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Attributes of 3D Computer Models for Learning the Structure of Atom by Undergraduate Science Teacher's Students

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Abstract

This paper focuses on examining the effectiveness of three-dimensional (3D) computer models on student teachers' academic achievement, mental model construction, and spatial ability used in learning the "atomic models" topic in this study. The students were randomly assigned into two groups: the treatment group (TG) where 3D computer models were used and the control group (CG) where models were not used for teaching. The treatment group was instructed using 3D computer models, while the traditional learning process was adopted in the control group. With the help of SPSS software, the independent-groups t-test and one way MANOVA were performed between the control and treatment groups. Cohen's d and eta-squared values were calculated for the effects of the computer models. Through this study, it was seen that the instruction using 3D computer models contributed to students' achievement, mental model construction, and spatial ability more than the traditional instructional process.

Keywords: 3D computer models, atomic models, modelling, spatial ability, mental models

Introduction

A model is a representation of an object, a process or a system which is commonly used in science (Gilbert & Boulter, 1998). Models are constructed when an object or a phenomenon is too small, too large, too complex, too distant or inaccessible (Valanides & Angeli, 2008). Models and modelling are important in science because they play an important role in technology and the nature of science (Bekiroglu Ogan, 2006). Based on the different researches cited from Krell, Upmeier zu Belzen, and Krüger (2014), their importance in scientific communication and reasoning is well known.

Models can be classified into two types which are mental (internal) and expressed(external) models (Gobert & Buckley, 2000). Mental or internal models refer to individuals' representation of their explanatory mechanisms, while expressed or external models are the external representations of internal models. Expressed models can be diagrammatic, physical or computational models (Kim & Lee, 2013) such as 3D computer models, simulations or animations. Learning environments with computer models in science education started years ago while using some computer software, which was studied in several researches (Chen, Hsiao, & She, 2015). Computer modeling has been stated as a useful instructional tool which can be used to encourage students in the design of scientific models for describing, explaining, and predicting scientific phenomena (Jara, Esquembre, Christian, Candelas, Torres, & Dormido, 2012). They are also seen as a key process for teaching and learning science (Acher, Arca, & Sanmarti, 2007), effective pedagogical tools for teaching (Halloun, 2007), and playing a central role in the justification and formation of knowledge in science education (Koponen, 2007). There are also other studies that recognize the importance of models in science education (e.g., Gilbert & Boulter, 1998; Gobert & Buckley, 2000; Justi & Gilbert, 2000).

Students have significant difficulties when learning science (Rutten, van Joolingen, & van der Veen, 2012) because many science concepts are invisible and abstract for students. As a result, students often create numerous alternative or inappropriate conceptions and models in their minds (Chen et al., 2015). Some studies have suggested several possible solutions to overcome these hard situations such as integrating some visualization tools (Barak & Hussein-Farraj, 2013) which are important for better understanding (Habraken, 1996) and communication (Ametller & Pinto, 2002) among students about science concepts. This helps them get the knowledge that they may not obtain from verbal explanations alone (Patrick, Carter, & Wiebe, 2005). 3D computer models enhance visual explanations of scientific phenomena that are not directly observable (Gobert, 2000) and provide a meaningful learning experience to make connections between observable phenomena and targeted concepts (Kim & Lee, 2013). For science, integrating computer models in instructional contexts may provide new or different opportunities to students to improve their understanding of unobservable phenomena (Barak, Ashkar, & Dori, 2011; Gilbert 2005; Zhang, Liu, & Krajcik, 2006), and to make abstract concepts visible (Barak & Hussein-Farraj, 2013).

Learning and 3D Computer Models

Why is learning with 3D computer models effective? Reasons for better learning with 3D models can be explained by Mayer's cognitive theory of multimedia learning. According to Mayer (2003), multimedia learning recognizes when students construct mental representations from words and pictures presented to them, and they can learn more from multimedia messages than from more traditional modes of presentation involving words only. This theory is based on three presumptions: (i) the dual channel presumption, (ii) the limited capacity presumption, and (iii) the active processing presumption (Mayer & Moreno, 2002). The dual channel assumption of Mayer uses the dual coding theory of Paivio which suggests teaching students about a system using both verbal and nonverbal codes (Moreno & Valdez, 2005). Mayer's assumption states that the presentation and processing of information in humans is cognitively cared for by two independent sub-systems: one concerned with verbal, and the other concerned with non-verbal (visual) materials. Thus, this assumption supports a dual coding hypothesis. Also, the limited capacity assumption is compatible with Baddeley's working memory model and Sweller's cognitive load theory (Paas, Tuovinen, Tabbers, & Van Gerven, 2003). The limited capacity presumption states that each working memory channel can build only a limited amount of visual or verbal information at any time (Mayer & Moreno, 2003). More so, the active processing assumption of Mayer stated that students note the relevant information, organize them by selection and exchange selected information into coherent mental representations, and integrate these mental representations into prior knowledge (Urhahne, Nick, & Schanze, 2009). According to this presumption, meaningful learning involves significant conscious processing within the verbal and visual channels (Moreno & Valdez, 2005).

The "learning by modelling" role of models in science education is highlighted by Gobert, O'Dwyer, Horwitz, Buckley, Levy, and Wilensky (2011). Krell, Reinisch, and Kruger (2015) have also cited the increasing value of using models to learn scientific content knowledge. As a type of models, the use of 3D computer visualization models in the science classroom has big potential to produce higher learning outcomes in ways not previously possible (Akpan, 2001). In their article, Rutten et al. (2012) reviewed the researches about the learning effects of computers in science education. They reported that computers had improved better understandings, more knowledge expansions, and higher learning outcomes. Similarly, Chen et al. (2015) cited that many studies have suggested that multimedia tools or software enable students to overcome the difficulty of learning successfully and thus help students to achieve better learning outcomes. This study intended to explore if students' achievement performance in the atomic models topic after learning with 3D computer models are different from students who learn in the traditional learning process where teachers use only static 2D pictures, figures, etc.

Mental Models and 3D Computer Models

One of the definitions of mental models was made by Johnson-Laird in 1983 that "*a mental model is a type of dynamic representation that people use to present the world in order to understand a body of knowledge, predict the development of the world, and generate follow up actions*". Norman in 1983 also stated that "*a mental model is an interactive product that people form as a result of the interactions between the environment, people, and the artifacts of technology*" (cited in Chen et al., 2015, p.171). In the years that followed, Franco and Colinvaux (2000) stated that mental models are people's internal representations of real situations in their minds which they use for understanding and perceiving what happens. It can therefore be said that mental models are a form of an individual's knowledge representations about their environment. Mental models are cognitive representations (Buckley & Boulter, 2000) that are personal and private (Gobert 2000), unscientific, incomplete and unstable (Greca & Moreira, 2000), and unique to the observer (Coll & Treagust, 2002). The main role of mental models is to allow their builder to explain and make predictions about the system represented by it (Greca & Moreira, 2000). They are constructed by learners and scientists to interpret their experiences and to make sense of the physical world (Coll & Treagust, 2002). They also interpret the result when people face specific situations in order to solve problems and create new concepts (Vasniadou & Brewer, 1992).

According to Greca and Moreira (2000), the idea behind computer models is that mental models can be considered as `mental simulation' of the real situation of the problem and as `feasible' causal models for the system or mechanism they represent. Therefore, this study aims to explore the effectiveness of 3D computer models with respect to students' mental model construction.

Spatial Ability and 3D Computer Models

Spatial ability is defined as the capacity to generate, retain, retrieve, and transform well-structured visual images (Lohman, 1993), and it involves representing, rotating, and inverting objects in three dimensions when they are presented in two dimensions (Barnea, 2000). Spatial ability is the capacity to imagine changes which have occurred after folding or rotating the two or three dimensional objects. It comes into prominence when rotating objects, visualizing images or arranging pieces of an entire system in a suitable way (ChanLin, 2000; Hartman, Connolly, Gilger, & Bertoline, 2006; Orde, 1997). According to Hartman et al. (2006), many tasks in our world require the ability to perform spatially. Without spatial ability, success within specific disciplines such as science, engineering, the arts, etc. can be limited. Similarly, Black (2005) stated that spatial ability is a cognitive factor that is linked to high performance in science. Since science is an abstract area, Orde (1997) stated that spatial skills have brain functions for the processing of information which enable the conversation of an abstract visualization to a concrete product. As mentioned above for science learning, it seems that 3D computer models are important constructs.

Hartman et al. (2006) also stated that in some situations, it may be possible to improve the spatial ability of students. This study thus aims to investigate if 3D computer models are able to impact students' spatial ability.

Purpose

The purpose of this study was to determine the effectiveness of 3D computer models, used in the atomic models topic in the Introduction to Modern Physics course, on first year science teacher candidates' achievement, mental models, and spatial ability before and after the teaching and learning process. The study aimed to answer the following research questions:

Research Question 1: Is there any significant difference in students' achievement between a learning environment supported by 3D computer models and a traditional learning environment in the topic of atomic models?

Research Question 2: Is there any significant difference in students' mental models between a learning environment supported by 3D computer models and a traditional learning environment in the topic of atomic models?

Research Question 3: Is there any significant difference in students' spatial ability between a learning environment supported by 3D computer models and a traditional learning environment in the topic of atomic models?

Methodology of Research

Participants and Procedure

Sixty-one second-year undergraduate (science teacher candidate) students from two classes of the "Introduction to Modern Physics" course, taught by the researcher, participated in this study. The students were randomly assigned into two groups: treatment group (TG) where 3D computer models were used and the control group (CG) where models were not used for teaching. The CG was taught the atomic models topic using 2D graphics, pictures, figures, etc. from textbooks in a teacher centered approach using talk-and-chalk type lessons, while the TG was taught using 3D computer models for two weeks. The pre-tests for achievement and spatial ability were given to students of both the control and treatment groups before they were taught the topic of atomic models. The post-tests for achievement, spatial ability, and mental models were given immediately to both control group and treatment group students after they finished two weeks of learning. The framework of the teaching and learning process involved in this study is summarized in Figure 1.

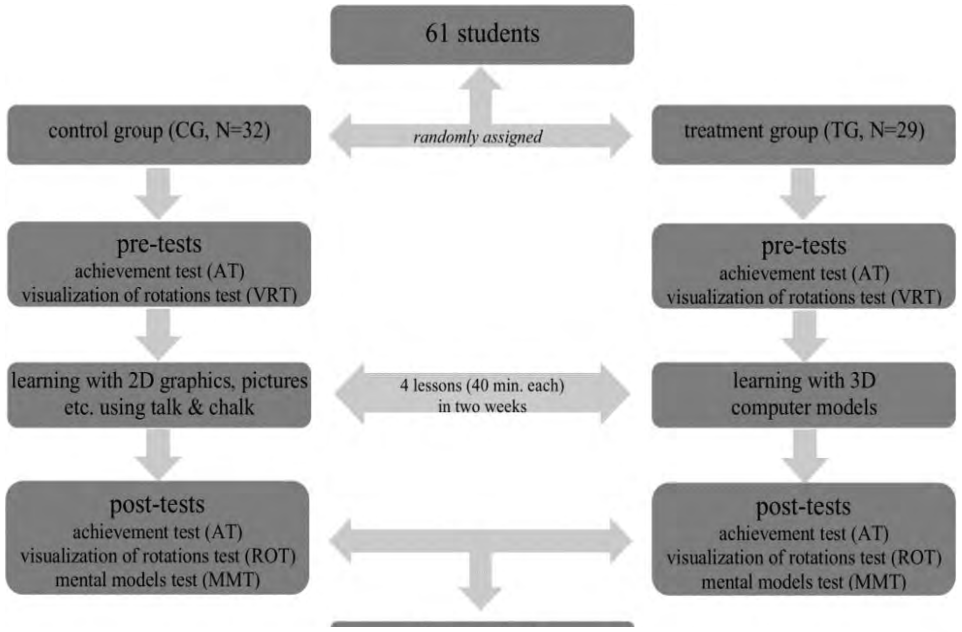


Figure 1. The framework of the study

Design of 3D Computer Models

The 3D computer models used in the treatment group for teaching were prepared using the 3D Studio Max 9 program in order to describe atomic models. This program is a professional 3D modeling, animation, and rendering software used mostly by design visualization specialists, game developers or visual effects artist. The models could also be thought of as a different type of animation films. Some properties of models used in instruction are given in Table 1.

Table 1. Properties of 3D computer models

Models	Subject	Purpose	time (s)
Model 1	Thomson's atomic model	To explain Thomson's atomic model and theory	91
Model 2-3-4	Rutherford's atomic model	To explain Rutherford's experiment (materials, process and results) To explain Rutherford's atomic model and theory To explain Rutherford's atomic model drawbacks	178 76 91
Model 5-6	Bohr's atomic model	To explain 1st postulate of Bohr's atomic model To explain 2nd postulate of Bohr's atomic model	90 90
Model 7-8	Energy levels in atom	To explain atomic excitation To explain relaxation back to the ground state of an atom	85 100

Some examples from the 3D computer models used for teaching in the treatment group are given below (Figure 2).

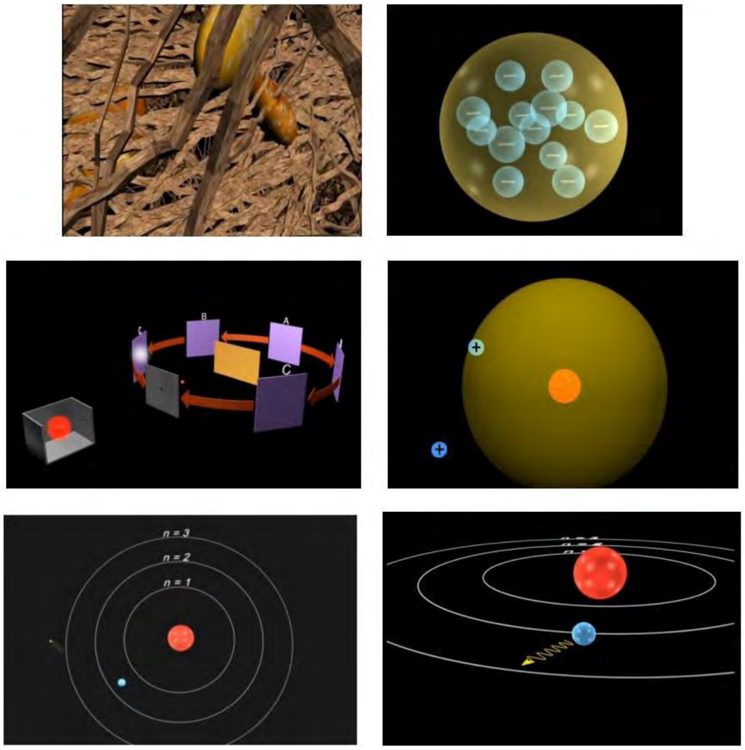


Figure 2. Screenshots from 3D computer models

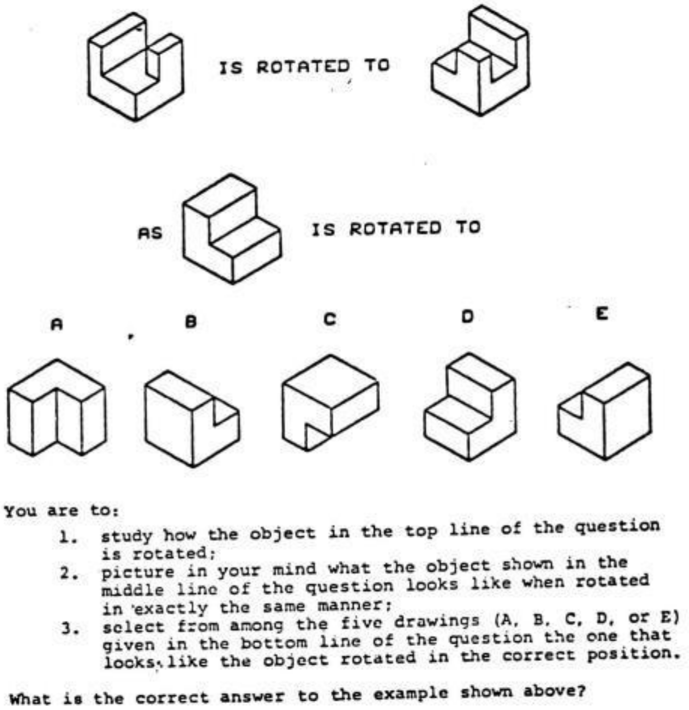
The achievement test (AT), developed by a panel of six experts (including the researcher, one science education researcher, three physics education researchers, and one chemistry education researcher), was used to determine students' achievement in the atomic models unit and to observe if there was a significant difference between the two groups. The AT is a multiple-choice test which consisted of 20 questions. Every question had five responses and a value for one point was awarded for a correct answer. Therefore, the test gives continuous scale scores ranging from 0 to 20. The Cronbach's α value was 0.72, thus the achievement test had satisfactory statistical reliability.

Mental Model Test

The mental model test (MMT) was developed to examine the accuracy of students' mental models and their construction of atomic models after instruction with 3D computer models. The same panel was involved in the process of designing the test. Five open-ended mental model construction questions related to Thomson's atomic model, Rutherford's experiment and its results, and Bohr's atomic model and his postulates were developed which required students to draw their mental models and provide explanations. For the MMT, the students' drawings and explanations in each item were analyzed. Scores from 0 to 2.0 was awarded for their wrong drawings and/or wrong explanations, 1 point was given for partial drawings and/or partial explanations, and 2 points was awarded for correct drawings and/or explanations. Thus, there was a total of 20 points for the MMT with a maximum possible score of 10 points for drawings and 10 points for explanations.

Purdue Visualization of Rotations Test

The Purdue visualization of rotations (ROT) test, one element of the Purdue Spatial Visualization Test Battery, was developed to measure students' spatial ability in terms of rotating 3D objects. ROT, which consisted of 20 items, was developed by Bodner and Guay (1997). The Kuder-Richardson (KR-20) reliability of the ROT test was found to be 0.80. This data suggested that the ROT test was internally consistent. An example of an item in the ROT test is given below (Bodner, 1976) in Figure 3:



You are to:

1. study how the object in the top line of the question is rotated;
2. picture in your mind what the object shown in the middle line of the question looks like when rotated in exactly the same manner;
3. select from among the five drawings (A, B, C, D, or E) given in the bottom line of the question the one that looks like the object rotated in the correct position.

What is the correct answer to the example shown above?

Figure 3. Directions and an example of ROT

Results of Research

Analysis of Achievement Test

Descriptive statistics and independent samples *T* test were employed to investigate if treatment group students made progress on their atomic models topic before and after learning. This was supported by 3D computer models in comparison with the control group. Analysis showed that there was no statistically significant difference between the groups in the pre-test ($T_{(59)} = 0.52, p > .05$). However, the TG students who learned the atomic models topic with 3D computer models made statistically significant differences in the post-test ($T_{(59)} = 5.95, p < .05$)

Table 2. The results of the achievement test

	Pre-test				Post-test			
	N	Mean	SD	t-value	*N*	Mean	SD	t-value
CG	32	6.47	2.34	0.52	32	12.88	2.15	5.95*
TG	29	6.14	2.61		29	15.66	1.37	

*p < .05

Cohen's *d* was also calculated for the effect size of 3D computer models in this process. The

Cohen’s *d* of the TG students in the achievement test in comparison to the CG students was found to be 1.54.

Analysis of Mental Models Test

After two weeks of the learning and teaching process, the MMT was administered to both students in the TG and the CG. As shown in Table 3, students in the TG had better scores than the students in the CG.

Table 3. The results of mental models test

		MMT-drawing		MMT-explanation		MMT-total	
	N	Mean	SD	Mean	SD	Mean	SD
CG	32	3.19	1.89	6.84	1.19	10.03	2.34
TG	29	7.76	1.38	7.21	1.74	14.97	2.57

One way MANOVA was conducted to explore whether students’ scores in the TG and the CG were statistically significant or not. It was found that Wilks’ Lambda significance value was .000 ($F_{2,58} = 57.083$, $p < .05$). Thus, there is a statistically significant difference between the CG and the TG for one or more dependent variable. As shown in Table 4, there was a statistically significant difference between the groups: MMT-drawing scores ($F_{1,59} = 114.230$, $p < .05$) and MMT-total scores ($F_{1,59} = 61.397$, $p < .05$). Also ^{2} values were found to be .659 for MMT- drawing scores and .510 for MMT-total scores. Considering the mean scores in Table 3, it is clearthat these differences are in favor of the TG.

Table 4. One way MANOVA results of the mental model test

Dependent variable	Sum of squares	df	Mean square	*F*	*p*	□^{2}
MMT-drawing	317.880	1	317.880	114.230	.000*	.659
MMT-explanation	2.006	1	2.006	.918	.342	.015
MMT-total	370.394	1	370.394	61.397	.000*	.510

*p < .05

Analysis of Purdue Visualization of Rotations Test

The descriptive statistics and independent samples *T* test was employed to determine whether the 3D computer models helped the TG students’ spatial ability in comparison with the CG. Analysis showed that there was no statistically significant difference between the groups in the pre-test ($T_{(59)} = 0.176$, $p > .05$). However, the TG students who were instructed in the atomic models topic with 3D computer models made statistically significant differences ($T_{(59)} = 4.50$, $p < .05$) from the pre-test to the post-test compared to the students in the CG. As seen in Table 5, the ROT test scores of students in the TG increased approximately to 16.7%.

Cohen's *d* was computed to determine the effect size. For the spatial ability performance of the TG students in comparison with the CG students, the effect of 3D computer models was found to be 1.16 according to the Cohen's *d* test.

Discussion and Conclusion

This study examined if 3D computer models could help students develop their learning, mental model construction, and spatial ability in the atomic models topic. The study suggests a possible way to overcome difficulties about learning abstract topics in science specific to atomic models and opens a new avenue for students to construct true and complete mental models.

According to the analysis of independent samples *T* test, 3D computer models are effective for better learning of the atomic models topic (see Table 2) in comparison with the traditional learning process with 2D representations involving pictures, figures, etc. in textbooks. This result is supported by other researches that suggest that 3D computer models provide higher academic achievement and learning performance in comparison with traditional approaches such as textbooks or 2D visualizations (Barab, Hay, Barnett, & Keating, 2000; Daugherty, Li, & Biocca, 2008; Dickey, 2005; Frederiksen, White, & Gutwill, 1999; Gobert & Pallant, 2004; Kim, 2006; Küçüközer, Korkusuz, Küçüközer, & Yürütmezoğlu, 2009; Sanger & Badger, 2001; Taylor, Barker, & Jones, 2003; Young, 2004). With this result, it can be clearly stated that abstract issues such as science 3D computer models must be included in learning and teaching if possible. Also, the effect size (Cohen's *d*) when using 3D computer models was found to be 1.54. According to McMillan and Schumacher (2006), 3D models have large effects on learning about the atomic models topic (see in page 295 for evaluation criteria of Cohen's *d*).

Another result obtained from the study focused on students' mental model construction. According to one way MANOVA analysis, students in the TG had more correct and clear mental models in comparison with students in the CG. As seen in Table 3, their drawing scores and total scores are better than those of the students in the CG. This result is supported by some researchers (e.g., Barak & Hussein-Farraj, 2013; Dalgarno, Hedberg, & Harper, 2002; Gobert & Pallant, 2004; Meheut, 2004; Urhahne et al., 2009; Wu & Chiang, 2013; Wu & Shah, 2004; Wu, Krajcik, & Soloway, 2001) who have reported that 3D computer models and representations are better tools than 2D representations or physical materials. This is because they have the potential for building new, correct, and clear models or changing incomplete mental models in students' minds. Also, the eta-squared ($\square^2 = .659$) value in Table 4 shows that 3D computer models have large effects on students mental models. For evaluation of eta-squared, Leech, Barrett, and Morgan (2005, p.133) pointed out that .31 and higher values are indicators of large effects.

Lastly, the results of the ROT demonstrated that 3D computer models are effective in facilitating students' spatial ability. As seen in Table 5, the students in the TG increased their ROT scores after instruction. This result shows parallelism with many other studies (Potter & Merwe, 2001; Alias, Black, & Gray, 2002; Kwon, 2003; Lajoie, 2003; Woolf, Romoser, Bergeron, & Fisher, 2003; Wu & Shah, 2004; Kim, Yoon, Whang, Tversky, & Morrison, 2007; Wang, Chang, & Li, 2007; Williamson & Jose, 2008) that report that 3D models and visualizations enhance students' spatial abilities. Also, Cohen's *d* was found to be 1.16, thus showing that 3D models have large effects on students' spatial ability. According to Hartman et al. (2006), it may be possible to improve the spatial ability of students.

In this study, the effects of 3D computer models for learning the atomic models topic were investigated. The results show that these models are very effective tools for better learning, better mental model construction, and enhancing spatial ability. It can be clearly pointed out that for abstract concepts in science or in other disciplines, it is important to concretize them. Therefore, it is suggested that if the usage of these models is possible, they certainly must be included in the learning and teaching process.

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