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# Visualizing cross sections: Training spatial thinking using interactive animations and virtual objects☆

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A B S T R A C T

In two experiments, we investigated the efficacy of a brief intervention that used interactive animation to train students to infer the two-dimensional cross section of a virtual three-dimensional geometric figure. Undergraduates with poor spatial ability were assigned to receive the intervention or to a control group. Compared to the control group, trained participants improved significantly on stimuli viewed during the intervention and demonstrated transfer to untrained stimuli. Results were considered with respect to two accounts of performance gains and transfer after spatial visualization training, an instance-based account and a process-based account. The instance-based account attributes performance gains to a larger store of memories and predicts no transfer to new stimuli or new spatial processes. The process-based account attributes performance gains to increased efficiency of mental processes and predicts transfer to new stimuli and tasks that share the same mental processes. The results of these experiments cannot be accounted for by an instance-based account alone. Performance gains and transfer in these experiments suggest that interactive animation and virtual solids are promising tools for training spatial thinking in undergraduates.

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## 1. Introduction

A geology student observes an outcrop of rocks and tries to visualize the cross-sectional structure of the landforms beneath it. An anatomy student examines a two-dimensional slice of liver tissue, notes its key spatial features, and infers that it is a longitudinal, rather than lateral section of the organ. A mechanical engineering student sketches a schematic diagram of a building's heating and electrical systems, anticipating the angles at which exhaust vents and electrical cables will cross. Each student is using spatial thinking skills to mentally represent a two-dimensional cross section, or slice, of a three-dimensional object or structure. The ability to infer the external shape and internal features of sections of objects and structures plays an important role in many domains of scientific thinking. It is a fundamental skill in geology, where it has been referred to as “visual penetration ability” (Kali & Orion, 1996; Orion, Ben-Chaim, & Kali, 1997). Anatomy students must learn to visualize, section, and rotate cross sections of physical structures, and learn to recognize these structures (Chariker, Naaz, & Pani, 2011; Rochford, 1985; Russell-Gebbett, 1985). In order to comprehend and use technologies, such as X-rays and magnetic resonance imagining (MRI), radiologists and other medical professionals must learn to infer the shapes of cross sections (Hegarty, Keehner, Cohen, Montello, & Lippa, 2007). Furthermore, understanding the cross-sectional structure of materials and mechanisms is a fundamental skill in engineering (Sorby, 2009).

On face value, identifying the cross section of a three-dimensional object appears to require spatial visualization abilities, which were characterized by Carroll (1993) as ability to encode spatial information and maintain it in working memory while transforming it. Previous studies determined that the ability to infer a cross section of an object is positively correlated with spatial visualization ability (Cohen & Hegarty, 2012; Kali & Orion, 1996; Keehner, Hegarty, Cohen, Khooshabeh, & Montello, 2008). Unfortunately, not all individuals are equally equipped with spatial visualization ability. There are large individual differences in spatial abilities (Hegarty & Waller, 2005; Voyer, Voyer, & Bryden, 1995), as well as evidence that deficits in spatial thinking affect high school and university students' performance in biology, anatomy, engineering, geology and physics (e.g., Kozhevnikov, Motes, & Hegarty, 2007; Orion et al., 1997; Rochford, 1985; Sorby, 2009). Thus, difficulty in understanding how to infer or interpret cross sections of three-dimensional structures is an example of how individuals with low spatial ability might be at a disadvantage in learning science.

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## 2. Mutability and training of spatial thinking

Piaget proposed that children develop spatial thinking skills by physically interacting with objects in their environment (Piaget & Inhelder, 1967). Meta-analyses investigating the malleability of spatial thinking provide evidence that such skills can be improved through training and experience (Baenninger & Newcombe, 1989; Linn & Petersen, 1985; Uttal et al., 2013). This evidence has led U.S. scientists and educators to call for systematic education of spatial thinking skills at all levels of education (National Research Council, 2006, p. 10).

Questions remain about how to best train spatial thinking skills and the nature of the learning that occurs as a result of training. Which tools and instructional methods lead to performance gains and transfer? What are the psychological mechanisms that account for improved performance and transfer after training? Motivated by evidence for the mutability of spatial thinking and by a need to develop new methods to train spatial thinking skills, we developed a brief intervention to train cross-sectioning skill. The stimuli in our experiments are derived from simple geometric solids (cone, cube, cylinder, prism and pyramid), which are among the most elementary recognizable three-dimensional forms (Biederman, 1987; Pani, Jeffries, Shippey, & Schwartz, 1996). We hypothesized that effective training for this task would permit participants to discover and encode the shapes of two-dimensional cross sections of geometric solids. We evaluate different accounts of what is learned from this training.

## 3. Cognitive analysis of the criterion task

In our experiments participants are asked to predict the two-dimensional cross section that will result when a simple or complex geometric solid is sliced by a cutting plane (see Fig. 1). Individuals can accomplish spatial thinking tasks such as this by using an imagistic approach (forming and manipulating mental images), and/or by using analytic strategies, such as comparing the features of two stimuli (Cohen & Hegarty, 2007, 2012; Hegarty, 2010; Schultz, 1991). Here we propose an informal task analysis of the steps in an imagistic approach to perform this task. One step is to encode the spatial characteristics of the figure, such as the shape of the geometric solid and the orientation of the cutting plane. Another step is to imagine slicing the object and removing the section of the sliced geometric solid between the viewer and the cutting plane. A further step is to create an image of the cross section of the geometric figure from an orientation that is orthogonal to the cut surface. We hypothesized that this step could be accomplished by mentally rotating the visualized cut geometric figure, by changing view perspective, or by retrieving from memory an image of a cross section of a similarly shaped object. In summary, mentally representing the cross-section of an object is a multi-step process. The sequence of the proposed steps may vary by individual.

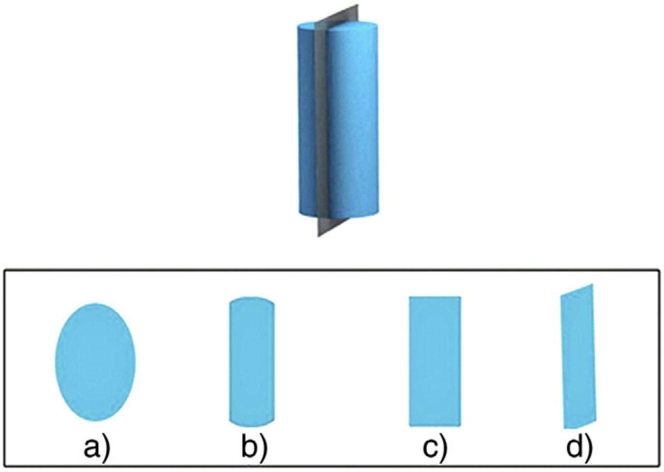

**Fig. 1.** Sample cross-section test problem. The participant is asked to choose the cross-sectional shape that would result from the intersection of the cutting plane and the geometric solid. The correct answer is (c).

Visuospatial working memory is the cognitive system that facilitates the formation and manipulation of mental images, and the ordering of steps in complex spatial visualization tasks. (Baddeley, 1992; Miyake, Rettinger, Friedman, Shah, & Hegarty, 2001). Theories of mental imagery suggest that spatial visualization ability can be characterized as differences in the ability to encode, retrieve from long-term memory, or transform mental images through dynamic mental processes, including rotation, translation, scanning and parsing (Kosslyn, Brunn, Cave, & Wallach, 1984). One possibility is that individuals with limited visuospatial ability have had less experience encoding and manipulating spatial images. As a result they might have a limited store of spatial images in long-term memory. They might also be less facile in basic imagery processes such as rotation and parsing. Here we examine how experience interacting with a virtual model affects both storage and processing of visuospatial stimuli.

## 4. Accounts of improved performance after spatial training

Studies in cognitive psychology and education show support for two accounts of the nature of learning after spatial visualization training. An *instance-based* account proposes that performance gains reflect an increased store of images accumulated during training (Heil, Rosler, Link, & Bajric, 1998; Kail & Park, 1990; Sims & Mayer, 2002; Tarr & Pinker, 1989). For example, Heil et al. (1998) and Tarr and Pinker (1989) found that training on mental rotation problems improved performance only on trained objects at their trained orientations. Sims and Mayer (2002) found that practice on Tetris, a computer game that involves the mental rotation of specific shapes, did not transfer to other mental rotation stimuli. Kail and Park (1990) found that practice on two-dimensional letter rotations did not transfer to mental rotation of unfamiliar letters. The authors accounted for these results by reference to *instance theory* (Logan, 1988), which proposes that practice on a task increases the strength and/or the number of memory representations of to-be-learned material, but not the underlying processes governing the transformation. The instance-based account predicts no transfer to new stimuli after training.

The *process-based* account of learning proposes that performance gains after spatial training can be accounted for by enhanced mental processing, rather than just a more robust store of encoded images (Leone, Taine, & Droulez, 1993; Wallace & Hofelich, 1992; Wright, Thompson, Ganis, Newcombe, and Kosslyn (2008). This account predicts wide transfer of the trained processes to new stimuli. For example, Leone et al. (1993) found that mental rotation practice on simple figures transferred to the mental rotation of more complex figures. The authors proposed that participants learned to rotate stimuli around their principal frames of reference rather rotating the entire object or its segments. Wallace and Hofelich (1992) found that mental rotation practice improved performance on a two-dimensional task that did not require mental rotation. Situating their results within Kosslyn et al.'s (1984) model, the authors attributed improvement on the distal task to the fact that it shared mental transformation processes with the trained task. Similarly, Wright et al. (2008) found transfer from mental rotation to paper folding and attributed the transfer effects to participants' improved ability to encode stimuli and initiate the transformation process.

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