Interdisciplinary Journal of Environmental and Science Education
2022, 18(4), e2288
ISSN 2633-6537 (Online)
https://www.ijese.com
Research Article

Examining Students' Spatial Ability and Its Impact on the Learning of Stereochemistry

Issa I. Salame [1*], Sheikh Aleena Kabir [1]

[1] The Department of Chemistry and Biochemistry, The City College of New York of the City University of New York, New York, NY, USA
***Corresponding Author:** isalame@ccny.cuny.edu

Citation: Salame, I. I., & Kabir, S. A. (2022). Examining Students' Spatial Ability and Its Impact on the Learning of Stereochemistry. *Interdisciplinary Journal of Environmental and Science Education, 18*(4), e2288. https://doi.org/10.21601/ijese/12099

ARTICLE INFO

Received: 6 Apr. 2022

Accepted: 15 May. 2022

ABSTRACT

The subject of stereochemistry in considered a difficult concept in organic chemistry because of its dependence on spatial ability. The challenges that students face in learning about stereochemistry can lead to poor performance and alternative conceptions, which in turn might hinder their progresses in various science and engineering academic careers. Development of successful conceptual understanding to solve stereochemistry related problems requires that students have a thorough understanding of the various types of spatial abilities in stereochemistry such as mental rotation and visualization of three-dimensional chemical molecules. This research project of the City College of New York (a minority serving, public, urban, and commuter institution) investigates some of the challenges that students face and approaches that students rely on to solve stereochemistry related problems and the role of spatial ability in the learning process. Likert-type surveys, spatial ability tests, and various open-ended questions were used to assess the understandings of 86 participants. The data indicated that one of barriers to learning about stereochemistry is the students' inabilities to mentally rotate and visualize three-dimensional molecular structures by looking at their chemical formulae, assigning priority functional groups, determining configurations, and remembering the various rules that are necessary for solving stereochemistry related questions. Spatial ability was found to be one of the factors for success in stereochemistry, and majority of the students believe that with practice and the use of three-dimensional molecular modeling kits, they can improve their spatial abilities in stereochemistry.

Keywords: spatial ability, stereochemistry, organic chemistry

INTRODUCTION

In the early 1927, Spearman (1927) saw special ability as a factor of intelligence that is procured by training or habit and described the term to be "broad enough to include a sphere of mental operations". According to him, special ability is different and independent from mathematical and verbal abilities, and a greater level of spatial ability corresponds to a higher probability of gaining higher education degrees in STEM fields.

Representations of molecular structures, reactions, and theories require spatial ability in almost all fields of chemistry education. For example, in general chemistry, spatial ability is required to learn the VSEPR and molecular geometry, and crystal and lattice structure; in organic chemistry, spatial ability is required to understand the mechanisms of S_N2 reactions, stereochemistry, chirality, molecular representations, and various structural representations such as boat and chair conformers, and in biochemistry, the shape of biomolecules such as proteins and nucleic acids, as well as enzyme substrate reactions require spatial ability (Harle & Towns, 2011).

Students with low spatial abilities find it difficult to mentally process the abstract information in chemical structures into three-dimensional materials (Harris, 2019). Various different abilities are incorporated together in spatial ability. According to Höffler and Leutner (2011), the three main factors in spatial ability are spatial relation (SR), spatial visualization (VZ), and multiple object dynamic spatial ability (MODSA). They defined SR as the ability to be able to rapidly visualize two-dimensional and three-dimensional objects accurately in a single step. They, along with Berney et al. (2015), defined VZ as the ability to transform mental representations and to imagine, encode, and manipulate motion. Finally, MODSA was defined by as the ability to spatial track the movements of an object with time (Harris, 2019).

Over the years, researchers have found that many factors could affect students' spatial abilities. These include age (Hausmann et al., 2000), gender (Jansen & Heil, 2009; Yuan et al., 2019), the learning characteristics of students (Hauptman & Cohen, 2011), their problem-solving strategies (Bilge &

Taylor, 2016), subject anxiety (Ferguson et al., 2015), and negative performance expectations (Tarampi et al., 2016). Learners with low spatial abilities may not be able to process and visualize the spatial information and representations if they are not explained to them enough in the course (Alt & Boniel-Nissim, 2018). These students might be at a disadvantage as they are usually unaware of the tools and methods that can be used improve their spatial abilities.

According to Oliver-Hoyo and Babilonia-Rosa (2017), unequivocal guidance to advance special aptitudes for chemistry and biochemistry students have been gradually increasing, however not at the degree of other psychological abilities of learning. Hence, more research needs to be carried out concerning spatial abilities and its teaching techniques. Research has proved there to be a positive correlation between students' science accomplishments and their special capacities (Hegarty, 2014; Tuckey & Salvaratnam, 1993). Low special ability obstructs cognitive comprehension which hinders scientific accomplishments. Therefore, students need to be explicitly instructed on special abilities.

Difficulties in understanding and interpreting chemistry representations can lead to students identifying chemical concepts at the macroscopic level instead of the microscopic or symbolic level, understanding the visual representations at the macroscopic level, and viewing chemical reactions as a static process (Krajcik, 1991; Nakhleh, 1992). A study found that high school chemistry students have difficulties in translating chemical formula, electron configuration, and ball-and-stick molecular models (Furio et al., 2000). Students also face difficulties identifying molecular structures from given empirical formulae (Furio et al., 2000), and they translated representations based on their conceptual understandings of representation rather than their visuospatial abilities.

Paivio's (1986) dual coding theory states that knowledge is composed of a verbal system and an imagery system. Although being structurally and functionally independent, these two systems are inter-connected to each other (Sadoski et al., 1991). Later research indicated that information is better comprehended and remembered if they are stored in both verbal and imagery systems, rather than in only one of the systems (Sadoski et al., 1993). Moreover, cognitive load during learning could be reduced by providing learners with external stimuli consisting of both types of systems (Yang et al., 2003).

In stereochemistry, students need to analyze the three-dimensional atomic arrangements, mentally manipulate molecular models, and picture them in chemical reactions. One of the variety of tools used to measure spatial abilities include the mental rotation test (MRT) (Vandenberg & Kuse, 1978), which is used for measuring spatial relations (Martín-Gutiérrez et al., 2017; Meneghetti et al., 2016). Spatial abilities can be monitored and improved using potential instruments which could measure eye movement (Chien et al., 2015). When 31 chemistry teachers, and 20 other science teachers were asked in a survey about which of the various models they use for teaching, most of them indicated ball-and-stick model to be the most prevalent model in teaching about simple molecules and organic compounds. According to the survey, 32% teachers used models in cooperative learning, 51% used it in demonstrative learning, while only 17% used it in individualized active learning (Dori & Barak, 2001).

Wu and Shah (2004) reviewed articles on students' visuospatial thinking in organic chemistry, correlation studies on spatial abilities, difficulties understanding visual representations, conceptual errors, and the different visualization tools in chemistry learning. They have suggested five principles for designing chemistry learning tools that could help students to better understand the concepts and improve their visuospatial thinking. The principles are providing multiple representations with descriptions, making the linked referential connections visible, showing both the dynamic and interactive nature of chemistry, showing two-dimensional and three-dimensional transformations, and presenting clear, explicit, and integrated information to students in order to decrease their cognitive loads. According to Wu and Shah (2004), learning tools that can decrease cognitive load will be most beneficial to students with low spatial abilities.

In an attempt to understand what different kinds of molecular structure representations used in chemistry learning mean to students, an experiment was conducted with 124 students from primary schools, secondary schools, and a university. The experiment used a computerized visualization test. The results suggested that the students' appreciation of the three-dimensional molecular structures was based on the kind of representation used. Their results indicate that correct understanding of three-dimensional molecular structure is essential for higher mental operations (Ferk et al., 2003). An increase in the complexity of the given tasks which required the use of several mental processes, resulted in a significant decrease in the students' successes.

Students have been observed to become uninterested and unmotivated when working with physical models for chemistry learning (Dominguez et al., 2012). Three-dimensional virtual graphics have been more popular in STEM education as computers have the ability to present information as well as interact with students (Barrett & Hegarty, 2016) and leads to improved performance. Studies have shown that a higher level of interactivity with molecular animations can improve a student's performance on structural and functional questions in chemistry. Moreover, animations that have greater variation to manipulate the structures are more likely to attract students.

A research was carried out to determine the effects of virtual and physical models on organic chemistry learning. 276 students from nine high schools in Haifa and northern part of Israel were taught chemistry using plastic and computerized three dimensional models. In comparison between physical and virtual chemistry models, both have their pros and cons (Dori & Barak, 2001). While physical models are tangible and can be manipulated in three dimensions, they are available in limited quantities, colors, and sizes, and cannot be used to carry out computational operations. The use of two and three-dimensional representations of molecules alone were not sufficient in promoting students' understanding of the chemical phenomena. Students who were actively constructing their own 3D models of chemical structures showed a significant improvement in their abilities to mentally traverse the four levels of chemistry understanding (Dori et al., 2003).

Teachers' spatial ability improved after molecular visualization training and that spatial ability decreases quickly without practice and increase quickly with practice (José & Williamson, 2008). Upon considering the cognitive abilities of various subjects, researchers concluded that training was beneficial to improving spatial ability (Mohler, 2009; Terlecki et al., 2008). In another research, students' spatial abilities were observed to increase when they were trained in strategy use and motivation (Moè, 2016; Sorby et al., 2013; Stieff et al., 2014).

Several studies on spatial ability and its difference between males and females have been performed over the years. The main questions that arise today are whether the gender differences in spatial ability has remained the same, decreased, or increased over the years (Harle & Towns, 2011). In a meta-analysis of gender differences in spatial ability, researchers have carried out a research on the birth year and the magnitude of gender differences on spatial ability (Voyer et al., 1995). In a study consisting of 286 spatial tests, the results indicated that males significantly performed better than females in mental rotation tasks. However, the difference in performance between both genders were a lot less in spatial perception tasks, and almost negligible in spatial visualization (Voyer et al., 1995).

The type of test administration might also play a role in the male and female performance differences. This is because in a study, males only performed significantly better under strict time limits (Maeda & Yoon, 2013). Moreover, in another study conducted in 2005, no gender differences were found with relaxed time limits (Peters, 2005). Environmental effects might also be responsible for higher performance of males in spatial ability. A study demonstrated that playing with building blocks during childhood, which is more common in males, positively correlates to spatial skills in four to seven-year-old children (Jirout & Newcombe, 2015).

According to Dawson (2019), as people become more adept at a subject, their knowledge replaces the need for spatial thinking. In a mathematics study, a moderate correlation was observed between spatial and mathematical abilities (Hegarty & Kozhevnikov, 1999). Spatial ability showed a correlation with mathematics score on the SAT. When other factors such as general intelligence were kept constant in the experiment, spatial ability proved to be a major predictor of mathematical ability (Rohde & Thompson, 2007). This also proves that spatial ability and general intelligence are two separate factors (Rodán et al., 2016).

Other studies have indicated that higher spatial abilities predict success in organic chemistry. However, it was still unclear if students use visual-spatial imagery to solve problems in chemistry. In his experiment, Stieff (2007) has demonstrated how expert chemists and even some students use analytic strategies and algorithms instead of using the spatial information provided in molecular diagrams to solve chemistry problems. In another study, researchers investigated the different strategies that students use to solve spatial chemistry. These strategies include algorithms and heuristics which students rely on to solve spatial problems instead of using their visual-spatial imagery (Stieff et al., 2012). The result of their study showed that some students do use these strategic approaches such as heuristics and drawing external diagrams rather than relying solely on imagistic reasoning, their choice of strategies was independent of their spatial ability, and that women strategize differently than men.

Other studies have examined the relationship between students' scores on standardized mental rotation tests and their performances on organic chemistry tests. However, none of the studies have found a significant correlation between achievement in organic chemistry tests and visual-spatial ability, and few of these studies have also controlled for the possibility that the common variance with general intelligence maybe reflected in the observed correlations (Harle & Towns, 2011). Several of studies have been carried out to explore the link between visual-spatial ability, gender differences, and chemistry achievement, and their results were conflicting (Barnea & Dori, 1999; Carter et al., 1987; Ferk et al., 2003; Pribyl & Bodner, 1987).

Guiding Research Questions

1. What are some of the challenges that students face while solving stereochemistry related questions?
2. What approaches do students use when solving stereochemistry related questions?
3. What role does spatial ability play on students' abilities to answer stereochemistry questions?

METHODS

The purpose of this research project was to examine two main issues in organic chemistry learning; the first one being the challenges and difficulties students face in learning about stereochemistry in a traditional teaching organic chemistry courses, and the second one is the importance of spatial ability in students' success of learning stereochemistry.

The research project took place at The City College of New York, a public, commuter, urban, and minority-serving institute. The participants' population represents a diverse number of majors including those in the sciences, engineering, and liberal arts, as well as post-baccalaureate students. The project took place during the period of Fall 2021 to Spring 2022.

For this research project, we administered a survey that consisted of five questions to test students' spatial ability, as well as Likert-type and open-ended questions about students' experience with spatial ability in stereochemistry. The survey was examined by two experts who agreed that the questions adequately capture the investigation about spatial ability and stereochemistry. We used the test-retest method to assess the reliability coefficient which was determined to be 0.84.

The research survey was administered and collected from 86 students (n=86) of The City College of New York. The participating students were a diverse group academically and ethnically. The students' majors included chemistry, biology, chemical engineering, civil engineering, and pre-health professionals. The majority of the students were minority students mostly Latino and African American. The student population also included White, Asian, and Middle Eastern students.

Table 1. Average responses of students to Likert-type questions in our survey about spatial ability

Question type	Average answer from respondents
Likert-type question	
I often try to visualize 3D molecular structures while solving stereochemistry questions.	3.52
It is difficult for me to rotate 3D molecular structures in my mind.	3.31
I struggle to answer stereochemistry questions.	3.37
It is easier to answer stereochemistry questions with the aid of 3D molecular kit.	3.28
I believe that with practice, I can improve my spatial ability skills.	4.37
It is difficult for me to visualize the 3D molecular picture of a compound just by looking at their chemical formula.	3.56
Open-ended question	
How important is the spatial ability, capacity to understand, reason, and remember the spatial relations among objects or space, in learning about stereochemistry?	4.32

For the Likert-type questions that were collected as part of the survey, the students' answers were converted to values as follows: strongly disagree=1, disagree=2, neutral=3, agree=4, and strongly agree=5. A single factor ANOVA was performed on the Likert-type questions found $p<.001$. $p\text{-value}<0.05$, which is strong evidence against the null hypothesis and shows that there is strong relationship between the variables. Furthermore, the mean square for our data is 13.56, which is much larger than the mean square within the treatments which is 1.07. The numerical values were then entered into Excel sheet and the average value was calculated for each of the questions. A bar chart was created using these data.

For the open-ended questions part of the survey, we coded the data and created figures. For two of the questions, we created a rubric using a scale of 1 to 5. The two researchers independently examined the answers using rubric. The data obtained were entered into an Excel sheet from which a bar chart was created. For the rest of the open-ended questions, we created categories based on the students' responses and converted them to percentages. Bar charts were then generated using those percentages. We also created scatter line charts to examine correlation between spatial ability and students' perceptions about their performance and learning based on the Likert-type questions.

RESULTS AND DISCUSSION

Table 1 presents the Likert-type questions and the average value from respondents that were a part of the survey on spatial ability. According to the data presented in **Table 1**, students agree that they often try to visualize 3D molecular structures while solving stereochemistry questions, it is difficult for them to visualize the 3D molecular picture of a compound just by looking at their molecular formula, they struggle to answer stereochemistry related questions.

Students agree that is easier to answer to answer stereochemistry questions with the aid of 3D molecular kit. Using modeling kits can improve students' spatial ability which is consistent with research findings that report students who were actively construct their own 3D models can improve their abilities to mentally traverse the different levels of chemistry understanding (Dori et al., 2003). Furthermore, students find it difficult to rotate 3D molecular structures in their minds. Moreover, majority of the students also agreed that with practice, they can improve their spatial ability skills

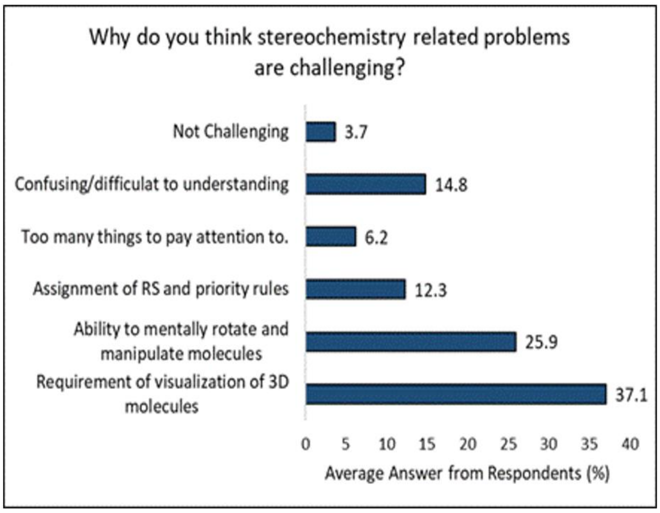

Figure 1. Students' average responses to an open-ended question about the reasons students think stereochemistry related problems are challenging

which is supported by chemistry education research about spatial ability improvement after molecular visualization training (José & Williamson, 2008).

Average answer from respondents to one of the open-ended questions based on rubric was calculated and is part of **Table 1**. The score of the answers were as follows: the level of importance increases as the score increases from 1 to 5, with a score of 1 being the least important, and a score of 5 being the most important. The score of 4.32 on the students' responses indicate that majority of the students agree that spatial is very important in learning about stereochemistry and they underscore their spatial ability importance to their performance and learning. Other research has reported similar findings that correct understanding of 3D molecular structure is importance for higher mental operations (Ferk et al., 2003).

Figure 1 is a bar chart depicting the students' perceptions of the reasons that stereochemistry related problems are challenging. Our data shows that 37.1% of students' perceptions refer to the requirement of visualization of molecules as an impediment to learning. Moreover, 25.9% of students think that mental rotation and manipulation of molecules are challenging. Since these categories of challenges fall under the field of spatial ability, a total of 63% students faces challenges related to spatial ability while solving stereochemistry related questions.

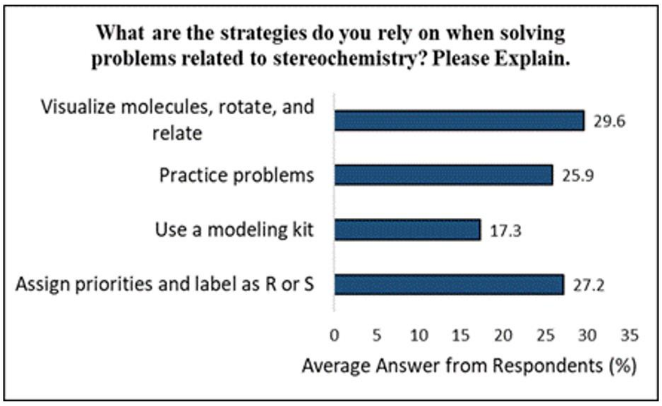

Figure 2. Students' average responses to an open-ended question about the kind of strategies they reply on when solving stereochemistry related problems

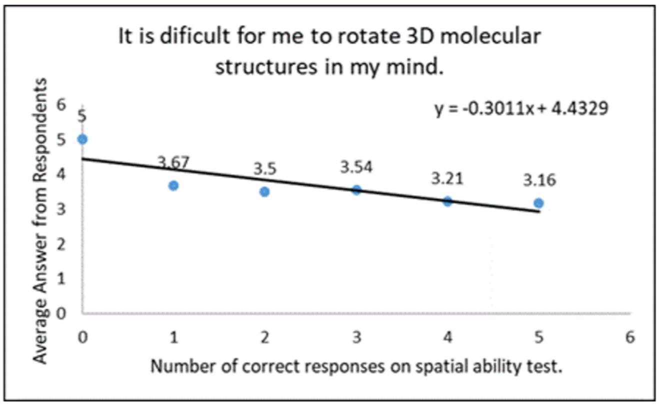

Figure 3. Graph of students' average answers on a scale of 1 to 5 about how much they agree that it is difficult to rotate 3D molecular structures in their mind versus the number of correct responses of those students on a spatial ability test

Spatial ability plays a significant role in solving problems related to stereochemistry and a weak spatial ability can hinder student learning and performance of the concept. Students with low spatial abilities may face difficulties in processing and visualizing spatial information and representations (Alt & Boniel-Nissim, 2018). Additionally, 14.8% of the students have responded that the stereochemistry questions are difficult to understand, 12.3% of students find it challenging to assign R and S configurations and priority groups to molecules, 6.2% of students have reported that there are too many things to pay attention to in stereochemistry related problems, and only 3.7% of students have responded that they do not find stereochemistry related problems to be challenging. The distribution of the students' average responses was fairly uniform, but the dominant response was the requirement of visualization of 3D molecules.

Figure 2 is a bar chart of strategies that students rely on when solving problems related to stereochemistry. According to the chart, 29.6% of students relied on spatial chemistry techniques such as molecular visualization, rotation, and relation, which could cause a problem due to challenges students face in mastering spatial abilities in identifying, visualizing, relating and rotating representations (Furio et al., 2000). Furthermore, 27.2% of students relied on assigning priorities and labelling R and S configurations. These strategies include algorithmic approaches to solving spatial problems instead of using their visual-spatial imagery (Stieff et al., 2012).

Additionally, 25.9% of students rely on practicing the problems which could help students improve their understanding and applying of spatial ability (Wu & Shah, 2004). Lastely, 17.3% of students relying on modeling kits which is in agreement with a study that reports the use of models in cooperative learning to improve learning (Dori & Barak, 2001). As seen from **Figure 2**, the responses were broken down into four principal categories. The distribution of the responses was very close, while replying on spatial ability to solve stereochemistry related problems was the dominant response.

Figure 3 is the graph of students' average answers on a scale of 1 to 5 about how much they agree that it is difficult to rotate 3D molecular structures in their mind versus the number of correct responses of those students on a spatial ability test. The responses to the Likert-type question on the *y*-axis have the following scores: strongly disagree=1, disagree=2, neutral=3, agree=4, and strongly agree=5. The graph has a negative trendline with an equation of $y=-0.3011x+4.4329$. SPSS data analysis show that $R^2=0.618$ and standard error of the estimates=1.15648.

The graph on **Figure 3** shows the correlation between the extent to which students find it difficult to mentally rotate 3D molecular structures and the number of correct responses of those students on a spatial ability test conducted during our experiment. According to the graph's trendline, a negative correlation exists between having difficulty in mentally rotating 3D molecular structures and doing well on spatial ability test. The better the students performed on the spatial ability test, the easier they find it to mentally rotate a molecular structure.

Although it can be seen that most students agreed to some extent that it is difficult for them to rotate 3D molecules on their mind, the students who least agreed to this statement with a score of 3.16 were able to correctly respond to all five of the spatial ability questions. Similarly, most of the students who strongly agreed that they have difficulties in mentally rotating 3D molecules, were not able to answer any of the five spatial ability test questions correctly. Therefore, this correlation demonstrates that the higher the spatial ability of students, the easier it is for them to mentally rotate 3D molecules. This notion is supported by research that reports to have found a positive correlation between students' science accomplishments and their spatial capacities (Hegarty, 2014).

The graph on **Figure 4** shows the correlation between the extent to which students agree that it is easier for them to answer stereochemistry questions with the aid of 3D molecular kits and the number of correct responses of those students on a spatial ability test conducted during our experiment. According to the graph's trendline, a positive correlation exists between students who find it easier to answer stereochemistry questions with the aid of 3D molecular kits and doing well on spatial ability test. Although most students agreed to some extent that it is easier to solve stereochemistry problems with the aid of 3D molecular kits, the students who least agreed to this statement with a score of around 3.01 were

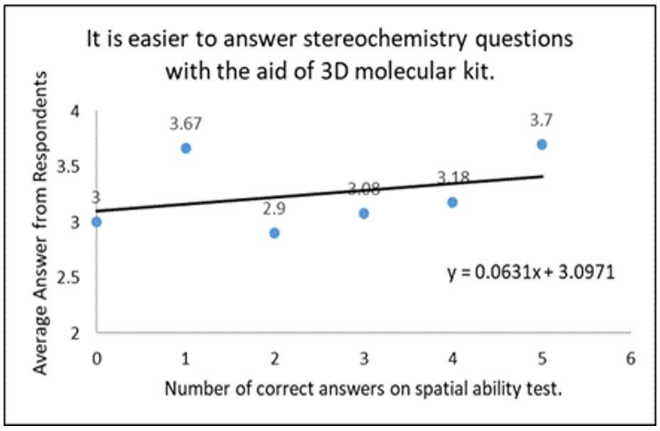

Figure 4. Graph of students' average answers on a scale of 1 to 5 about how much they agree that it is easier for them to answer stereochemistry questions with the aid of 3D molecular kits versus the number of correct responses of those students on a spatial ability test

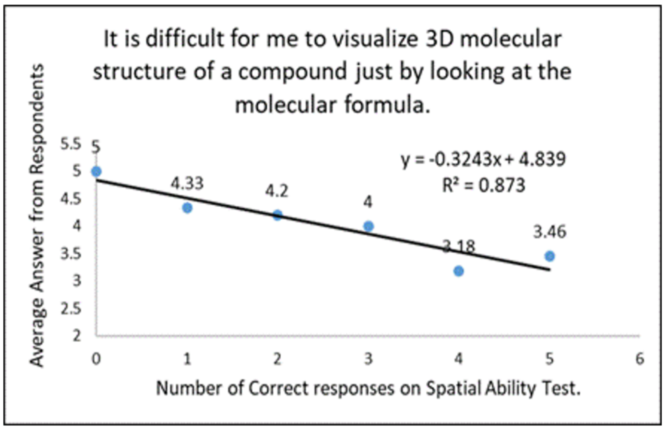

Figure 5. Graph of students' average answers on a scale of 1 to 5 about how the extent to which they agree that it is difficult for them to visualize 3D molecular structure of a compound just by looking at their molecular formula versus the number of correct responses of those students on a spatial ability test

not able to correctly respond to any of the five spatial ability questions. Similarly, most of the students who agreed that to the statement, were able to correctly answer all five of the spatial ability test question. Therefore, this graph suggests that using 3D molecular kits are successful in aiding students in their stereochemistry questions. The responses to the Likert-type question on the *y*-axis have the following scores: strongly disagree=1, disagree=2, neutral=3, agree=4, and strongly agree=5. The graph has a positive trendline with an equation of $y=0.0631x+3.0971$. SPSS data analysis produced an $R^2=0.117$ and standard error of the estimates=1.96575.

The graph on **Figure 5** shows the correlation between the extent to which students find it difficult to visualize 3D molecular structure of a compound just by looking at their molecular formula and the number of correct responses of those students on a spatial ability test conducted during our experiment. According to the graph's trendline, a nearly perfect negative correlation exists between difficulties in visualizing 3D molecular structures and doing well on spatial ability test.

The responses to the Likert-type question on the *y*-axis have the following scores: strongly disagree=1, disagree=2, neutral=3, agree=4, and strongly agree=5. The graph has a negative trendline with an equation of $y=-0.3243x+4.839$. SPSS data analysis produced a value for R^2 of 0.873 and standard error of the estimates of 0.74545.

Although it can be seen that most students agreed to some extent that it is difficult for them to mentally visualize 3D molecules, the students who least agreed to this statement with a score of 3.46 were able to correctly respond to all five of the spatial ability questions. Similarly, most of the students who strongly agreed that they have difficulties in mentally visualizing 3D molecules, were not able to answer any of the five spatial ability test questions correctly. Therefore, this graph demonstrates that the higher the spatial ability of students, the easier it is for them to mentally visualize 3D molecules just by looking at their molecular formula.

CONCLUSION

The data obtained from this research project suggests that students' spatial ability plays an important role on their performance and learning of stereochemistry. Majority of the 86 students in this study consider spatial ability to be an important factor in understanding stereochemistry related problems and find problems which require spatial ability to be especially challenging such as mental rotation and visualization of 3D molecules, assigning priority functional groups to molecules, identifying R and S configurations. Our data show a direct negative correlation between students' scores in a spatial ability test and how difficult they find mental rotation and visualization of 3D molecules to be. Mental rotation and visualization of 3D molecules are two of the fundamental parts of spatial ability in stereochemistry. The data also have indicated that students who do not find these spatial ability tasks to be difficult seemed to perform significantly better in the spatial ability tests. These findings support that notion that spatial ability is an essential requirement for performing well in stereochemistry and majority of the students from different areas of studies seem to be aware of this.

Majority of the students also seem to believe that spatial ability in stereochemistry can be improved with practice and the use of 3D molecular kits for tackling stereochemistry related questions. Students who find it easier to rely on 3D molecular kits to solve stereochemistry problems scored significantly higher than those who do not. These data demonstrate that with practice and the right kind of tools, spatial ability for solving stereochemistry problems could be improved. While this research answers the initial questions needed to identify the spatial ability related challenges students face in stereochemistry and their perception of those challenges, further studies are needed to gain a deeper understanding into the types of spatial ability trainings and practices that could improve students' performances in stereochemistry and other spatial ability related fields.

Author contributions: All co-authors have involved in all stages of this study while preparing the final version. They all agree with the results and conclusions.

Funding: No external funding is received for this article.

Declaration of interest: The authors declare that they have no competing interests.

Ethics approval and consent to participate: Not applicable.

Availability of data and materials: All data generated or analyzed during this study are available for sharing when appropriate request is directed to corresponding author.

REFERENCES

Alt, D., & Boniel-Nissim, M. (2018). Links between adolescents deep and surface learning approaches, problematic internet use, and fear of missing out (FoMO). *Internet Interventions, 13*, 30-39. https://doi.org/10.1016/j.invent.2018.05.002

Barnea, N., & Dori, Y. J. (1999). High school chemistry students' performance and gender differences in a computerized molecular modeling learning environment. *Journal of Science Education and Technology, 8*(4), 257-271. https://doi.org/10.1023/A:1009436509753

Barrett, T. J., & Hegarty, M. (2016). Effects of interface and spatial ability on manipulation of virtual models in a STEM domain. *Computers in Human Behavior, 65*, 220-231. https://doi.org/10.1016/j.chb.2016.06.026

Berney, S., Bétrancourt, M., Molinari, G., & Hoyek, N. (2015). How spatial abilities and dynamic visualizations interplay when learning functional anatomy with 3D anatomical models. *Anatomical Sciences Education, 8*(5), 452-462. https://doi.org/10.1002/ase.1524

Bilge, A. R., & Taylor, H. A. (2016). Framing the figure: Mental rotation revisited in light of cognitive strategies. *Memory & Cognition, 45*(1), 63-80. https://doi.org/10.3758/s13421-016-0648-1

Carter, C. S., LaRussa, M. A., & Bodner, G. M. (1987). A study of two measures of spatial ability as predictors of success in different levels of general chemistry. *Journal of Research in Science Teaching, 24*(7), 645-657. https://doi.org/10.1002/tea.3660240705

Chien, K.-P., Tsai, C.-Y., Chen, H.-L., Chang, W.-H., & Chen, S. (2015). Learning differences and eye fixation patterns in virtual and physical science laboratories. *Computers & Education, 82*, 191-201. https://doi.org/10.1016/j.compedu.2014.11.023

Dawson, C. (2019). Tackling Limited Spatial Ability: Lowering One Barrier into STEM? *European Journal of Science and Mathematics Education, 7*(1), 14-31. https://doi.org/10.30935/scimath/9531

Dominguez, M. G., Gutierrez, J. M., Gonzalez, C. R., & Corredeaguas, C. M. M. (2012). Methodologies and tools to improve spatial ability, *Procedia-Social and Behavioral Sciences, 51*, 736-744. https://doi.org/10.1016/j.sbspro.2012.08.233

Dori, Y. J., & Barak. M. (2001). Virtual and physical molecular modeling: Fostering model perception and spatial understanding. *Educational Technology & Society,* 4(1), 61-74.

Dori, Y. J., Barak, M., & Adir, N. (2003). A web-based chemistry course as a means to foster freshmen learning. *Journal of Chemical Education, 80*(9), 1084-1092. https://doi.org/10.1021/ed080p1084

Ferguson, A. M., Maloney, E. A., Fugelsang, J., & Risko, E. F. (2015). On the relation between math and spatial ability: The case of math anxiety. *Learning and Individual Differences, 39*, 1-12. https://doi.org/10.1016/j.lindif.2015.02.007

Ferk, V., Vrtacnik, M., Blejec, A., & Gril, A. (2003). Students understanding of molecular structure representations. *International Journal of Science Education, 25*(10), 1227-1245. https://doi.org/10.1080/0950069022000038231

Furio, C., Calatayud, M. L., Barcenas, S. L., & Padilla, O. M. (2000). Functional fixedness and functional reduction as common sense reasonings in chemical equilibrium and in geometry and polarity of molecules. *Science Education, 84*(5), 545-565. https://doi.org/10.1002/1098-237X(200009)84:5<545::AID-SCE1>3.0.CO;2-1

Harle, M., & Towns, M. (2011). A review of spatial ability literature, its connection to chemistry, and implications for instruction. *Journal of Chemical Education, 88*(3), 351-360. https://doi.org/10.1021/ed900003n

Harris, P. A. (2019). *Spatializing an undergraduate chemistry curriculum: Action research to assist students with low visual-spatial ability* [Ed.D. dissertation, Northcentral University].

Hauptman, H., & Cohen, A. (2011). The synergetic effect of learning styles on the interaction between virtual environments and the enhancement of spatial thinking. *Computers & Education, 57*(3), 2106-2117. https://doi.org/10.1016/j.compedu.2011.05.008

Hausmann, M., Slabbekoorn, D., Goozen, S. H. M. V., Cohen-Kettenis, P. T., & Gunturkun, O. (2000). Sex hormones affect spatial abilities during the menstrual cycle. *Behavioral Neuroscience, 114*(6), 1245-1250. https://doi.org/10.1037/0735-7044.114.6.1245

Hegarty, M. (2014). Spatial thinking in undergraduate science education. *Spatial Cognition and Computation: An Interdisciplinary Journal, 14*(2), 142-167. https://doi.org/10.1080/13875868.2014.889696

Hegarty, M., & Kozhevnikov, M. (1999). Types of visual-spatial representations and mathematical problem solving. *Journal of Educational Psychology, 91*(4), 684-689. https://doi.org/10.1037/0022-0663.91.4.684

Höffler, T. N., & Leutner, D. (2011). The role of spatial ability in learning from instructional animations–Evidence for an ability-as-compensator hypothesis. *Computers in Human Behavior, 27*(1), 209-216. https://doi.org/10.1016/j.chb.2010.07.042

Jansen, P., & Heil, M. (2009). Gender differences in mental rotation across adulthood. *Experimental Aging Research, 36*(1), 94-104.https://doi.org/10.1080/03610730903422762

Jirout, J. J., & Newcombe, N. S. (2015). Building blocks for developing spatial skills. Evidence from a large, representative U.S. sample. *Psychological Science, 26*(3), 302-310. https://doi.org/10.1177/0956797614563338

José, T. J., & Williamson, V. M. (2008). The effects of a two-year molecular visualization experience on teachers attitudes, content knowledge, and spatial ability. *Journal of Chemical Education, 85*(5), 718. https://doi.org/10.1021/ed085p718

Krajcik, J. S. (1991). Developing students' understanding of chemical concepts. In Y. S. M. Glynn, R. H. Yanny, & B. K. Britton (Eds.), *The psychology of learning science: International perspective on the psychological foundations of technology-based learning environments* (pp. 117-145). Erlbaum.

Maeda, Y., & Yoon, S. Y. (2013). A meta-analysis on gender differences in mental rotation ability measured by the Purdue spatial visualization tests: Visualization of rotations (PSVT: R). *Educational Psychology Review, 25* (1), 69-94. https://doi.org/10.1007/s10648-012-9215-x

Martín-Gutiérrez, J., Mora, C. E., Añorbe-Díaz, B., & González-Marrero, A. (2017). Virtual technologies trends in education. *EURASIA Journal of Mathematics, Science and Technology Education, 13*(2), 469-486. https://doi.org/10.12973/eurasia.2017.00626a

Meneghetti, C., Cardillo, R., Mammarella, I. C., Caviola, S., & Borella, E. (2016). The role of practice and strategy in mental rotation training: Transfer and maintenance effects. *Psychological Research, 81*(2), 415-431. https://doi.org/10.1007/s00426-016-0749-2

Moè, A. (2016). Does experience with spatial school subjects favour girls mental rotation performance? *Learning and Individual Differences, 47*, 11-16. https://doi.org/10.1016/j.lindif.2015.12.007

Mohler, J. L. (2009). Computer graphics education: Where and how do we develop spatial ability? In *Proceedings of Eurographics* (pp. 79-86). Lausanne, Switzerland.

Nakhleh, M. B. (1992). Why some students don't learn chemistry. *Journal of Chemical Education, 69*(3), 191-196. https://doi.org/10.1021/ed069p191

Oliver-Hoyo, M., & Babilonia-Rosa, M. A. (2017). Promotion of spatial skills in chemistry and biochemistry education at the college level. *Journal of Chemical Education, 94*(8), 996-1006. https://doi.org/10.1021/acs.jchemed.7b00094

Paivio, A. (1986) *Mental representations: A dual coding approach.* Oxford University Press.

Peters, M. (2005). Sex differences and the factor of time in solving Vandenberg and Kuse mental rotation problems. *Brain and Cognition, 57*(2), 176-184. https://doi.org/10.1016/j.bandc.2004.08.052

Pribyl, J. R., & Bodner, G. M. (1987). Spatial ability and its role in organic chemistry: A study of four organic courses. *Journal of Research in Science Teaching, 24*(3), 229-240. https://doi.org/10.1002/tea.3660240304

Rodán, A., Contreras, M. J., Elosúa, M. R., & Gimeno, P. (2016). Experimental but not sex differences of a mental rotation training program on adolescents. *Frontiers of Psychology,* 7(1050), 1-12. https://doi.org/10.3389/fpsyg.2016.01050

Rohde, T. E., & Thompson, L. A. (2007). Predicting academic achievement with cognitive ability. *Intelligence, 35*, 83-92. https://doi.org/10.1016/j.intell.2006.05.004

Sadoski, M. Goetze, T. & Fritz, J. B. (1993) Impact of concreteness on comprehensibility, interest, and memory for text: Implications for dual coding theory and text design. *Journal of Educational Psychology, 85*, 291-304. https://doi.org/10.1037/0022-0663.85.2.291

Sadoski, M., Paivio, A., & Goetze, T. (1991). A critique of schema theory in reading and a dual coding alternative. *Reading Research Quarterly, 25*, 463-485. https://doi.org/10.2307/747898

Sorby, S., Casey, B., Veurink, N., & Dulaney, A. (2013). The role of spatial training in improving spatial and calculus performance in engineering students. *Learning and Individual Differences, 26*, 20-29. https://doi.org/10.1016/j.lindif.2013.03.010

Spearman, C. E. (1927). *The abilities of man: Their nature and measurement*. Macmillan.

Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and Instruction, 17*(2), 219-234. https://doi.org/10.1016/j.learninstruc.2007.01.012

Stieff, M., Lira, M., & Sesutter, D. (2014). Representational competence and spatial thinking in STEM. In *Proceedings of International Conference of the Learning Sciences* (pp. 987-991).

Stieff, M., Ryu, M., Dixon, B., & Hegarty, M. (2012). The role of spatial ability and strategy preference for spatial problem solving in organic chemistry. *Journal of Chemical Education, 89*(7), 854-859. https://doi.org/10.1021/ed200071d

Tarampi, M. R., Heydari, N., & Hegarty, M. (2016). A tale of two types of perspective taking. *Psychological Science, 27*(11), 1507-1516. https://doi.org/10.1177/0956797616667459

Terlecki, M., Newcombe, N., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology, 22*, 996-1013. https://doi.org/10.1002/acp.1420

Tuckey, H., & Salvaratnam, M. (1993). Studies involving three-dimensional visualization skills in chemistry: A review. *Studies in Science Education, 21*(1), 99-121. https://doi.org/10.1080/03057269308560015

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*(2), 599-604. https://doi.org/10.2466/pms.1978.47.2.599

Voyer, D., Voyer, S. & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin, 117*(2), 250-270. https://doi.org/10.1037/0033-2909.117.2.250

Wu, H.-K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education, 88*(3), 465-492. https://doi.org/10.1002/sce.10126

Yang, E.-M., Andre, T., Greenbowe, T. J., & Tibell, L. (2003). Spatial ability and the impact of visualization/animation on learning electrochemistry. *International Journal of Science Education, 25*(3), 329-349. https://doi.org/10.1080/09500690210126784

Yuan, L., Kong, F., Luo, Y., Zeng, S., Lan, J., & You, X. (2019). Gender differences in large-scale and small-scale spatial ability: A systematic review based on behavioral and neuroimaging research. *Frontiers in Behavioral Neuroscience, 13*, 128. https://doi.org/10.3389/fnbeh.2019.00128