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Isometric Projection as a Threat to Validity in the PSVT:R

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Abstract

This work describes a study of graphics interpretation in a common test of spatial ability, the Purdue Spatial Visualization Test: Rotations (PSVT:R). Tests of spatial abilities have long been considered to assess a cognitive ability of manipulating shapes in the mind's eye, and are often used for student assessment in engineering educational contexts. However, researchers are increasingly finding that some widely-used assessment instruments are confounded by other factors that do not necessarily fit within the confines of the traditional understanding of spatial ability. The purpose of this study is to investigate the images used as stimuli in the revised PSVT:R to determine whether they are naturally perceived as three-dimensional forms. The PSVT:R utilizes black and white isometric line drawings of shapes of various complexity, which test takers are supposed to "mentally rotate" into different orientations and select the correct view of the shape from an answer bank.

Some researchers have suggested that the isometric shapes on the PSVT:R can look confusing and can be mistaken for flat patterns instead of 2D images. Hoffman's rules related to the principles of generic views explain why many of the shapes would be difficult to interpret as 3D forms. For example, lines that would not be coinciding in 3D coincide in the isometric drawings in the PSVT:R.

In our study, we showed a subset of the shapes on the revised PSVT:R to a group of 111 engineering students enrolled in an introductory engineering graphics course, and had them perform a sorting task to determine which shapes they viewed as real 3D shapes and which they did not. Our results showed that at least 19% of the answer bank shapes in the PSVT:R were not viewed as real 3D shapes by most participants, and at least 38% were not viewed as real 3D shapes by some participants. We conclude that the use of isometric views in the PSVT:R presents a threat to instrument validity if the test is to be considered to assess mental rotation ability. Performance on the test is likely impacted by the test-taker's acquired knowledge of the conventions of isometric drawing in the Cartesian coordinate plane and the use of deductive reasoning to relate ambiguous generic views to 3D forms.

Introduction

Spatial ability is a broad term encompassing various skills related to mentally visualizing and manipulating three-dimensional (3D) space. Spatial skills are important for success in science, technology, engineering, and mathematics (STEM) disciplines, and are used by STEM professionals to solve problems in the real world [1]. Performance on spatial ability assessments is correlated with selection and performance in STEM courses [2].

Though spatial ability testing has a long history, more recently, many researchers are finding that some widely-used spatial tests are confounded by other factors that do not necessarily fit with the traditional definition of spatial ability. This paper discusses a potential limitation of the Purdue

Spatial Visualizations Test of Rotations (PSVT:R) [3], which was designed to measure spatial ability, and is one of the most commonly used tests of spatial ability in engineering design graphics research [4].

The PSVT:R consists of 30 multiple-choice questions that are presented in an analogous format. The test-taker needs to first assess the degree and direction of rotation that the primary shape moves from its first position to its second position. Then, this same rotation should be applied to the shape in question, and the answer choice selected that represents the correct rotated position for that shape. An example problem from the PSVT:R is shown in Figure 1.

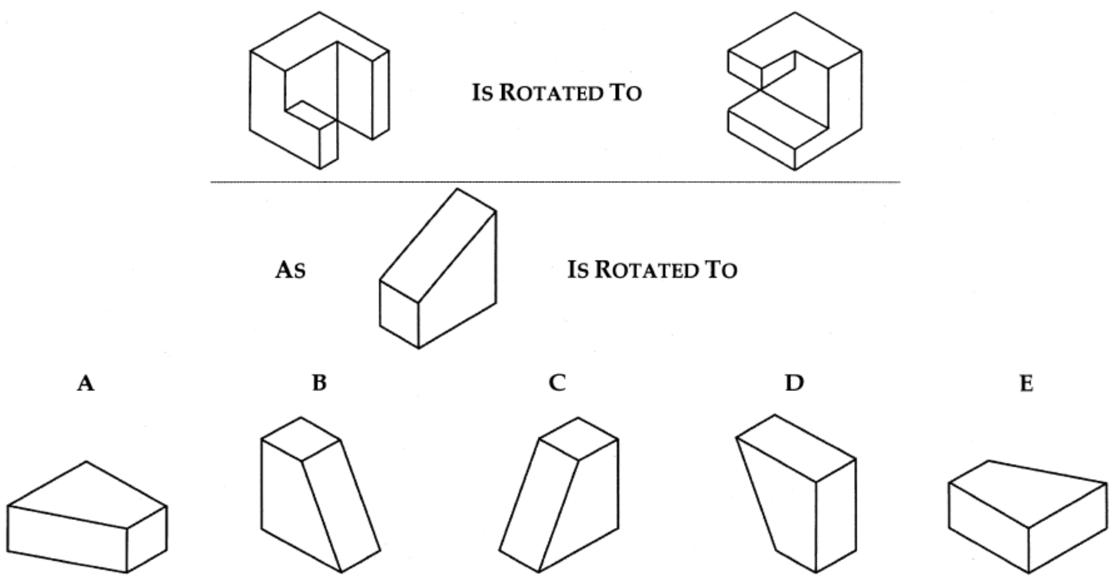


FIGURE 1. EXAMPLE PROBLEM FROM THE REVISED PSVT:R [5]

The PSVT:R depicts shapes using isometric projection, a method of representing three-dimensional shapes in two dimensions. Isometric projections are commonly used in engineering drawings or technical drawings [6], but do not naturally replicate human vision the way that perspective drawings do [7]. Isometric projections are parallel projections, meaning the main axes of a shape are all parallel or perpendicular to the picture plane [7]. Based on informal exit interviews with subjects, Branoff [8] reported that subjects taking the PSVT:R assessment interpreted some of the images on the PSVT:R as "two-dimensional patterns" rather than three dimensional objects [8]. This study seeks to formally test whether some of the shapes in the PSVT:R are more likely to be interpreted as 2D patterns rather than 3D shapes.

Review of Literature

The creator of the PSVT:R claimed that the test uses "holistic" or "gestalt" processing, and that this processing style "has been widely accepted as the key cognitive component of spatial ability" [9]. They defined Gestalt processing as occurring "when an individual forms and transforms visual images as an organized whole – in much the same way that one recognizes faces," versus analytic processing, which would involve breaking the "whole" into individual parts [9].

If the PSVT:R relies on "gestalt processing" as defined by Bodner & Guay [9], one would expect the images in the instrument to be intuitive to interpret. However, this is not necessarily the case. Researchers studying the PSVT:R have encountered many problems with the instrument, often connected to the isometric presentation of the shapes. Yue [10] noted mistakes in the isometric drawings in 7 of the 30 items of the instrument, including missing features, extra features, or misrepresented features of the shapes [10]. In 2011, Yoon created a revised version of the instrument in which those errors were corrected [11]. The revised version continues to present the shapes in isometric views, but isometric views have been criticized for their ambiguity, as some viewers may interpret them as 2D patterns rather than 3D shapes [8, 10]. Takahashi & Connolly [12] determined that solving items on the PSVT-R test may require an initial step to recognize and comprehend each 3D model, and proposed that this may be "a separate spatial task on its own" [12].

A few efforts have been made to make the stimuli in the PSVT:R more clear, including the addition of a coordinate axis [13], use of trimetric projections [8], or the use of computer rendered shapes [14], all of which led to at least some level of improvement in scores. The revision from isometric to trimetric projections also led to a significant decrease in time needed to complete the test [8]. Time has been found to impact performance on the PSVT:R, and a meta-analysis found that gender differences on the PSVT:R were greater under stricter time limits [15]. Though the authors of the meta-analysis speculated that "anxiety for completing the test on time" might have been to blame [15], we wonder if having more time to complete the test enabled more participants to decipher unclear stimuli and answer more questions correctly.

In their initial experiments on mental rotation, Shepard & Metlzer found a linear relationship between the time it took subjects to solve questions, and the degree of rotation required for the shapes in question [16]. However, in the case of the PSVT:R, complexity of rotation is not the only variable that explains the item difficulty perceived by respondents [5]. Instead, the complexity of the 3D objects may contribute to item difficulty [5]. According to the findings of a factor analysis, the PSVT-R cannot be considered a single-construct measure of mental rotation ability [17, 18].

In general, performance on spatial ability assessments has been shown to improve with practice [19]. Background experience with engineering graphics appears to impact performance on the PSVT:R, and people who had taken courses or had job-related experience that dealt with projection drawings performed better on the PSVT:R than novice learners who had not had these training experiences [4]. If interpreting the shapes in the instrument is something that makes the test more difficult for some individuals, it would make sense that people with prior graphics training would perform better, as they might have an easier time interpreting the isometric drawings.

Hoffman's rules related to the principle of generic views explain why some of the shapes in the PSVT:R might be difficult to perceive as 3D objects. Multiple shapes in the PSVT:R may encounter issues because of these three rules: rule one, "always interpret a straight line in an image as straight in 3D" rule two, "If the tips of two lines coincide in an image, then always interpret them as coinciding in 3D," and rule three, "we interpret lines collinear in an image as collinear in 3D" [20]. Figure 2 shows an example of a shape from the PSVT:R with properties related to these rules. Figure 2A shows answer choice option 8c from the PSVT:R. The red highlighted line in 2B shows lines that are depicted as collinear in the image, meaning they would be interpreted as colinear in 3D, but these lines are not actually collinear in the 3D shape. Figure 2C shows a red circle around a vertex where the tips of multiple lines coincide in the 2D drawing, meaning they would be interpreted as coinciding in 3D, but these lines do not all coincide in 3D.

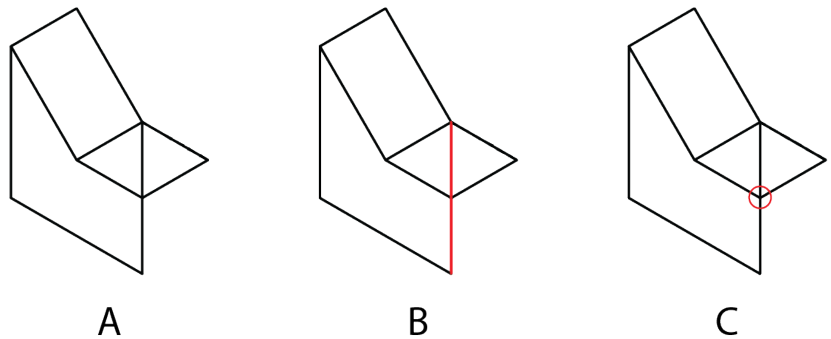


FIGURE 2. VISUAL PROBLEMS WITH ANSWER CHOICE OPTION 8C FROM THE PSVT:R (FIGURE A FROM YOON [11], B AND C CREATED BY THE AUTHORS).

Figure 3 shows a perspective-view rendering of the same shape, rotated slightly. In this view, we can see that the problems depicted in Figure 2 no longer apply.

Another attribute of some PSVT:R shapes that may make them harder to interpret as 3D shapes is the fact that the isometric viewing angle can cause some features to "disappear." For example, the shape shown in figure 4 contains a triangular prism on the lower half, but from this angle, the lower point of the diamond shape appears to have no thickness, like a sheet of paper.

FIGURE 3. PERSPECTIVE-VIEW RENDERING OF SHAPE SHOWN IN ANSWER CHOICE 8C FROM THE PSVT:R (CREATED BY THE AUTHORS).

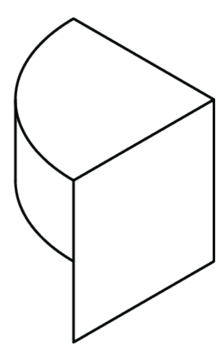


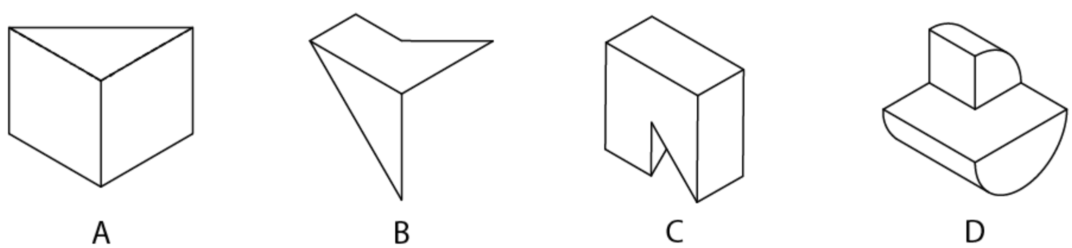
FIGURE 4. ANSWER CHOICE 9B FROM THE PSVT:R [11].

Methods

We identified shapes from revised PSVT:R [11] likely to have the potential interpretation issues above as depicted in Figures 2 and 4. We identified 74 shapes, but due to a mistake in setting up the experiment in the software, only 72 shapes were included in our study. These 72 shapes represent 30% of the shapes in the PSVT:R instrument. We hypothesized that most people would not interpret at least some of these 72 shapes as “real 3D solid shapes.” We elected to not place all 240 shapes in the PSVT:R in the assessment to avoid making the task overly burdensome or boring for participants, so we focused only on the shapes that we identified as having potential interpretation issues.

The instructions provided to participants are shown in Figure 5. In Figure 5, shapes A, C, and D are shapes from the PSVT:R, and shape B is a shape from the PSVT:R with a line removed to ensure that it does not look like a real solid 3D shape.

You will be shown a series of shapes and asked to identify whether or not you perceive each one as a real 3D solid shape. There are no right or wrong answers, different people may see the shapes differently. Here are some examples of the kinds of images you will be asked about:



From the images above, I would choose "real 3D solid shape" for A, C, and D, but I would choose "not a 3D solid shape" for B. I see shape B as two flat sides joined at an edge, not as a solid 3D shape. Only select "Real 3D solid shape" if you see the entire shape as a solid object.

FIGURE 5. INSTRUMENT INSTRUCTIONS PROVIDED TO PARTICIPANTS

Participants were then presented with groups of 7 to 10 shapes at a time, and used a drag-and-drop software interface to drag the shapes into the categories “real 3D solid shape” and “not a 3D solid shape.” The participants in the study were 111 undergraduate students taking a computer-aided design course. The students were majoring in various disciplines of engineering. The participants completed the task for course credit.

Results

For each shape shown in our experiment, we calculated the percentage of participants who selected “not a real 3D solid shape.” On the one hand, we could conclude that any time a single person responded “not a real 3D solid shape,” that would indicate that at least some people have difficulty seeing the shape in question as a real solid shape. To account for possible sources of error in responses, we took the more conservative approach of counting the number of shapes for which at least 5% of participants responded "not a real 3D solid shape." We also counted the number of shapes for which at least 50% of respondents said "not a real 3D solid shape," as this would suggest that most people don't naturally see the shape as 3D.

Our results showed that 57 of the 72 shapes we showed in the task, representing 24% of the shapes in the PSVT:R overall, were not viewed as solid 3D shapes by at least 5% of participants. In the PSVT:R, each question contains eight shape images overall, five of which are in the answer bank (see Figure 1.) These 57 shapes comprise 38% of the overall answer bank options. Twenty-nine of the 72 shapes, comprising 12% of the shapes in the instrument overall, were not viewed as solid 3D shapes by at least 50% of participants. These 29 shapes comprise 19% of the overall answer bank options. Results are summarized in Table 1.

TABLE 1. PERCENTAGES OF SHAPES THAT WERE NOT SEEN AS A REAL 3D SHAPE. N =111

	Percent of respondents who answered "not a real 3D solid shape"	
	≥ 5%	**≥ 50%**
All shapes in instrument	24%	12%
Shapes in answer options	38%	19%

Figure 6 shows a few of the shapes from the PSVT:R which were seen as 3D solid shapes by fewer than 10% of participants.

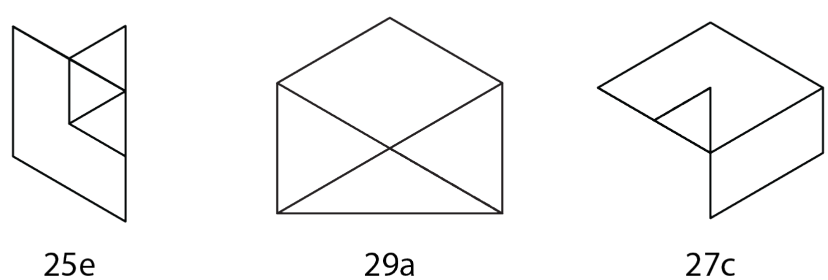


FIGURE 6. SOME OF THE PSVT:R ANSWER OPTIONS WHICH WERE LEAST LIKELY TO BE VIEWED AS "REAL 3D SOLID SHAPES"

Question 8 in the PSVT:R, shown in Figure 7, was found to have problematic shapes in four out of the five answer options. Fewer than 5% of participants saw answer options B, C, and D as real 3D shapes, and only 39% of participants saw option A as a real 3D shape. The correct answer for this question is option E.

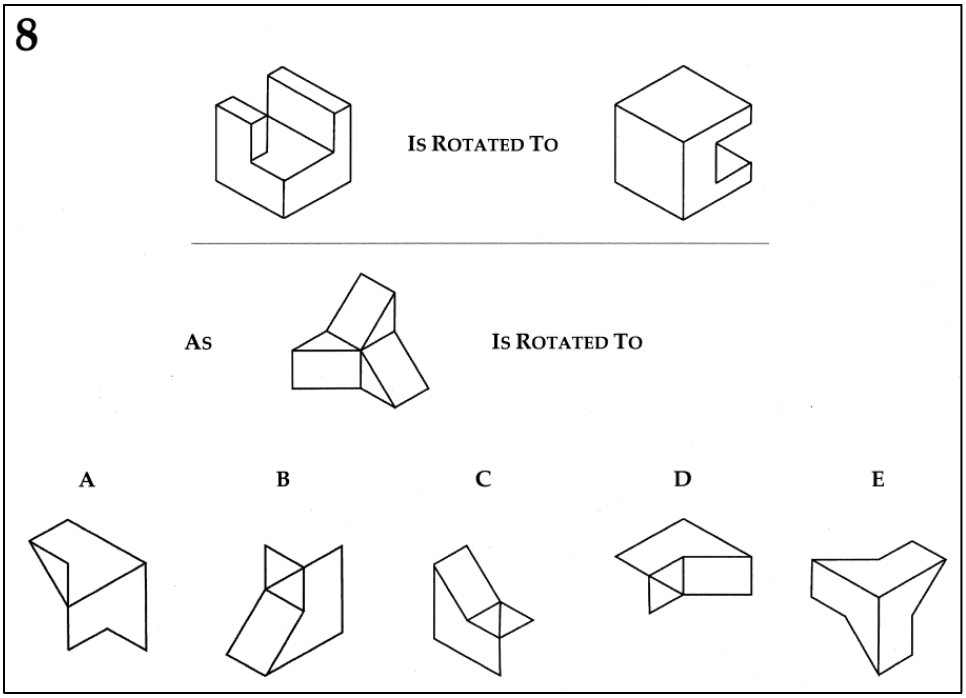


FIGURE 7. QUESTION 8 IN THE PSVT:R TEST

Discussion and Conclusions

If it is true that the PSVT:R elicits Gestalt processing the same way that that one "recognizes faces" [9], we would expect the shapes in the test to be intuitive to recognize, which is not supported by this study. Our findings suggest that the PSVT:R actually contains shapes that are not easy to recognize. The fact that 38% of the answer-bank shapes were not seen as "real 3D solid shapes" by at least some people and 19% of the answer-bank shapes were not seen as "real 3D solid shapes" by most people is a threat to the validity of the PSVT:R. Our findings align with Branoff [8] who found in informal exit interviews that students were confused by some of the shapes in the test and interpreted them as 2D rather than 3D [8]. The confusing shapes present in the instrument may explain, at least in part, why complexity of rotation is not the only variable that explains the item difficulty [5], and why the PSVT-R was not found to be a single-construct measure of spatial ability [17, 18].

It is important to note that all the answer choice items in the PSVT:R are technically correct isometric projection drawings of the shape in question rotated to different positions. Therefore, one cannot actually eliminate an answer choice based on appearance alone, one can only eliminate an answer choice based on its position or rotation. However, many test-takers may not be aware of this fact. In some cases, eliminating the "not real 3D shapes" could lead to the elimination of the correct answer. In other cases, eliminating the "not real 3D shapes" shapes may end up helping the test-taker narrow down the options more quickly to find the correct answer, provided the correct answer looks more like a 3D shape than do the distractors. This is likely to be the case in question 8, which, based on the complexity of the rotation, would theoretically be one of the more difficult items on the test. In the original test, Guay ordered the items based on degree of rotation and the number of rotations required to solve the spatial task, and this item was placed number 24 out of 30 [5]. However, Yoon [5] found this item was among the easiest according to how participants perform on the instrument, so she moved the item to position 8 when reordering the questions in the revised instrument in order of item difficulty based on item-response theory [5]. We suspect that part of the reason that item 8 is easier than theoretically expected is because of the appearance of the answer choice options.

Given the findings of this study, we question whether the PSVT:R is an appropriate instrument to assess the construct of mental rotation. Performance on the test is likely impacted by the test-taker's acquired knowledge of the conventions of isometric drawing and the use of deductive reasoning to relate ambiguous generic views to 3D forms. It is unlikely that someone who is unfamiliar with the conventions of isometric projection would be able to answer all the questions correctly, because even if they envisioned the correct rotation of the shape, they may not be able to identify the correct answer. Some people who have a good level of understanding of the conventions of isometric projection may not have difficulty seeing all the answer choices as different rotations of the model shape. More research is needed to understand how the lack of a natural 3D appearance of some answer choice shapes affects test outcomes. If researchers want to continue using the PSVT:R to assess spatial abilities in general, a revised version with more realistic, natural-looking projections may yield more accurate results. We propose making a revised version of the instrument using computer rendered shapes like the one shown in Figure 3, or like the rendered shapes used by Yue [14]. We plan to repeat this study with a larger number of participants, as well as to develop and test a revised instrument with more natural-looking shapes.

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