism as paper-based activities and tests, and is immediately engaging and accessible to a range of people.

5.2 Video Games

Video games have previously proved to be effective means of developing spatial skills [28, 30]. For example, playing Tetris, a puzzle game where blocks need to be rotated to sustain gameplay, consequently improves performance on spatial skills tasks [30]. However, the applicability of Tetris for spatial skills training may be limited to tasks that are similar to the game itself, such as mental rotation.

Uttal et al. specifically discussed action games (i.e., single-user role playing games) being more effective than non-action games (i.e., puzzle solving) [30]. We can speculate that these games require rapid navigation through complex 3-D spaces, and the process of memorizing and navigating quickly in this fashion improves spatial skills in several dimensions, but it can be hard to tease out the precise activities in commercial, off-the-shelf games which develop spatial skills. For example, one video game which appears to develop spatial skills is *Medal of Honor: Pacific Assault* [7]. The core gameplay loop involves spawning into an area with your team, eliminating the other players and capturing their command posts. At a surface level, the most important keys for success could be seen to be precision (to aim carefully with analogue sticks or a mouse), reaction time, and knowledge of the game context (e.g., using weapons with correct effective ranges for different situations).

One might not consider navigation and understanding of a complex 3-D environment to be important, but it is a core part of action games. The challenge in using commercial games for spatial skill development is that all the other skills are required and no single skill can be extracted and trained in isolation.

To disentangle some of these factors, Wauck and Bailey has worked on developing a spatial skill development "test-bed" with very deliberate spatial activities built into a game [31, 34]. The game involves distinct navigation levels and construction levels, each aimed to target specific spatial skills. The game was found to be successful in increasing spatial skills so whilst maintaining interest and motivation [32]. However, constructing such a tool is challenging and expensive for researchers, especially when commercial, off-the-shelf video games can be much more polished and feel more satisfying.

As a route to developing spatial skills in computing, video games may be viable. Similar to block toys, they are highly engaging and are already familiar in some form to a large majority of the population; the challenge is to ensure that the correct skills are being developed through play.

5.3 Computer Science Activities

Rather than contextualizing spatial skills in blocks or video games, these skills could be situated in the domain itself with the design of spatial-specific CS activities. This idea was sparked by a finding that Wauck discovered regarding students placed in three training conditions: playing a spatial video game, completing some exercises from Sorby's workbook, and learning Python turtle graphics. The students learning Python enjoyed the activity the most and students enjoyed the workbook training the least [33].

Further, following the work of Pallrand and Seeber [16], Parkinson et al. explored whether studying CS could lead to improved spatial skills [23]. It could, but only by about 3-7% on a spatial test after a whole semester, while Sorby's training usually improves scores by about 20% after only 10 hours.

While Sorby's methods remain more effective, this suggests that with carefully designed CS activities we could improve students' spatial skills simply by having them take part in CS. This would alleviate concerns about transfer and instructors and TAs not understanding why the spatial activities were useful. In practice, the intentionally created activities would actually be perceived as CS activities, but they would also happen to develop spatial skills. Work similar to this is already taking place in primary schools in Australia and Scotland, where spatial skills are being embedded into the math curriculum so that students can develop them while taking part in "normal" math classes [9–11].

It is hard to imagine just what these activities could look like and if they could be generated in enough quantities and with enough precision to develop spatial skills effectively. However, embedding spatial development into the CS curriculum seems like an obvious and effective method of ensuring that all students enrolled have the chance to develop the underlying skills they need to succeed.

6 An example case to explore alternative methods

All of the methods described above require further investigation in computing education research to ascertain their efficacy in our field. We use one of the alternative methods described above, video games, and provide an example of how future work may adapt what is used in other STEM education fields to add to what is known in computing education. In the case that follows, one author conducted an experimental study comparing the short-term effects of one module of the sketching workbook with playing Tetris, a block-stacking video game. While this was ultimately a small-scale study, it provides an example of how we, as a community, can conduct studies to explore and compare the efficacy of different spatial skills training methods. Although we focus on a video game in this case, block play or CS activities could have been used in a similar manner.

6.1 Context

Students were recruited from a CS program at a large university in the United States. Students qualified for the study if they had completed the first CS course in the degree program at that institution. After indicating interest, students could sign up for a time slot. When they arrived, students were asked to complete a consent form and were given an overview of study procedures. Then, students took pre-tests of spatial skills and CS ability, followed by 40 minutes of a spatial training task, and concluding with the same tests of spatial skills and CS ability as a post-measure.

6.2 Study Design

The two conditions for the study were to complete a module of a spatial skills training workbook or to play Tetris. The workbook module was Module 3 of Sorby's training materials, which involved isometric drawings and coded plans, including those seen in Figure 1. Tetris was chosen for the experimental condition as prior research has indicated that Tetris can improve mental rotation ability [28, 30]. Although action-type games can lead to more spatial skill improvements, Tetris is a neutral game that does not carry any potential negative connotations. Each time slot had a different condition associated with it, and participants did not know what conditions were available or what condition each time slot corresponded to when they signed up. This information was only mentioned after their session had started. Ultimately, we recruited 16 students for the Workbook condition and 20 students for the Tetris condition.

The tests used in this study were derived from reliable and valid assessments from the research community. The pre- and post-spatial skills test was the 20-question Purdue Visualization of Rotations Test (ROT) [2]. The ROT is a subset of the full Revised Purdue Spatial Visualization Test and instructions are to administer the test with a 10-minute time limit. The pre- and post- CS test was a subset of the Second CS1 knowledge assessment (SCS1) [17]. Given the time frame for our study, we selected 5 questions from the SCS1 that have indicated the strongest performance in past research [17].

Table 1: Mean values of the pre-/post-tests for each condition

Condition	Pre Spatial	Post Spatial	Pre CS	Post CS
Tetris	0.703	0.721	0.720	0.750
Workbook	0.603	0.691	0.800	0.863

Table 2: Results of Wilcoxon Signed Rank Tests on pre- to post-performance on spatial skills and computer science within each condition. $^*p < 0.025$**, the Bonferroni corrected significance value.**

	Spatial Skills	Computer Science
Tetris	z = 0.857, p = 0.391	z = 0.905, p = 0.366
Workbook	z = 2.423, p = 0.015*	z = 1.890, p = 0.059

6.3 Results and Discussion

The average values for each pre- and post-test in the two conditions can be found in Table 1. All scores on the pre- and post-tests are presented as the number of questions scored correctly out of the total number of questions. We chose to use non-parametric statistics to analyze the data given the small sample size.

Even though the study was randomized, the pre-test spatial skills scores appear dramatically different (0.703 for the Tetris condition; 0.603 for the Workbook condition). However, the Mann Whitney U tests comparing the means did not show a statistically significant difference between the two groups for this measure (z=-1.053, p=0.305) nor any measure we used.

As seen in Table 2, the only statistically significant difference in the pre- to post- test scores was within the workbook group for the spatial skills measure. The workbook training group, improved from 0.603 to 0.691 (z=2.423, p =0.015). This significance holds even after conducting a Bonferroni correction on the significance value to account for the two comparison tests conducted on the sample.

These findings indicate that the Workbook method was superior in improving students' spatial skills. However, this study was designed using an abbreviated subset of training materials, by only providing one modules of the workbook and providing less time to play Tetris than in prior studies. This was intentional: if the effects were pronounced within a short time period, then that too makes spatial skills training more accessible, be it with video games or the workbook. However, we should be cautious with interpreting the findings due to the small sample sizes. More analyses with a larger sample are required before putting together a more resounding claim about the effectiveness of either method in a short-term study. Additional research is needed to expand this study to provide more conclusive claims. As a result, this study is presented here as a case of how to study alternative spatial skills methods from a study design perspective, more than it is presented for its findings in and of themselves.

7 Concluding Remarks

In this position paper, we have highlighted the ongoing use of sketching workbooks for spatial skills training in computing education. We discussed challenges in implementing that training, including cost and instructional support. In response, we presented possible alternative methods for spatial skills training, derived from the literature. We have also briefly described a study that explored the impact of completing a workbook module versus playing Tetris on student spatial and computing scores; the only significant result was the improvement of spatial skills for the workbook training group. This case serves as an example for how alternative methods in spatial skills training can be implemented, investigated, and compared with existing methods to understand their efficacy and effectiveness.

While it currently appears that Sorby's workbook exercises are the most effective and well-tested means of developing spatial skills, they still have challenges in implementation. Primarily, these barriers include the hidden strategies and mechanisms for making teaching effective, and the motivational challenges faced by both students and TAs without expertise. There are other ways to develop spatial skills, but these are not well understood and it is difficult to disentangle the spatial elements of the activities from their other components. Ultimately, it would be ideal to develop spatial skills through "normal" CS instruction, but we do not yet know how to do this effectively. Additionally, our student bodies are not homogeneous, and since there are many ways to develop spatial skills, maybe certain methods will be far more effective for some students more than others. Therefore, the authors' position is that CS education researchers with an interest in this area should consider alternative ways to develop spatial skills for CS students.

We would like to further acknowledge that spatial skills, and their connections to computing outcomes, do not exist in a vacuum. For one, these factors are *measured* by assessments, which contain their own biases and constraints. If we are measuring students' spatial rotation ability, but it is truly their spatial orientation ability (a nuanced but distinct difference) that is being trained or that is important for computing, then our claims around spatial skills and their malleability are not adequately based on evidence. The same goes for the CS knowledge assessments if they are not capturing the aspect of computing that would change the most with spatial skills training. There is FMRI evidence to suggest that data structures are an area of computing that corresponds to spatial skills [8], but this deserves further investigation. Additionally, we recognize the role that deliberate practice [6] and student intrinsic, versus instructor extrinsic, motivation [24] plays in the effectiveness of any classroom intervention. Spatial skills training, regardless of method, only works if students intentionally practice their skills, with feedback and with the context of why this growth is important for them. There are many factors beyond these listed here, but consideration of different spatial skills training methods is important for the furthering of this area in computing.

Acknowledgments

Many thanks to Sheryl Sorby for the licensed use of her training workbooks. We also thank the students who participated in the research study and the undergraduate student researchers who helped to run the study.

References

[1] Ryan Bockmon, Stephen Cooper, William Koperski, Jonathan Gratch, Sheryl Sorby, and Mohsen Dorodchi. 2020. A CS1 Spatial Skills Intervention and the

Impact on Introductory Programming Abilities. In *Proceedings of the 51st ACM Technical Symposium on Computer Science Education (SIGCSE '20)*. ACM, New York, NY, USA, 766–772. https://doi.org/10.1145/3328778.3366829

[2] George M Bodner and Roland B Guay. 1997. The Purdue visualization of rotations test. *The chemical educator* 2, 4 (1997), 1–17.

[3] Beth M. Casey, Nicole Andrews, Holly Schindler, Joanne E. Kersh, Alexandra Samper, and Juanita Copley. 2008. The Development of Spatial Skills Through Interventions Involving Block Building Activities. *Cognition and Instruction* 26, 3 (July 2008), 269–309. https://doi.org/10.1080/07370000802177177

[4] Stephen Cooper, Karen Wang, Maya Israni, and Sheryl Sorby. 2015. Spatial Skills Training in Introductory Computing. In *Proceedings of the Eleventh Annual International Conference on International Computing Education Research (ICER '15)*. ACM, New York, NY, USA, 13–20. https://doi.org/10.1145/2787622.2787728

[5] Madeline Endres, Madison Fansher, Priti Shah, and Westley Weimer. 2021. To read or to rotate? comparing the effects of technical reading training and spatial skills training on novice programming ability. In *Proceedings of the 29th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering*. ACM, New York, NY, USA, 754–766. https://doi.org/10.1145/3468264.3468583

[6] K Anders Ericsson. 2008. Deliberate practice and acquisition of expert performance: a general overview. *Academic emergency medicine* 15, 11 (2008), 988–994.

[7] Jing Feng, Ian Spence, and Jay Pratt. 2007. Playing an Action Video Game Reduces Gender Differences in Spatial Cognition. *Psychological Science* 18, 10 (Oct. 2007), 850–855. https://doi.org/10.1111/j.1467-9280.2007.01990.x

[8] Yu Huang, Xinyu Liu, Ryan Krueger, Tyler Santander, Xiaosu Hu, Kevin Leach, and Westley Weimer. 2019. Distilling Neural Representations of Data Structure Manipulation using fMRI and fNIRS. In *Proceedings of the IEEE/ACM 41st International Conference on Software Engineering*. IEEE, New York, NY, USA, 396–407. https://doi.org/10.1109/ICSE.2019.00053

[9] Tom Lowrie, Danielle Harris, Tracy Logan, and Mary Hegarty. 2021. The Impact of a Spatial Intervention Program on Students' Spatial Reasoning and Mathematics Performance. *The Journal of Experimental Education* 89, 2 (April 2021), 259–277. https://doi.org/10.1080/00220973.2019.1684869

[10] Tom Lowrie, Tracy Logan, Danielle Harris, and Mary Hegarty. 2018. The impact of an intervention program on students' spatial reasoning: student engagement through mathematics-enhanced learning activities. *Cognitive Research: Principles and Implications* 3, 1 (Dec. 2018), 50. https://doi.org/10.1186/s41235-018-0147-y

[11] Tom Lowrie, Tracy Logan, and Mary Hegarty. 2019. The Influence of Spatial Visualization Training on Students' Spatial Reasoning and Mathematics Performance. *Journal of Cognition and Development* 20, 5 (Oct. 2019), 729–751. https://doi.org/10.1080/15248372.2019.1653298

[12] Anna Ly, Jack Parkinson, Quintin Cutts, Michael Liut, and Andrew Petersen. 2021. Spatial Skills and Demographic Factors in CS1. In *21st Koli Calling International Conference on Computing Education Research*. ACM, New York, NY, USA, 1–10. https://doi.org/10.1145/3488042.3488049

[13] Lauren E. Margulieux. 2019. Spatial Encoding Strategy Theory: The Relationship between Spatial Skill and STEM Achievement. In *Proceedings of the 2019 ACM Conference on International Computing Education Research (ICER '19)*. ACM, New York, NY, USA, 81–90. https://doi.org/10.1145/3291279.3339414

[14] Emily McDougal, Priya Silverstein, Oscar Treleaven, Lewis Jerrom, Katie Gilligan-Lee, Camilla Gilmore, and Emily K. Farran. 2023. Assessing the impact of LEGO® construction training on spatial and mathematical skills. *Developmental Science* 27, 2 (July 2023), e13432. https://doi.org/10.1111/desc.13432

[15] Sharlene D. Newman, Erin Loughery, Ambur Ecklund, Cindy You, Hannah Von Werder, and Firat Soylu. 2021. Structured versus free block play: the impact on arithmetic processing. *Trends in Neuroscience and Education* 22 (March 2021), 100146. https://doi.org/10.1016/j.tine.2020.100146

[16] George J. Pallrand and Fred Seeber. 1984. Spatial ability and achievement in introductory physics. *Journal of Research in Science Teaching* 21, 5 (May 1984), 507–516. https://doi.org/10.1002/tea.3660210508

[17] Miranda C. Parker, Mark Guzdial, and Shelly Engleman. 2016. Replication, Validation, and Use of a Language Independent CS1 Knowledge Assessment. In *Proceedings of the 2016 ACM Conference on International Computing Education Research (ICER '16)*. ACM, New York, NY, USA, 93–101. https://doi.org/10.1145/2960310.2960316

[18] Miranda C. Parker, James Marsh, Anna Nguyen, Chloe Salazar, and Garen Vehouni. 2024. The Effect (or Lack Thereof) of Spatial Skills Training in a Mid-Major Computing Course. In *Proceedings of the 24th Koli Calling International Conference on Computing Education Research*. ACM, New York, NY, USA, 1–11. https://doi.org/10.1145/3699538.3699566

[19] Jack Parkinson, Ryan Bockmon, Quintin Cutts, Michael Liut, Andrew Petersen, and Sheryl Sorby. 2021. Practice report: six studies of spatial skills training in introductory computer science. *ACM Inroads* 12, 4 (Dec. 2021), 18–29. https://doi.org/10.1145/3494574

[20] Jack Parkinson and Quintin Cutts. 2018. Investigating the Relationship Between Spatial Skills and Computer Science. In *Proceedings of the 2018 ACM Conference on International Computing Education Research (ICER '18)*. ACM, New York, NY, USA, 106–114. https://doi.org/10.1145/3230977.3230990

[21] Jack Parkinson and Quintin Cutts. 2020. The Effect of a Spatial Skills Training Course in Introductory Computing. In *Proceedings of the 2020 ACM Conference on Innovation and Technology in Computer Science Education (ITiCSE '20)*. ACM, New York, NY, USA, 439–445. https://doi.org/10.1145/3341525.3387413

[22] Jack Parkinson and Quintin Cutts. 2023. Understanding Spatial Skills and Encoding Strategies in Student Problem Solving Activities. In *Proceedings of the 2023 ACM Conference on International Computing Education Research V.1*. ACM, New York, NY, USA, 14. https://doi.org/10.1145/3568813.3600134

[23] Jack Parkinson, Sebastian Dziallas, Fiona McNeill, and James Stephen Williams. 2023. Exploring Models and Theories of Spatial Skills in CS through a Multi-National Study. In *Proceedings of the 2023 ACM Conference on International Computing Education Research V.1*. ACM, New York, NY, USA, 122–133. https://doi.org/10.1145/3568813.3600129

[24] Richard M Ryan and Edward L Deci. 2000. Intrinsic and extrinsic motivations: Classic definitions and new directions. *Contemporary educational psychology* 25, 1 (2000), 54–67.

[25] Sheryl Sorby, Norma Veurink, and Scott Streiner. 2018. Does spatial skills instruction improve STEM outcomes? The answer is 'yes'. *Learning and Individual Differences* 67 (2018), 209–222. https://doi.org/10.1016/j.lindif.2018.09.001

[26] Sheryl Sorby, Anne Francis Wysocki, and Beverly Baartmans. 2003. *Introduction to 3D Spatial Visualization: An Active Approach* (1 ed.). Thomson Delmar Learning, Clifton Park, NY, US.

[27] Sheryl A. Sorby and Beverly J. Baartmans. 2000. The Development and Assessment of a Course for Enhancing the 3-D Spatial Visualization Skills of First Year Engineering Students. *Journal of Engineering Education* 89, 3 (July 2000), 301–307. https://doi.org/10.1002/j.2168-9830.2000.tb00529.x

[28] Ian Spence and Jing Feng. 2010. Video Games and Spatial Cognition. *Review of General Psychology* 14, 2 (June 2010), 92–104. https://doi.org/10.1037/a0019491

[29] David H. Uttal and Cheryl A. Cohen. 2012. Spatial Thinking and STEM Education. In *Psychology of Learning and Motivation*. Vol. 57. Elsevier, Amsterdam, 147–181. https://doi.org/10.1016/B978-0-12-394293-7.00004-2

[30] David H. Uttal, Nathaniel G. Meadow, Elizabeth Tipton, Linda L. Hand, Alison R. Alden, Christopher Warren, and Nora S. Newcombe. 2013. The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin* 139, 2 (March 2013), 352–402. https://doi.org/10.1037/a0028446

[31] Helen Wauck and Brian Bailey. 2019. A Testbed for Fun and Effective Features in Spatial Skill Training Games. In *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play*. ACM, New York, NY, USA, 763–771. https://doi.org/10.1145/3341215.3356298

[32] Helen Wauck, Brian S. Woodard, Ziang Xiao, Tiffany Wenting Li, and Brian P. Bailey. 2020. A Data-Driven, Player-Centric Approach to Evaluating Spatial Skill Training Games. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*. ACM, Virtual Event Canada, 349–361. https://doi.org/10.1145/3410404.3414255

[33] Helen Catherine Wauck. 2020. *A data-driven, player-centric approach to designing spatial skill training video games*. Ph.D. University of Illinois at Urbana-Champaign, Urbana, IL, USA. http://hdl.handle.net/2142/107962

[34] Helen C. Wauck, Elisa D. Mekler, and Wai-Tat Fu. 2019. A Player-Centric Approach to Designing Spatial Skill Training Games. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300296