Effect of Spatial Visualization on Learning Engineering Technology and Engineering Programs

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WIP: Effect of Spatial Ability on Solid Mechanics Education in Engineering Technology and Engineering Programs

Abstract

The distinction between undergraduate educational programs for engineering and engineering technology at many US institutions has led to different admission requirements for students applying to the two programs. This distinction is typically characterized by the adoption of different curricula, instructional approaches, a mix of lectures and laboratories, and textbooks. It is broadly expected that such an approach would facilitate the development of different domains of knowledge, ranging from more abstract and theoretical for engineering students to more applied and hands-on for engineering technology students. Considering the disproportionate differences in the spatial contents, tools of spatial representation, and associated spatial reasoning processes in fundamental courses such as solid mechanics or fluid dynamics, this study seeks to find a relationship, if any, between students' spatial abilities and their learning of key concepts in solid mechanics. The performance of engineering and engineering technology students in solid mechanics has been assessed in two fundamental courses, Statics and Strength of Materials, and their spatial abilities have been measured by the revised Purdue Spatial Visualization Rotation Test and the Santa Barbara Solids Test. The preliminary data analysis of the first cohort of students reveals that the adopted spatial ability instruments are less likely to detect the difference between engineering and engineering technology in learning solid mechanics courses. Although the literature indicates that a strong spatial ability is crucial to the success of first-year engineering students, it might play a diminishing role in students' learning as their academic seniority grows. This will be investigated in the near future by continuing the study and collecting data from different groups of students.

Keywords: spatial visualization, solids mechanics education, statics, strength of materials

Introduction

Statics and Strength of Materials are two major engineering courses in solid mechanics (SMC) that are common in most of the mechanical and civil engineering and technology programs. At (name of university), both these courses are required in the four-year programs in engineering (ENGR) with a concentration in mechanical engineering as well as engineering technology (ENGT) with a concentration in applied systems technology. A previous study in engineering mechanics [1] suggests that to master the SMC course content, besides physics and mathematical skills, students need to have a strong spatial ability to retrieve and interpret spatial information from engineering structures and produce efficient spatial reasoning for solving problems. Spatial ability is the cognitive capability that helps people to apprehend, maintain, and manipulate 3D objects in their mind and is considered as a set of several spatial ability factors [2, 3, 4]. References [2, 4, 5, 6] cite spatial visualization, mental rotation, spatial orientation, spatial perception, and cross-sectioning abilities among spatial ability factors. Some of the references in the literature [4, 7, 8] consider spatial ability as a narrowed concept of spatial thinking which in turn is "a constructive amalgam" of three cognitive skills, "concepts of space, tools of representation, and processes of reasoning" by National Research Council [9].

Stemming from the differences in the uses of spatial concepts, tools of spatial representations, and levels of spatial reasoning in SMC textbooks adopted for ENGR and ENGT programs, one might ask whether there is any different requirement of spatial competencies to learn and succeed in SMC courses. The SMC textbooks adopted for ENGR program are typically calculus-based such as "Engineering Mechanics: Statics," 14th edition [10], and "Mechanics of Materials," 10th edition [11], both by R. C. Hibbeler. The SMC textbooks for ENGT program are typically algebra-based and may include "Applied Statics and Strength of Materials," 5th edition [12], by G. F. Limbrunner and L. Spiegel for the Statics and "Applied Strength of Materials," 5th edition [13], by R. L. Mott, for the Strength of Materials course. Although the respective SMC textbooks for both programs share many similar solid mechanics concepts and problem-solving techniques, the ones for ENGR program contain more complex spatial concepts, tools of representations, spatial reasoning related to 3D space as compared to the ENGT program. For example, a large percentage of forces, moments, stresses, and strains are presented and discussed in the SMC textbooks for ENGR students [10] using 3D graphics (such as illustrations, coordinates, free body diagrams or FBDs) and tools such as cross products, vector notations, right hand rule, etc. Meanwhile, the concepts related to forces, moments, etc. are generally presented and discussed in 2D in the SMC textbooks for ENGT students. As a result, SMC problems for ENGR program might provoke students to synthesize and visualize structures in 3D from text descriptions, distinguish spatial information from overlapped features of 3D views, analyze spatial relationships among features, and create FBDs of the structures. These cognitive processes are considered to be the highest level of spatial thinking, according to the taxonomy of spatial thinking developed in the literature [14].

Research findings consistently confirm the important role of spatial ability in predicting the success of first-year STEM students [3, 4, 15, 16]. In geology, chemistry, and physics programs [4, 17], spatial abilities have been found to correlate well with students' learning during the first year but it is observed that such abilities become irrelevant as students grow academically and develop expertise in their area of study. In engineering education, it is not yet known when and whether a student's competency of spatial ability factors can be used to predict success in ENGR or ENGT programs. Furthermore, the academic level at which a student's spatial ability becomes unrelated to ENGR and ENGT learning is not clear. Currently, students are admitted into ENGR and ENGT programs based on their high school mathematics and physics scores as well as standardized test scores in most institutions. Typically, students with relatively higher scores in mathematics are recommended to pursue ENGR while others are recommended to enroll in ENGT programs. This admission criteria for ENGR and ENGT programs may not be the most effective tool for placing students into these two programs, however this is currently considered to be acceptable due to the greatly varying standards of educational achievement in high schools across the U.S. [18]. The long term aim of this study is to possibly consider spatial abilities in placing students appropriately into the ENGR and ENGT programs, this would provide admission personnel and career advisors with an additional tool to advise and assist students in choosing an engineering or engineering technology program.

Research questions

This preliminary study seeks to answer the following two research questions: "Is there any significant difference in spatial abilities between ENGR and ENGT students?" and "Is there any significant difference between ENGR and ENGT students in the relationships of their SMC course performances and spatial ability test scores?" It may be noted that this study is a work-in-progress and will continue for the next year. The results presented in this paper are from the data that has been gathered and processed so far.

Method and Procedure

Students who took Statics and Strength of Materials courses at Western Carolina University during Fall 2018 were invited to participate in this study. STA students were in their third semester of the eight-semester ENGR program and SOM students were in their fifth semester of the eight-semester ENGT program. During week 14, when the classes were about to end, students who agreed to participate in the study and signed the informed consent forms were provided the link to take a 40~50-minute survey on the Qualtrics website. The survey consisted of 30 questions of the revised Purdue Spatial Visualization: Rotation test (PSVT:R) [19] and 30 questions of the Santa Barbara Solids Test (SBST) [20]. These two instruments were chosen because they measure different constructs of students' spatial abilities and have consistent validities and reliabilities. The revised PSVT: R test has high consistency and reliability (Cronbach's alpha 0.849, N=585) and has been frequently used by researchers in STEM education to measure spatial visualization ability [15]. The SBST (Cronbach's alpha 0.86 in [20]) measures students' abilities to infer the cross section of a 3D object with a cutting plane in various orientations. For this study, the revised PSVT:R and SBST are found to have reliabilities of 0.93 and 0.92 respectively, as measured by using the Cronbach's alpha value. Figures 1 and 2 show sample questions from the PSVT:R and SBST instruments respectively. In Fall 2018, 44 students participated in the survey but only 38 score sets, 23 from STA and 15 from SOM classes, remained valid for data analysis. Students' final scores of the Statics and Strength of Materials courses were also collected from the instructor of each course for analysis.

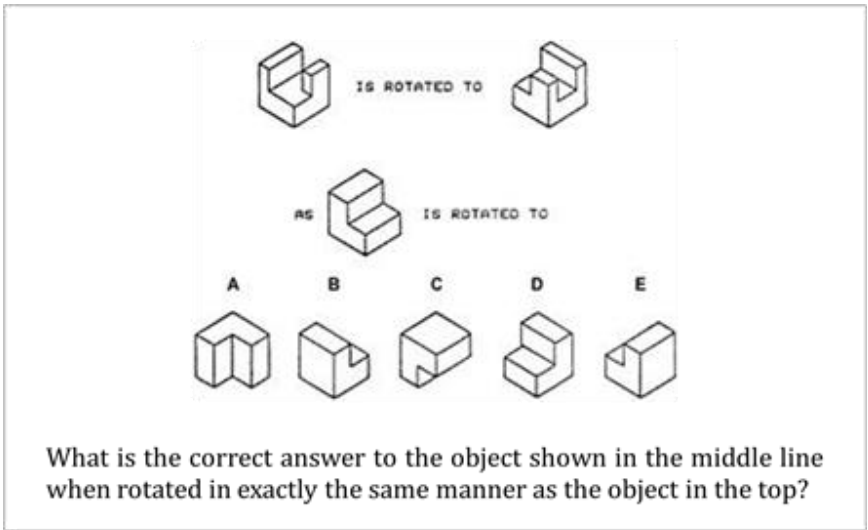

Figure 1. An item in the revised Purdue Spatial Visualization: Rotation test (PSVT:R) instrument.

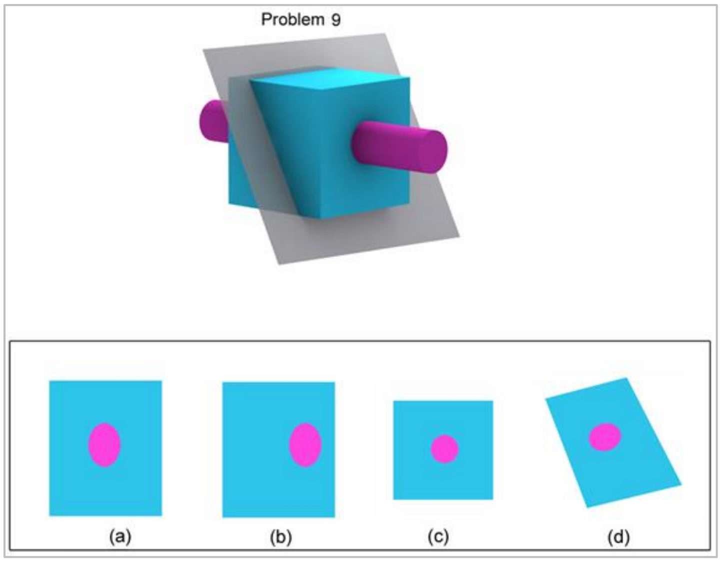

Figure 2. An item in the Santa Barbara Solids Test (SBST) instrument.

Results and Discussion

The distributions of spatial ability test scores on the revised PSVT:R and SBST and their frequency distributions by engineering students are presented in Table 1 and Figure 3 respectively. Due to different instructional approaches and curriculum contents among instructors and institutions, the students' scores in SMC courses are not reported in this preliminary study but have been used to evaluate the correlations with students' spatial ability test scores. Student performances on the two spatial ability factors are reported by the mean, standard deviation (SD), and median. Since there are very few female students in these two classes, their PSVT:R and SBST scores are collected and reported collectively with all participants. As the distribution of test scores are skewed (Figure 3), all analyses are conducted with non-parametric statistics.

Table 1. Distribution of spatial ability scores by engineering (ENGR) and engineering technology (ENGT) students.

	PSVT:R					SBST				
	Min.	Max.	Mean	SD	Median	Min.	Max.	Mean	SD	Median
ENGR (N = 23)	7	28	21.57	6.79	23.00	6	29	21.83	7.35	26.00
ENGT (N = 15)	3	30	22.20	5.68	24.00	17	29	24.87	3.64	26.00

Note: PSVT:R = Purdue Spatial Visualization: Rotation Test, SBST = Santa Barbara Solids Test

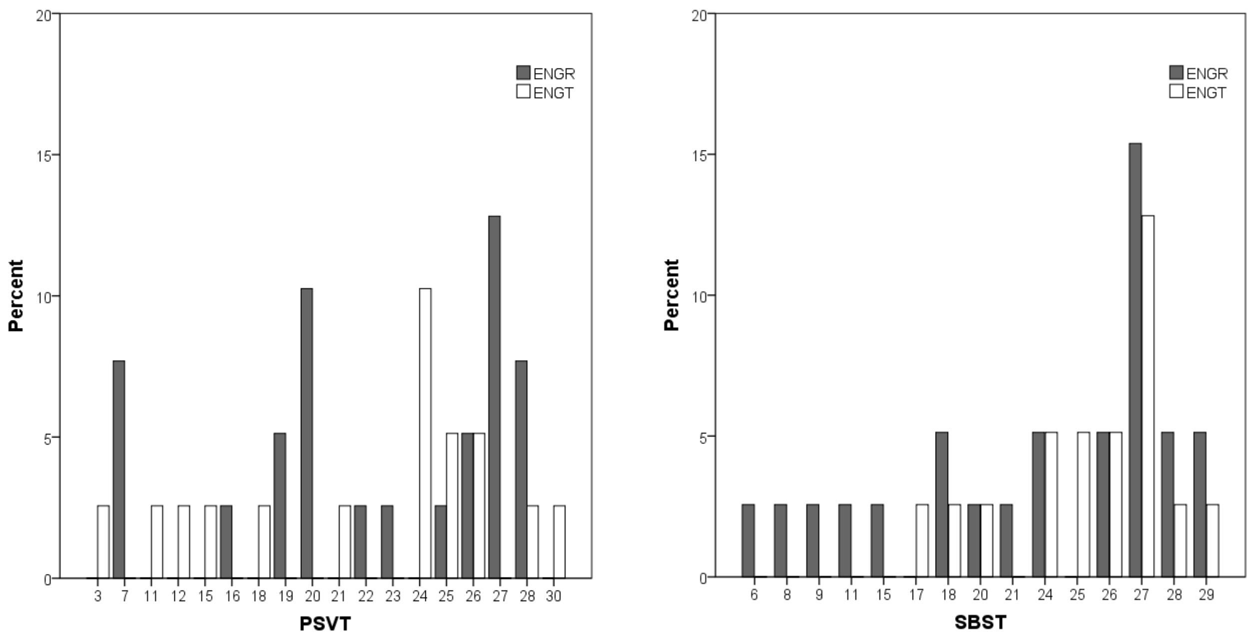

Figure 3. Frequency distribution of the revised PSVT:R and SBST scores.

"Is there any significant difference in spatial abilities between ENGR and ENGT students?"

The ENGT students have higher means and medians of PSVT:R and SBST test scores than the ENGR students (Table 1). However, the results of Mann-Whitney *U* test reveals that there is no significant difference between the medians of PSVT:R ($p = 0.755$) or SBST ($p = 0.662$) of ENGR and ENGT students. At the time of data collection for this study, the ENGR and ENGT students finished their third and fifth semesters and accumulated, on average, 50 and 80 credit hours respectively out of 126 credit hours. For PSVT:R scores, this result further confirmed the ceiling effect of this psychometric test [21] because "the test is relatively easy for this population" [15]. For SBST, it could be possible that ENGT students have higher and more consistent test scores than ENGR students because they studied SOM course with more cross-sectional views than ENGR students do with STA course.

"Is there any significant difference between ENGR and ENGT students in the relationships of their SMC course performances and spatial ability test scores?"

Additional analysis has been conducted using non-parametric correlation to find any difference between ENGR and ENGT students in the relationships between their PSVT:R test score and SMC course performances. Table 2 lists correlations between students' PSVT:R and SBST test scores and their final SMC course grades. The SMC course for ENGR students is Statics and for ENGT students is Strength of Materials.

Table 2. Correlations of spatial abilities scores and SMC courses performances.

	PSVT:R & SMC course		SBST & SMC course	
	Correlation	*p* value	Correlation	*p* value
ENGR (N = 23)	0.498	0.016	0.136	0.535
ENGT (N = 15)	0.049	0.863	0.075	0.791

Note: PSVT:R = Purdue Spatial Visualization: Rotation Test, SBST = Santa Barbara Solids Test

The results in Table 2 reveal that the spatial visualization measured by the revised PSVT:R might help sophomore ENGR students learn the SMC course evidenced by the moderately significant correlation (ρ = 0.498). Meanwhile, this spatial ability factor might not help junior ENGT students learn the SMC course evidenced by the negligible correlation (ρ = 0.049). This result is understandable because the revised PSVT:R test measures students' mental rotation ability to comprehend and manipulate 3D objects and ENGR Statics course deals with significantly more 3D spatial concepts, graphics, and structures than the ENGT Strength of Materials course. The Spearman's correlations found in Table 2 can be used to evaluate the effect size (ρ^2) values and explain the proportion of variance shared by the PSVT:R scores in the performances of SMC courses. For ENGR students, there is a low (ρ^2 = 0.248) association between their PSVT:R and the course performance. It could be interpreted that the spatial visualization factor measured by PSVT:R explains up to 25% of the performance variance in the Statics score of ENGR students. However, this proportion of variance could be negligible if the effects of many confounding factors such as prior and current exposures, engagement in spatially rich activities, etc. are identified and controlled.

In the case of SBST, the study does not find any relationship between students' cross sectioning skills and their performances in the SMC course, this is evidenced by the negligible correlation coefficients between SBST scores and SMC course grades for both groups of students. Also, the effect size is found to be negligible (ρ^2 = 0.018), suggesting that students' cross sectioning skills might not be contributing to the learning of Statics for ENGR or Strength of Materials for ENGT students. It may be possible that the ENGR Statics course has less mechanics concepts involved with cross sections while ENGT Strength of Materials course has mainly 2D orthogonal views of structural cross sections, thereby losing all depth cues associated with the 3D structures. This finding is contradictory to the result from a previous study carried out by the same author(s)[1]. The previous study found a significant positive correlation (ρ = 0.552 at p = 0.01) between SBST scores of mechanical engineering students and their performance in the Mechanics of Materials (MOM) course. It is noted that the engineering students' performances in MOM in the previous study was measured by using the MOM concept inventory [22], a survey consisting of 23 conceptual understanding questions, not the final course grades as utilized in this study. It is believed that the final course grade is a better indicator of students' mastery of the subject matter than the concept inventory. This is because the final course grade measures both students' conceptual understanding and problem-solving skills for the whole semester.

Conclusion and Implication

Spatial abilities are fundamental to higher level thinking and reasoning processes, and therefore play a crucial role in developing expertise and being successful in learning engineering content. Spatial ability is not a unitary construct, but a set of factors which includes, among others, spatial visualization, mental rotation, spatial orientation, and cross-sectioning. This preliminary study focuses on the relationship between the students' spatial ability factors and their performance in the SOM courses. It is found that there is no significant difference between ENGR and ENGT students in the relationships of their spatial abilities and performances in the SMC courses. The spatial visualization ability, as measured by the PSVT:R test, played a moderate role in the learning of Statics, one of the solid mechanics courses investigated in this study, for ENGR students. However, this role would become limited if confounding factors influencing to the relationship between spatial visualization ability and course performance are identified and controlled. Students' cross section ability, as measured by the SBST test, do not correlate with their performances of SMC courses of any engineering program.

This study indicates that spatial ability may be playing a diminishing role in student learning of SMC content as they reach academic maturity and develop expertise in their areas of study. High spatial abilities test scores are considered as good indicators to predict the success of first-year engineering students, but might not be helpful to explain the learning of students after their first year of study. The results of this study support the cause of investing in spatial training of the first-year engineering students and low spatial performers. From sophomore level and up, students are exposed to extensive external visual-spatial representations and engage in spatially rich activities; this limits the role of spatial abilities in their learning [17, 23]. The spatially rich activities include, but are not limited to, working with computer simulations, participating in laboratory experiments, taking computer drafting and modeling courses, and other STEM courses. It could be said that engineering students self-improve their spatial abilities as they grow academically with the pursuit of courses in their program of study. At the time of data collection for this study, the ENGR and ENGT students had finished their third and fifth semesters and accumulated 50 to 80 credit hours in their program of study. It is possible that PSVT:R and SBST are psychometric tests that measure a student's spatial cognitive capability in a piecemeal fashion and do not reflect a more complex spatial thinking. Reference [17] suggests that educators and researchers should "look more broadly than psychometric tests of spatial ability to identify components of spatial intelligence or adaptive spatial thinking."

There are several limitations in implementing this study. First, the assessment of the relationship between the two test scores did not involve a pretest, and the data analysis in this study provided a snapshot of the relationship between the two test scores at the end of the study (posttest) only. This practice might justify the correlational analysis when two score sets are collected at the same place and time, but there is a high possibility that students could develop spatial skills during the course of instruction when they are exposed to many visual-spatial graphical representations from the course content. Thus, the students might have a good spatial ability test score, but this score may not correlate to their performance in the course. This phenomenon has been well described in the literature [23, 24]. Second, the sample size for this study is small at this stage, thereby reducing the validity and reliability of the study's findings. In the future, this study will increase sample sizes for each group of participants to improve validity and reliability of the findings and adopt spatial ability tests appropriate for this population. The future study might also employ cognitive elicitation techniques such as interviews or focused studies, as suggested in the literature [17], to examine how students understand specific spatial representations in the context of solid mechanics learning.

References

[1] Ha, O., & Brown, S. A. (2017, June), Spatial Reasoning Difference between Civil and Mechanical Engineering Students in Learning Mechanics of Materials Course: A Case of Cross-sectional Inference. In Proceedings of the 2017 ASEE Annual Conference & Exposition, Columbus, Ohio. https://peer.asee.org/28836.

[2] Hegarty, M., & Waller, D. (2005). Individual differences in spatial abilities. In P. Shah, & A. Miyake (Eds.) The Cambridge handbook of visuospatial thinking (pp. 121-167). New York: Cambridge University Press.

[3] Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C. & Newcombe, N. S., (2013). The malleability of spatial skills: A meta-analysis of training studies. Psychological Bulletin, 139(2), pp. 352-402. doi: 10.1037/a0028446.

[4] Uttal, D. H. & Cohen, C. A. (2012), Spatial Thinking and STEM Education: When, Why, and How? In B. H. Ross (Ed.), The Psychology of Learning and Motivation, 57, pp. 147-181, Elsevier.

[5] Hegarty, M. (2011). The role of spatial thinking in undergraduate science education. In Third Committee Meeting on Status, Contributions, and Future Directions of Discipline-Based Education Research. Available: http://www7. nationalacademies. org/bose/DBER_Hegarty_December_Paper. pdf.

[6] Steinhauer, H. M. (2013). Correlation between a student's performance on the Mental Cutting Test and their 3D parametric modeling ability. Engineering Design Graphics Journal, 76(3).

[7] Lee, J., & Bednarz, R. (2012). Components of spatial thinking: Evidence from a spatial thinking ability test. Journal of Geography, 111(1), 15-26.

[8] Wood, S. D., Goodridge, W. H., & Call, B. J. (2016). Preliminary analysis of spatial ability improvement within an engineering mechanics course: Statics.

[9] National Research Council. (2006) Learning To Think Spatially.Washington, D.C.: National Academy Press.

[10] Hibbeler, R. C. (2015). Engineering Mechanics: Statics, 14th Ed. Pearson.

[11] Hibbeler, R. C. (2016). Mechanics of Materials, 10th Ed. Pearson

[12] Limbrunner, G. F., & Spiegel, L. (2008). Applied Statics and Strength of Materials. 5^{th} Ed. Pearson.

[13] Mott, R. L. (2008). Applied strength of materials. 5^{th} Ed. Pearson.

[14] Jo, I., & Bednarz, S. W. (2009). Evaluating geography textbook questions from a spatial perspective: Using concepts of space, tools of representation, and cognitive processes to evaluate spatiality. Journal of Geography, 108(1), 4-13.

[15] Maeda, Y., & Yoon, S. Y. (2011). Scaling the Revised PSVT-R: Characteristics of the first year engineering students' spatial ability. In Proceedings of the American Society for Engineering Education (ASEE) Annual Conference and Exposition (Vol. 2582).

[16] Sorby, S. A., & Baartmans, B. J. (2000). The development and assessment of a course for enhancing the 3-D spatial visualization skills of first year engineering students. Journal of Engineering Education, 89(3), 301-307.

[17] Hegarty, M. (2010). Components of spatial intelligence. In Psychology of learning and motivation (Vol. 52, pp. 265-297). Academic Press.

[18] Meyer, M., & Marx, S. (2014). Engineering dropouts: A qualitative examination of why undergraduates leave engineering. Journal of Engineering Education, 103(4), 525-548.
[19] Yoon, S. Y. (2011). Psychometric properties of the revised purdue spatial visualization tests: visualization of rotations (The Revised PSVT: R). Purdue University.
[20] Cohen, C. A., & Hegarty, M. (2012). Inferring cross sections of 3D objects: A new spatial thinking test. Learning and Individual Differences, 22(6), 868-874.
[21] Call, B. J. and Goodridge, W.H. (2016). Spatial Ability Instrument Ceiling Effect and Implications, ASEE Annual Conference. New Orleans, LA, ASEE.
[22] Richardson, J., Steif, P., Morgan, J., & Dantzler, J. (2003, November). Development of a concept inventory for strength of materials. In Frontiers in Education, 2003. FIE 2003 33rd Annual (Vol. 1, pp. T3D-29). IEEE.
[23] Kozhevnikov, M., & Thornton, R. (2006). Real-time data display, spatial visualization ability, and learning force and motion concepts. Journal of Science Education and Technology, 15(1), 111.
[24] Uttal, D. H. (2005). Spatial Symbols and Spatial Thought: Cross-Cultural, Developmental, and Historical Perspectives on the Relation Between Map Use and Spatial Cognition. In Emory Symposia in Cognition, Oct, 2002, Atlanta, GA, US. Lawrence Erlbaum Associates Publishers.