Spatial Ability for University Biology Education

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Abstract. Studying and pursuing careers of Science, Technology, Engineering, and Mathematics (STEM) fields demand spatial ability. Completing a university degree in biology is no exception. The aim of this study is to summarize key findings showing that there is a two-way relation between university biology education and spatial ability. The first aspect of this relation is the most investigated: spatial ability facilitates learning biology. However, the other aspect is also possible: learning biology may improve spatial ability. We present empirical evidence to support both possibilities. The focus is on university biology, and the spatial abilities of mental rotation and mental folding (spatial visualization). We present findings showing that these spatial abilities affect university biology learning and achievement from textual and visual materials. We also present correlational studies and experiments showing that university biology learning positively affects mental rotation and mental folding.

Keywords: Biology · STEM · Spatial ability · Mental rotation
Mental folding and spatial visualization

1 Introduction

We know that learning and practicing Science, Technology, Engineering, and Mathematics (STEM) requires high levels of spatial ability [1]. The relation between STEM achievement and spatial ability seems to be stronger in Engineering, Physical Science, and Maths/Computer Science, as compared to Biological Sciences [2]. For example, Hegarty [3] used an on-line instrument to assess the self-rated spatial abilities of over 700 professionals. Notably, biologists rated their spatial abilities as rather low; their self-ratings were comparable to those of the humanities professionals, and markedly lower than the self-ratings of respondents from physics, geosciences, or engineering. Nevertheless, this difference does not mean that studying and pursuing a biology career does not request spatial abilities, as the ratings in this study were based solely on self-assessment. In fact, thriving in university biology demands spatial abilities such as mental rotation and mental folding. Consider three examples: (a) mental rotation is necessary with tasks involving macroscopic and microscopic biology [4]; (b) mental rotation helps in rotating biochemistry and chemistry molecules, and mental folding assists learning about protein structure and folding [5]; and (c) mental rotation aids in the use and understanding of difficult 3D models of animal and plant cells [6].

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However, these spatial abilities not only help in learning university biology, but the other direction of effects may also be observed (see Sect. 4). As such, the aim of this review is to summarize key findings showing the two-way relation between success in learning university biology and spatial ability. Here, we focus on university participants, and the spatial abilities of mental rotation and mental folding, which are described next.

2 Spatial Ability as Mental Rotation and Mental Folding

Mental rotation is the ability to perceive a whole figure and rotate it with the mind [e.g., 7]. There are three-dimensional (3D) and two-dimensional (2D) tests of mental rotation, the former requiring three and the latter demanding only two axes of rotation. Tests to measure mental rotation, both of 3D and 2D objects, typically involve comparing a target shape against "same" (rotated) or "different" (mirrored and rotated) figures. A distinctive feature of mental rotation, reported by Shepard, Metzler [8], is that the greater the difference in angles between the target and the test images to rotate and compare, the longer it takes. In other words, mental rotation may be the mental equivalent of a manipulative rotation.

Mental folding (also known as spatial visualization) employs mental rotation but also additional resources involving mental restructuring and serial operations [e.g., 7]. As reported in Shepard and Feng [9], tasks involving more steps of mental folding will demand more time than tasks that involve fewer folds. Hence, as in mental rotation, mental folding may be the mental equivalent of a manipulative folding.

Because mental folding relies partially on mental rotation, mental folding test scores are usually correlated with mental rotation test scores [10]. For example, in a study with 170 adults [11], there were medium to large correlations (all rs > .45, all ps < .01) between instruments of 3D mental rotation, 2D mental rotation, and mental folding. Similarly, Vandenberg and Kuse [12] investigated a large sample of participants, ranging in ages from 14 to 60 years, and reported medium to large correlations (all rs > .39) between tests of 3D mental rotation, 2D mental rotation, and mental folding. Because of the generally high correlations between mental rotation and mental folding, the two abilities are often included in the same category of spatial abilities. For example, a recent meta-analysis [13] incorporated both in the group of *intrinsic* and *dynamic* spatial abilities. Both mental rotation and mental folding are intrinsic because they involve transforming mentally the properties of an object, so is an intrinsic manipulation to that object. Both abilities are dynamic because the object must be imagined in motion, such as with rotations or folds.

Despite the similarities, mental rotation and mental folding do differ [10]. An important difference [14] is that mental rotation is a rigid body mental transformation (the distances between the points of the objects are preserved), whereas mental folding is a non-rigid body mental transformation (the distances between the points of the objects can be changed). Another important difference is that men generally perform substantially better than women on mental rotation, but the sex difference is smaller for mental folding tasks [see 15].

Standard instruments that measure 3D mental rotation are: (a) the Mental Rotations Test, (b) the Cube Comparisons Test, and (c) the Purdue Visualization of Rotations. The

Mental Rotations Test was developed by Vandenberg and Kuse [12], employing shapes like those used by Shepard and Metzler [8]. Every item of this instrument presents an abstract 3D shape, like a "Tetris" blocks, and four comparable images at the side. The task is to mark which of the response options are a rotated version of the target. The other two shapes, which are both rotated and mirrored versions of the target, should not be marked, as they are incorrect (see Fig. 1a). The second standard 3D instrument, the Cube Comparisons Test, was included in the battery of Ekstrom et al. [7]. The respondent is asked to compare two cubes with different letters in their faces. The participant must determine if the two cubes are rotated version of each other or entirely different. Lastly, the Purdue Visualization of Rotations was reported by Pribyl and Bodner [16]. Participants are given two identical 3D shapes, one rotated in relation to the other, and they must solve how the volumetric shape was rotated, so they can apply the same rotation to a new shape.

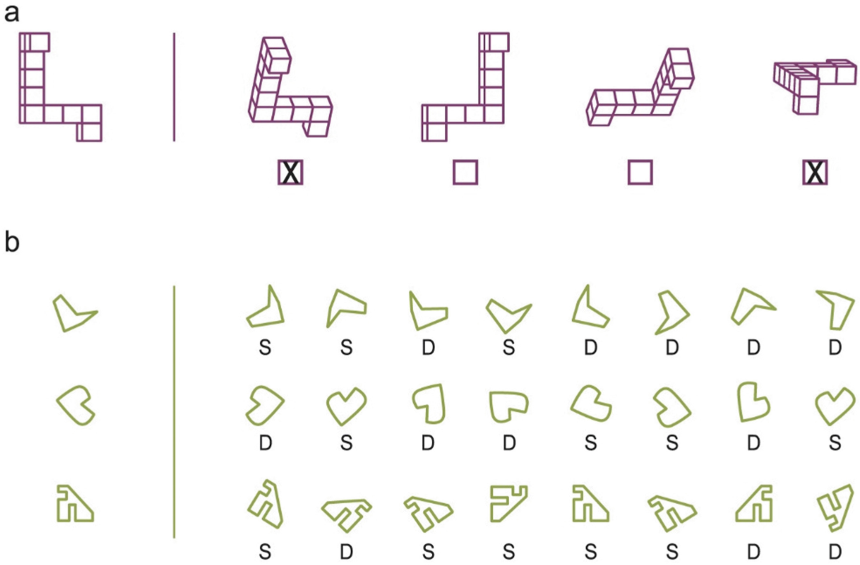

Fig. 1. (a) Adapted item from the Mental Rotations Test. (b) Three items from the Novel Virtual Card Rotations Test. The correct answers in both tests are shown.

Regarding 2D mental rotations, a standard instrument to measure this spatial ability is the Card Rotations Test, which was developed by Ekstrom et al. [7]. Every question of this instrument asks the participant to compare one abstract shape to eight different versions at the side. The task is to judge which of these depictions are the same shape, only rotated, and which are both rotated and mirrored. There is a recent version of this test, the Novel Virtual Card Rotations Test [17], which is computerized and includes new abstract shapes. By clicking the computer mouse, the answer is toggled between S (same) or D (different; see Fig. 1b). In addition, there are several instruments that have been developed to measure 2D mental rotation with original illustrations, including abstract shapes [e.g., 18], molecular diagrams [e.g., 19], and symbolic figures [e.g., 20].

A number of standard tests are used to measure mental folding or spatial visualization. These include the Paper Folding Test and the Surface Development Test, which are both included in the battery by Ekstrom et al. [7]. In the Paper Folding Test, several folds are made to a sheet of paper, and then the folded paper is punctured. The participant's task is to determine how the holes would look when the paper is unfolded, comparing among five alternatives (see Fig. 2). In the Surface Development Test subjects are asked how a 2D flat depiction would fold into a given 3D volumetric shape. Results of these mental folding tests, as those of mental rotation instruments, have been linked to results in university biology education, as described next.

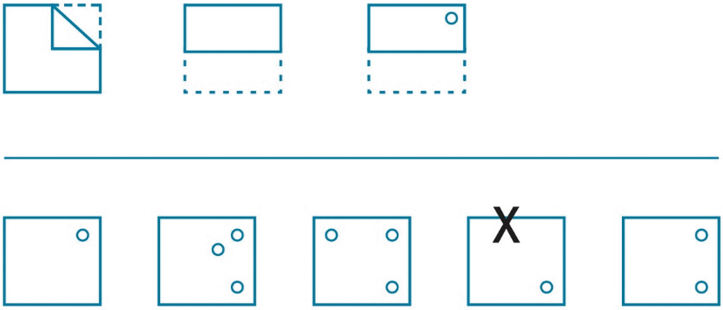

Fig. 2. Adapted item from the Paper Folding Test. The correct answer is shown.

3 Spatial Ability Affects Biology Learning and Achievement

Biology education involves textual (verbal) materials, as well as visualizations. In both cases, spatial ability is an important asset. An example regarding textual information is Fiorella and Mayer [21] study of undergraduate participants learning from text-only passages about the human respiratory system. A composite score of spatial ability was calculated from tests of 3D mental rotation and of mental folding. Results showed that spatial ability was a significant predictor for learning, including measures of retention, transfer, and also drawing. In a related area to biology, that of meteorology [22], two experiments with a total of 144 university students (64% females) assessed learning about the phenomenon known as El Niño. The participants were given textual-only passages of this weather topic, with or without the aid of written analogies. Mental folding scores predicted performance in this weather phenomenon for all learning measures.

In addition to these examples of spatial ability aiding textual understanding, most of the studies involve understanding materials that also include visualizations. For example, the study by Bartholomé and Bromme [23] with 84 university participants (77% females), used an aggregated score of spatial ability. This score, which combined mental rotation and other spatial skills, was significantly corelated with learning multimedia botany. Likewise, Huk [6], investigated 106 high school and university biology students (67% females) learning multimedia cell biology. High 3D mental rotation ability students could learn better with the inclusion of 3D models of the cells, as compared to low mental rotators. A follow-up study [24] was conducted with 112 high school and university biology participants (64% females) learning the same topic. Only high 3D mental rotators befitted from connecting lines designed to help understanding the cellular structures. Another example is provided by Loftus et al. [25]. Investigating 29 adult participants (35% females), the authors produced a split between high and low 3D mental rotators. In this case, those exhibiting high spatial ability could solve human anatomy problems (involving cross-sections, mental rotations, and intersecting planes) better than those with low spatial ability. In the Experiment 2 of the study reported by Mayer and Sims [26], the 2D mental rotation and mental folding of 97 university participants was measured. The students were given a multimedia module of the human respiratory system, in which a short animation and concurrent narration explained the inhaling, exchanging, and exhaling processes. After watching these animations with simultaneous narrations, students were given transfer problems. Participants in the high spatial range outperformed those in the lower side. Experiment 2 in [27] involved 78 university participants (74% females) studying a multimedia presentation about the structure and function of the enzyme ATP-Synthase. Spatial ability, measured with 2D mental rotation and mental folding tests, was a significant predictor of performance in the comprehension and transfer tests. Another example with visualizations comes from Brucker et al. [28], who studied 80 university participants (75% females) learning fish swimming patterns under different presentation conditions. Regression analyses showed that 3D mental rotation was a significant predictor of learning from these visualizations. In the related realm of health sciences [29], 146 anatomy students (50% females) learned from computer visualizations of a human hand model. Scores in a previous 3D mental rotation test were significant predictors of higher grades in the hand anatomy test. Also, in a related area of memorizing symbolic elements [30], it was observed that for 104 university students (50% females), 2D mental rotation could predict their accuracy in these abstract tasks, after studying them from either animated or static presentations. For a last example [4], the 3D mental rotation and mental folding of 250 university students was assessed with standard tests at the beginning of a biology course. Those in the lowest third of spatial ability were divided into experimental and control groups, and the treatment involved spatial activities with volumes and shapes. At the end of the course, students who received spatial training outperformed the control group in the final biology assessments, which involved, among other tasks, the interpretation of graphs and diagrams, and the understanding of macroscopic and microscopic biology.

In short, the evidence, employing educational materials with textual information and visualizations, suggests that spatial ability, as measured through mental rotation or mental folding, supports biology learning. The opposite direction, that of biology knowledge and practice supporting spatial abilities, is described next.

4 Biology Learning Affects Spatial Ability

The potential influences of learning biology on performance on spatial ability tasks has been less investigated than the opposite direction, but evidence is mounting that learning biology does affect mental rotation and mental folding. The literature that shows these effects can be categorized in (a) correlational studies or (b) experiments. Correlational studies show that spatial ability is correlated with biology or science participation. In other words, students from biology or related science disciplines tend to outperform students from different areas in spatial ability tests. For example, Sharobeam [31] investigated university students ($N > 700$) from different majors, mostly from Years 3 and 4. They were measured in a novel test of mental rotations in 2D and 3D. The researchers compared the performance of participants in the science fields (biology, biochemistry, computer science, geology, marine science, physics, others) versus those in non-science fields (business, economics, education, language, literature, philosophy, sociology, others). Science participants (66% correct answers) significantly outperformed non-science students (52% correct). Recruiting a larger number of university students ($N > 2000$), Peters et al. [32] reported analyses of three studies, combining Canadian, German and Japanese samples. When measuring performance on the 3D instrument Mental Rotations Test, participants in the sciences disciplines significantly outperformed students in the social sciences programs, with medium to large effect sizes. These outcomes were observed in each of the three countries.

In general, experimental evidence allows more robust conclusions than correlational evidence. An example of experimental findings is the work of Macnab and Johnstone [33], who investigated the spatial abilities of participants ranging from primary school to the postgraduate level. In addition to reporting an improvement of mental rotation and mental folding with age, the researchers found that these spatial abilities were higher in the participants who had taken biology classes, as compared to students without this academic background. Another example is Lennon [34], who studied the effects of weekly modeling with clay bacteria on three spatial abilities in 59 microbiology undergraduates. Although the effects on mental rotation and mental folding were non-significant, the modeling treatment was effective for the related spatial ability of field independence. In the discipline of human anatomy, which is related to biology, Lufler et al. [35] investigated 255 first-year medicine students who belonged to a gross anatomy course. The semester course included three main sections: head and neck; back and limbs; and thorax, abdomen, and pelvis. Students were required to dissect cadavers and study 2D anatomical images from textbooks and radiographs. For both genders, 3D mental rotation improved from the beginning to the end of the anatomy course. From another related area, that of veterinary science, Provo et al. [36] investigated 128 students (75% females) enrolled in a canine anatomy class. The researchers found that the class was effective in improving the scores in a test of 3D mental rotation.

5 Conclusion

Pursuing university biology education and following a biology career later demand spatial abilities, such as 2D mental rotation, 3D mental rotation, and mental folding. This review showed that the relationship between spatial ability and biology is two-ways: spatial ability can help biology learning and achievement, but also biological knowledge and practice can improve spatial ability. Future research may reveal new variables involved in this two-ways relation.

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