Assessing Productive and Receptive Spatial Skills in a Computerized Test Battery

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This empirical full paper examines the assessment of productive spatial skills. It compares the results to various other skills, including visual-motor, spatial memory, and planning, using a computerized test battery. Spatial Visualization (SV) skills are frequently assessed using multiple-choice tests, such as the Revised Purdue Spatial Visualization Test with Rotations (Revised PSVT: R) [1] and the Mental Rotations Test (MRT) [2]. These assessments of understanding are referred to here as receptive skills. Productive spatial skills require the use of spatial skills to create a product, such as scientific modeling, computer coding, and engineering drawing and design. There is no valid and reliable formal measure of productive spatial skills to date. In response to this need, a novel Spatial Grid Drawing Task was developed using point-and-click digital line drawing to assess productive skills. A series of studies were conducted, beginning with Study 1A (N=30) and 1B (N=26) in which a battery of spatial assessments of object memory, visual/spatial memory, two-dimensional (2D) and three-dimensional (3D) rotation skills, spatial memory and planning tasks, along with the novel Spatial Grid Drawing Task were administered to compare first year engineering participants' receptive and productive spatial skills. Scores on the battery were also compared within-subject with Revised PSVT: R scores from their university orientation. A low-to-moderate positive correlation was found across all assessments, with a unique construct identified in the productive Spatial Grid Drawing Task. Future studies will use the MRT-A (version A) paper-pencil assessment of receptive SV skills and a revised Spatial Grid Drawing Task, incorporating 2D and 3D rotation drawings, to assess participants' productive SV skills from the Psychology and Human Factors student research participant pool at an R1 University.

Background

Spatial skills have been studied extensively, especially as they relate to success in STEM fields (physics and chemistry) [3, 4]. According to the Spatial Encoding Strategy Theory, spatial skills are needed for higher-level abstract thinking, such as engineering drawing and design, computer coding, scientific modeling [5, 6], and mathematical graphing, especially those used in calculus [7, 8]. Currently, assessments of spatial skills, including spatial visualization skills, measure only receptive skills, or the ability to understand spatial information. To address this, an assessment of productive spatial skills was developed to measure the ability to apply spatial information to problem-solving using digital drawing, The Spatial Grid Drawing Task. It is the first of its kind, is computerized, scorable, and scalable. A digital drawing tool can assess the ability to use encoded spatial information, taking the guesswork out of high-stakes decisions. In fact, assessment results may determine college course placement or even admission to a college of engineering [9].

According to a meta-analysis conducted by Uttal [10] of various instructional approaches, spatial skills can increase with experience and instruction. Sorby and Baartmans [11] developed an engineering drawing course for students who scored below 19/30 on the PSVT at orientation, and conducted a six-year longitudinal study of the academic outcomes of students who did or did not take the course. Simply put, students who took the course had higher grades compared to their other STEM courses. This course focuses on hand-drawing of isometric and orthographic objects in one, two, or three rotations about the x, y, and z axes [10], and is used by other STEM disciplines around the world, including in computer science to improve spatial skills (Parkinson & Cutts, 2022). Other engineering programs around the country use similar hand-drawing instruction to Sorby's, including a digital platform, SketchtTivity developed collaboratively by Texas A & M, Purdue, Georgia Tech, and San Jose University [12]. Spatial Vis, another digital platform that can be taught in person [13], was developed at UC San Diego and is used by other Universities, as well. These programs provide assessment questions and digital feedback on drawing. Spatial skills are not only important in engineering, but surgeons [14], pilots [15], and other careers use assessments of spatial skills for placement and admission decisions, as well.

Many spatial assessments focus on 3D mental rotation, as measured by the PSVT-R, MRT, and others. Other spatial skills, including visuospatial skills and spatial working memory, object memory, spatial planning, and visual-spatial motor control, are often not assessed. These skills are measured with standard assessments, but they have not been examined in relation to mental rotation and its application in engineering programs. Productive spatial skills are more difficult to measure, as hand-drawn assessments of accuracy must currently be scored by hand. As a result, spatial assessment in these and other settings has relied on a test that is easy to administer and score, while ignoring many other related skills that may indicate spatial abilities needed by engineering and other STEM disciplines.

The Purdue Spatial Visualization Test (PSVT) was first developed by Guay [4] and comprised four subtests, one of which was Rotations. The Purdue Spatial Visualization Test with Rotations (PSVT: R) was developed in 1997 by Bodner and Guay [16] from the Rotations subtest of the PSVT and included 30 mental rotations in a multiple-choice format, 13 regular and 17 irregular shapes, with a 20-minute time limit. In 2011, Yoon [1] revised the PSVT: R by digitizing it, correcting some minor drawing errors, and re-ordering the items from easy to difficult. Also in 2011, Maeda and Yoon [17] conducted a study with 600 first-year engineering students using the Revised PSVT: R to analyze the item- and test-level functions of the assessment using Classical Test Theory and Item Response Theory. They also examined students' academic abilities to assess construct validity. Overall, their results indicate that the Revised PSVT: R measures a single subcomponent of spatial ability (rotation), and the scores accurately represent the spatial visualization abilities of first-year engineering students.

The use of a productive skill measure, specifically engineering drawings, may give educators at all age levels a better understanding of specific skill attainment than a general SV ability level, as indicated by receptive measures. This information may indicate the need for further instruction and practice in finite skills, such as drawing 2D or 3D object rotations. Previous research on SV skills has shown that engineering students with highly developed drawing skills perform better in their engineering, math, and science courses required for their degree [18]. We also know that drawing skills are malleable [10, 19], but to date, there is no efficient way to assess the productive spatial skills of large groups of students. Hand-scoring hand-drawings is time-consuming, and individual course assignments vary in type and difficulty.

To address this problem, we created a broad set of spatial tests (see Table 1) using the PEBL platform [20]. This battery included a spatial working memory task (VSPAN) Luck-Vogel [21], the Corsi Block Task [22], a mental rotation task (MROT) [23], Object Judgment [21], the 3D rotation Manikin Task, the Traveling Salesman Problem task (TSP) [24], a mirror object tracking

(Move-to-Target) task, and a novel drawing task, the Spatial Grid Drawing Task. We examined how these different spatial skills were related in a group of introductory engineering students who also completed the PSVT: R. The Spatial Grid Drawing Task was designed to be a valid and reliable way to quickly measure productive spatial visualization skills (up to 25 minutes, compared to 20 minutes for the PSVT: R) and to allow for digital scoring.

Assessment in Battery	Description
Manikin task (3D mental rotation)	A timed mental rotation task, adapted from the military version, requiring a left or right shift key press to match the background color and shape with the hand in which the figure (manikin) is holding the same shape and color. The manikin appears front-facing, backward-facing, right-side up and upside down.
Luck-Vogel (visual/spatial working memory and visual attention)	Participants briefly view an array of colored blocks and then identify whether a second array matches the first after a brief black screen.
Corsi Block (visual/spatial working memory)	Participants observe a sequence of highlighted blocks and then reproduce the sequence in the same order by clicking the blocks. The series begins with two blocks and increases by 1 with each correct response.
Object Judgment (2D spatial rotation; visual/spatial memory, and discrimination)	Participants compare two shapes, one in rotation, and judge whether they match.
Traveling Salesman Problem (spatial planning and visual-motor skills)	Participants select the most efficient route by connecting dots.
Move-to-Target (visual-motor skills)	Participants control a cursor that is backward controlled to stay aligned with a moving target.
Maze (spatial navigation and planning)	Participants move through a maze to reach the goal as efficiently as possible.
Spatial Grid Drawing Task (a novel block draw task to assess SV production skills)	This task includes four point-and-click to draw objects with varying degrees of difficulty. All are drawn on 2D orthographic dots requiring no rotation.

Table 1

Assessments in the spatial battery used in Study 1A (high spatial skills), including the area assessed and a brief description. In Study 1B, Move-to-target and Maze tasks were removed.

Introduction

This two-part study, comprising Study 1A and 1B, was designed to develop a productive online spatial assessment that could be administered and scored digitally, aligning with other assessments of spatial skills, including visual/spatial memory, spatial planning, and visual-motor skills. The goal is to provide additional, reliable information during initial spatial assessment, progress monitoring, and instructional design for first-year engineering students at the university level. Study 1A was conducted in the spring semester with participants with comparatively high spatial skills, and Study 1B was conducted the following fall with participants with low spatial skills. We compared not only scores on the PSVT: R at orientation for low- and high-scoring groups, but also compared the low group of students with less instruction in engineering education in general to those with higher skill and more instruction to ensure the Spatial Grid Drawing Task was neither too difficult nor too easy for this population. One of the goals of this work is to make this productive skills assessment scalable to other ages and settings, i.e. middle and high school, Career and Technical Education (CTE), 2-year college programs, trades, and other STEM domains.

Research Question: How do the results of a productive spatial skills assessment align with those of a receptive spatial skills assessment and other spatial skills measures?

Hypothesis 1: The student scores of the productive spatial skill assessment, Spatial Grid Drawing Task, will be correlated with a receptive spatial skill assessment, the PSVT: R.
Hypothesis 2: All student scores of assessments of spatial skills in the battery (see Table 1) will be correlated.
Hypothesis 3: The productive spatial skill assessment will provide unique information about student spatial skills.

Studies 1A and 1B: Methods:

Participants

The first in a series of two studies was conducted in the Spring semester at an R1 University. Participants' engineering majors are listed in Table 2. All entering first-year students take the PSVT-R at orientation, and those with scores above 19/30 do not need to take additional coursework to further develop SV skills. The participants for Study 1A (N=30) were all second-semester first-year engineering students with PSVT: R score between 17 and 30 out of a possible 30 (See Figure 1).

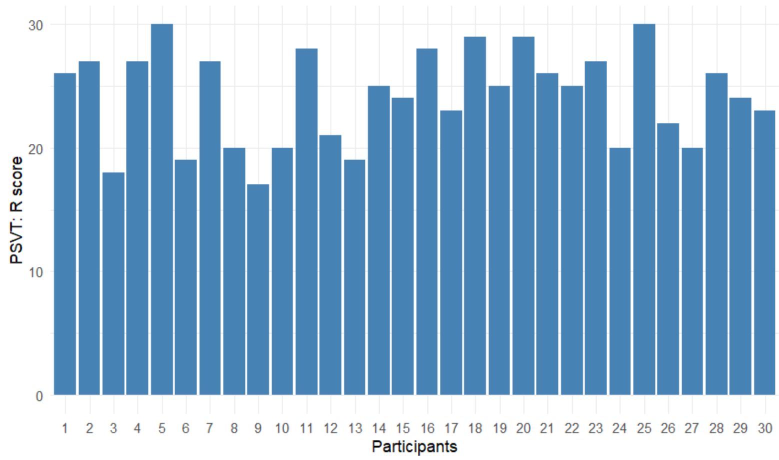

Figure 1:
*Distribution of PSVT: R Scores ranged from 17/30 to 30/30, considered to be high spatial skills, Study 1A (N=30)*The second part of the study, Study 1B, was conducted in the Fall of 2023 at the same University, and participants were first-year engineering students in their first semester. All were enrolled in a remedial course, ENG1002, Intro to Spatial Visualization, which was required for incoming students who scored less than 19/30 on the PSVT: R at orientation (See Figure 2).

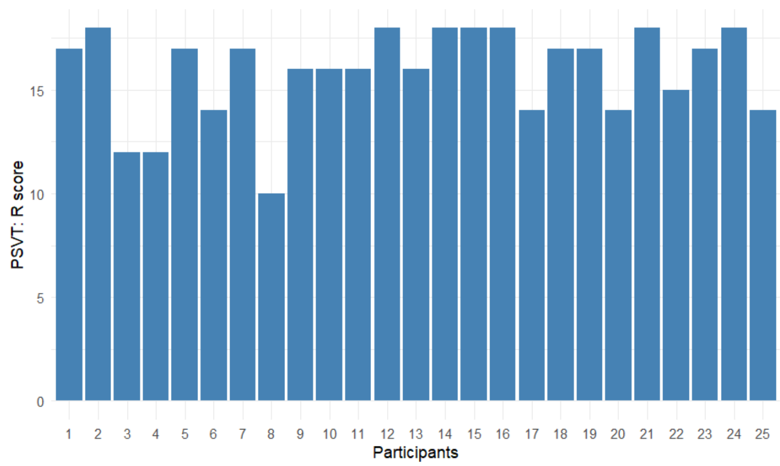

Figure 2*:*
Distribution of PSVT: R Scores, which ranged from 10/30 to 18/30, considered low spatial skill level, Study 1B (N=25)

<u>*Recruitment*</u>
Students were informed of the Studies by their instructor of their respective engineering course, ENG1102, Engineering Modeling and Design, and ENG 1002, Intro to Spatial Visualization, and participants signed up for the study through their course's student information system (CANVAS) page. Each participant was assigned a unique code for later data de-identification. Participants signed up for an hour-long session, each with four time slots. They were seated in a small lab and adjoining office space, each at a laptop computer with a mouse, with this researcher and a lab assistant.

	Study 1A- High Spatial Skills	Study 1B- Low Spatial Skills
Gender	M=19, F=11(N = 30)	M=7, F=19 (N = 26)
Majors	Geospatial, Mechanical, Computer, Biomechanical, Robotics, Electrical, Environmental, and Chemical Engineering, and Engineering Management	Civil, Robotics, and Biomedical Engineering, Engineering Management, General and Mechanical Engineering, Human Biology, Electrical Engineering, Material Science, Environmental

		Engineering, Mechatronics, and Audio Production

Table 2
Comparison of demographics between Study 1A and 1B

Upon completion of a consent form, students completed a brief demographic survey.
Each participant in the study was logged in to the PEBL Platform, an open-source program downloaded from it, using a unique code. Each was given brief instructions on how to start the series of assessments and to follow the instructions for each assessment. Each participant took approximately 55 minutes to complete the set of evaluations, which included the novel Spatial Grid Drawing Task, the Corsi Block Task, Luck-Vogel, the Manikin task, a move-to-target task, a maze, a traveling salesperson task, a 2D object judgement task, and a rotation task.

Each participant completed a battery of spatial skill assessments (See Table 1) compiled from the Psychology Experiment Building Language (PEBL) platform [20]. All assessments were timed. The following is a list of the assessments included in the battery used in Study 1A, some of which are shown in Figure 2. Two assessments were removed from the battery for Study 1B, maze and move-to-target, as they did not add any information during the analysis of data.

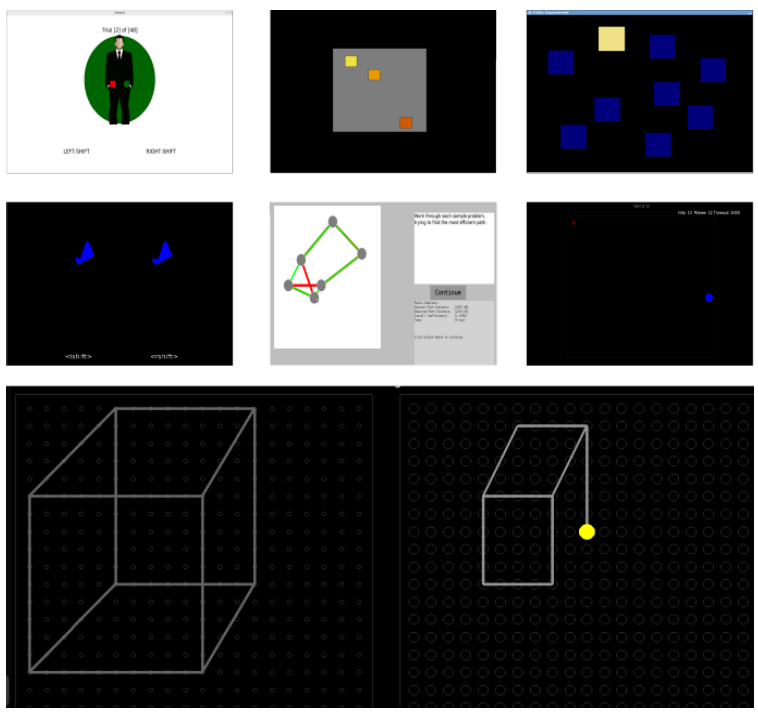

Figure 2:
Screenshots of 7 of the spatial test battery tasks used in Study 1B., including from top left Manikin (3D rotation), Luck-Vogel, Corsi, Object judgment (2D rotation), TSP, move-to-target, and the novel Spatial Grid Drawing Task. Removed after Study 1A: maze task (not shown) and move-to-target.

Digital scoring of the Spatial Grid Drawing Task was developed in R Studio (see Figure 3). Two options were examined: comparing full-line drawings to the standard (shown on the left in Figure 3) and comparing partial-line drawings to the standard (shown on the right in Figure 3). Complete line scoring yielded a lower overall score and fewer opportunities to capture partially correct lines. Some participants drew their line one segment at a time, resulting in errors on the full-line scoring method. Researchers reviewed the results of each method to assess whether the scoring was accurate and made sense. Partial-line scoring was selected for these studies to more accurately measure and represent correctly drawn segments.

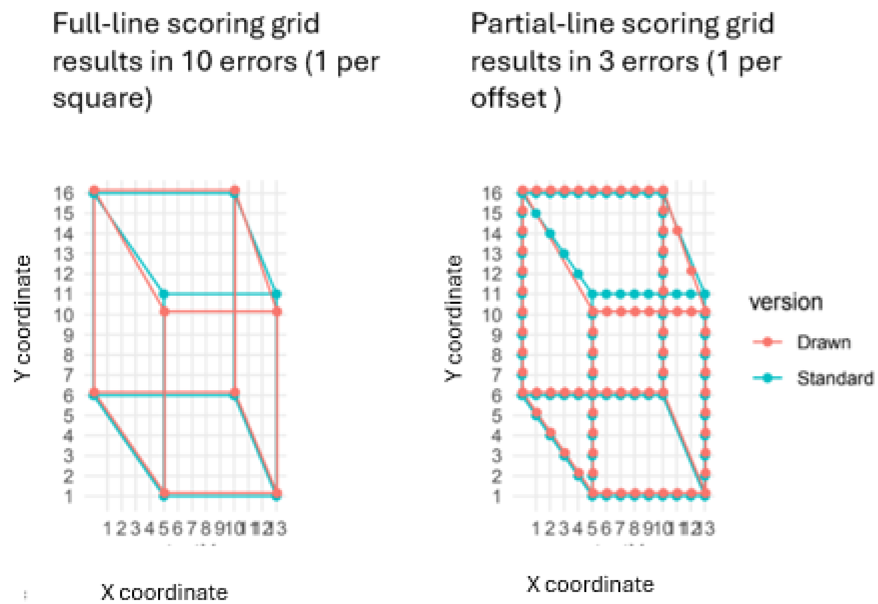

Figure 3:

Example of scoring using R Studio to compare the object as drawn to the standard (correct). The correct lines are shown in light blue, and the lines as drawn by each participant are shown in pink.

In study 1B (low spatial skills), each participant took approximately 45 minutes to complete the set of evaluations, which included the novel Spatial Grid Drawing Task, the Corsi Block Task, Luck-Vogel, the Manikin task, a traveling salesperson task, a 2D object judgement task, and a rotation task. The move-to-target and maze tasks were removed from Study 1B because they did not add any variability to the data in Study 1A (high spatial skills). The move-to-target task results, which require motor skills, were negatively correlated with the PSVT: R, indicating that faster motor skills resulted in better scores on mental rotation.

<u>Results:</u>

The data from the two studies, Study 1A (high spatial skills) and 1B (low spatial skills), were combined for analysis. All spatial skills were found to be related, with correlations ranging from low to moderate. The PSVT: R scores were moderately correlated with the Spatial Grid Drawing accuracy ($r = 0.56$; see Figure 4). First, we obtained the accuracy scores from each test (excluding the PSVT: R) and ran a MANOVA to determine whether the two studies (1A vs. 1B) differed across these measures (excluding the Spatial Grid Drawing task). The results showed that Study was a significant predictor (Pillai's statistic = 0.46; $F(7, 38) = 4.7$, $p < .001$), indicating that high- and low-ability students performed differently on this set of spatial measures.

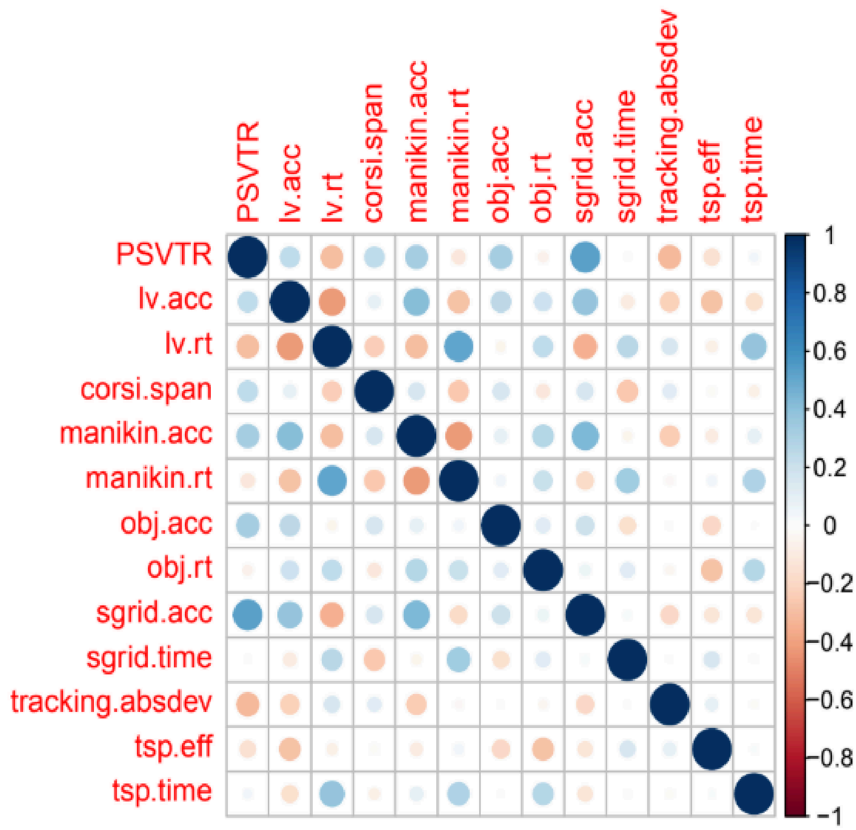

Figure 4:
A correlational plot combining Study 1A (high spatial skills) and 1B (low spatial skills) indicates that all measures in the spatial skill battery were low to moderately correlated with PSVT: R, and PSVT: R was moderately correlated with Spatial Grid accuracy (rho = 0.56).

Next, we used a regression-style model to predict PSVT: R using R scores from the other tests' accuracy scores. A Type-II ANOVA showed that the motor tracking absolute deviation score significantly predicted PSVT: R ($F(1,39) = 4.1$, $p = 0.049$). The correlation between motor tracking and PSVT: R was -0.32. Most of the other tests also showed small-to-moderate correlations with PSVT (around 0.25 or higher), except for the TSP (see Figure 4).

We also found that the two factors were moderately related ($r = -0.395$). One factor was strongly linked to PSVT: R and Spatial Grid Drawing accuracy, while the other factor was more strongly linked to the spatial working memory task, the manikin mental rotation task, and Spatial Grid Drawing accuracy. This suggests that PSVT-R and the Spatial Grid Drawing task overlap in what they measure, but the Spatial Grid Drawing task also captures additional aspects—especially skills related to visual memory and the construction of 3D mental representations.

The findings of this study support the three hypotheses:

H1: Supported
Productive and receptive spatial skills assessment results are moderately correlated.
We found a moderate correlation between PSVT: R and Spatial Grid Drawing scores ($r = 0.56$).

H2: Supported
All spatial skills assessed are related and moderately correlated.
Two factors identified are moderately related ($r = -0.395$).

H3: Supported
Productive spatial skills are distinct from receptive spatial skills, and assessing them provides unique additional information for the instructor and student after receptive skills are accounted for.

Conclusion:
Results from receptive and productive spatial skills assessments are moderately positively correlated. While receptive measures may be reliable and valid, productive spatial skills are also essential in many skilled professions, including engineering, architecture, manufacturing, assembly, aerospace, and medicine, where abstract spatial skills are used to draw, design, assemble, model, and code. Many of these disciplines use traditional receptive spatial measures for selection and assessment only, but a digital drawing assessment requires a demonstration of encoded spatial abilities, rather than a multiple-choice format that must factor in guessing. If productive and receptive spatial skills are the same, this would be acceptable. However, this research shows that productive skills provide unique insights beyond traditional receptive spatial assessments and can be measured and scored digitally.

This work suggests that spatial ability comprises many distinct constructs, including the productive Spatial Grid Drawing Task, spatial working memory, visual-motor skills, and others. We are currently pursuing the following steps: developing a more formal, productive measure, conducting psychometric assessments, and evaluating it in the first-year engineering classroom to determine its construct validity for engineering students.

The Spatial Grid Drawing Task has the potential to serve as a digitally administered, scored, and time-limited productive spatial skill assessment tool. This measure also has the potential to provide information for engineering educators, indicating a specific skill level rather than merely predicting future potential in STEM during initial assessment. It may be useful for instructional planning and for pre- and post-instruction assessment, since we know that spatial skills can be improved with a variety of instructional strategies and curricula, including but not limited to hand-drawing of engineering drawings. Students who are assessed using this tool will have concrete feedback about their ability to perform productive spatial tasks, will have a clear understanding of what they can do to improve their skills, and may have an increased motivation to obtain those skills before advanced work in their field, ie. CAD, computer coding, print reading, etc.

Beyond the academic setting, the Spatial Grid Drawing Task also has potential in real-world applications in careers that require spatial skills, such as manufacturing, construction, and military fields. For example, a productive assessment could be used in hiring and placement decisions for positions in manufacturing that require print-reading to machine and assemble parts. It may also be useful in medical fields, such as dentistry, which currently uses receptive spatial skill assessments only for acceptance into dental programs.

Limitations of the current study include relatively small sample sizes in the high- and low-spatial ability groups from engineering education courses. Future research should include larger sample sizes of students from various STEM domains, various career fields, and across a range of ages, including middle and high school students. Also, the initial design of the Spatial Grid Drawing Task required orthographic copying of 2D objects without the opportunity to rotate objects or draw isometric projections. Future studies will include a modified Spatial Grid Drawing Task with orthographic and isometric drawings with rotations.

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