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Science learning in virtual environments: a descriptive study

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Abstract

Usually, students learn more if the method of instruction matches their learning style. Since Physics and Chemistry deal with three-dimensional (3-D) objects, the ability to visualize and mentally manipulate shapes is very helpful in their learning. In fact, much of what Physics and Chemistry students know takes the form of images. However, little attention has been given to the pedagogical effectiveness of visual stimuli in those disciplines. Computers are being increasingly used as teaching tools. The new approaches include simulations, multimedia presentations and, more recently, virtual environments. Computer-based worlds are useful to visualize physical and chemical processes allowing for better conceptual understanding. Since 3-D virtual environments need to be explored and evaluated in science education, we have created a virtual environment (*Virtual Water*) for studying phases of matter, phase transitions and atomic orbitals at the final year of high school and first year of university levels. Based on that work, we discuss the implications of visual learning in designing strategies to cater for differences in learning modes. Our study indicates that 3-D virtual environments may help students with high spatial aptitude to acquire better conceptual understandings. However, only some parameters (interactivity, navigation and 3-D perception) have shown to be relevant and only for some topics. On the other hand, stereoscopic visualizations do not seem to be relevant, with the exception of crystalline structures.

Introduction

We all learn through a variety of mechanisms and we learn more if the mode of instruction matches our learning style. Gardner (1983) and Felder and Silverman (1988) have studied different learning styles and have developed schemes for determining the preferred learning and teaching styles. According to Gardner (1983), among

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the various natural learning styles the visual-spatial style is prominent (*ie*, understanding the world through the eyes and expressing ideas through graphical arts).

Felder and Silverman (1988) have developed a scheme which classifies the learning styles preferred by engineering teachers and students into five groups (sensory/intuitive, visual/verbal, inductive/deductive, active/reflective, sequential/global). They concluded that, in general, the teaching style of most teachers does not match the learning style of most students: students learn better from processes which are sensory, visual, inductive, and active, while lectures tend to be verbal, deductive, and passive.

Visual-spatial aptitude is the ability to form and control a mental image. On the other hand, visual-spatial understanding is the ability to juxtapose, manipulate, and orient an object mentally and to create mind structures from written and verbal directions. It has been subdivided into two parts: spatial orientation, concerning the awareness or appreciation of spatial relations and image constancy; and spatial visualization, concerning mental manipulations into other visual patterns (Lord, 1985).

The visual-spatial aptitude has been strongly linked to academic mastery of several sciences. For example, when perceptual-spatial tests have been given to 64 eminent scientists they all showed superior scores in visual-spatial accuracy (Roe, 1952). Siemonhowski and MacKnight (1971) gave a series of spatial tests to a group of college undergraduates (half of them were science majors, while the other half were in non-science, liberal arts courses). They found that not only was the science group score much higher on the visual-spatial measures but also that they performed significantly better than their liberal arts colleagues. Since then, spatial aptitude has been identified in good students of Physics (Pallrand and Seeber, 1984) and Chemistry (Baker and Taylor, 1972).

Visual-spatial learners may dislike traditional schooling because of its overemphasis on lecturing, rote memorization, drill and practice exercises. Various authors have alerted educators to the need for student's involvement other than simply listening to lectures or reading books (Roe, 1952; Arnheim, 1969; Baker and Taylor, 1972; Pallrand and Seeber, 1984; Lord, 1985, 1987; Mathewson, 1999).

Motivated by these problems, we have built a virtual reality program to support the study of some concepts of Physics and Chemistry at the final year high school and first year university levels—*Virtual Water*. We have tested the software with students, looking for the relationship between visual-spatial ability and conceptual understanding.

Imagery in science

Imagery experiments focus on generating new scientific facts by means of mental images, propositional processes or both (Miller, 1996; Resnick, 1983). Many physicists used imaginary worlds to get new insights: Maxwell's demon, Einstein's train and Heisenberg's microscope have become part of the teaching of thermodynamics, special relativity and quantum mechanics, respectively. Others examples are Galileo's thought experiment on falling bodies of different weights, Faraday's visualization of lines of force surrounding charged objects and magnetic poles, Kekulé's dream of the cyclic structure of benzene and Gamow's tale about swimming in a pool of water and alcohol molecules (Gamow and Stannard, 1999). The refinement of mental experiments is supported by external graphical representations (Reiner, 1998). If visual-spatial cognition is so fundamental in science, it should also be important in teaching science. Unlike the formal manipulations so often used in teaching, thought experiments capitalize on the human capacity for imagery and allow learners to see dynamic processes and therefore to construct more perfect and more permanent understandings.

Imagery in Physics and Chemistry teaching may be justified for several reasons:

a) First of all, its sensorial directness.
b) Imagery "experiments" are likely to play a major role in strategies to discard previous misconceptions.
c) Using images, a teacher is "talking science", *ie*, emphasizes relevant concepts and principles.

In Quantum Physics and Chemistry the need for visualizing invisible entities presents a problem in high school and college teaching. Current models used to visualize the microscopic world have proven to be too difficult for students. In fact, scientists use molecular dynamics to explain chemical kinetics, gas laws, and reaction equilibrium, and orbitals to describe the electronic "clouds" in atoms and molecules, but students have problems relating the macroscopic observations to the underlying molecular and atomic behavior.

There are a variety of areas in which students' misconceptions are produced in the study of quantal phenomena. Students have only seen 2-D representations and some of them are unable to visualize a scientific model in 3-D. Difficulties arise sometimes from an inability to mentally rotate the 3-D model, a lack of depth perception, or a limited sense of perspective. A student who is not a visual learner or has problems thinking in 3-D is clearly at disadvantage.

Computer technologies for visualization

Graphics is one of the major outputs of modern computer technologies. Indeed, static and dynamic representations provide a powerful language tool when words and gestures are poor. Markham (1998) argued that graphical simulations, which accompany experimental activities, allow for mental imagery and associative knowledge. The following effective strategies have been found for teaching students with visual-spatial aptitudes (Silverman, 1998):

- Use computers to present visual materials.
- Use visual aids, such as overhead projection.
- Emphasize creativity, imagination, new insights and new approaches rather than passive learning.
- Group together gifted visual-spatial learners.

- Use manipulative materials to allow hands-on experience.
- Have students discover their own methods of problem solving.
- Avoid rote memorization, using inductive approaches.
- Find out what students have already learned before teaching them new facts.
- Emphasize mastery of higher-level concepts rather than perfection of simpler concepts.
- Engage students in independent studies or group projects which involve problem-finding and problem-solving.
- Allow students to construct, draw and create visual representations.

Advances in computer technology have lead to various high-quality educational tools including interactive programs, multimedia presentations and, more recently, virtual reality. Virtual reality is a computer interface characterized by a high degree of immersion, plausibility, and interaction, making the user believe that he is actually *inside* the artificial environment. In a perfect virtual environment, a user would be completely unable to determine whether he is experiencing a computer simulation or the "real thing". Although the concept of virtual reality has been around for over thirty years, only recently have advances in hardware and software brought this technology to within the reach of ordinary researchers and users. High-quality solutions are not yet affordable.

Virtual environments

Virtual environments, based on 3-D graphics, may facilitate the formation of conceptual models since they provide the capabilities to develop applications addressing higher skills. There are three main factors contributing to that:

1. Immersion—virtual environments may represent, in visible and manipulable forms, concepts which are intangible in real world. These activities enable students to experience phenomena themselves rather than through the eyes of a teacher or a textbook writer.
2. Interaction—educators have always asserted that a student must interact with an environment in order to learn. When interactive systems are used in learning, students move from passive observers to active thinkers. Interactions with objects of a virtual environment provide an effective and meaningful response.
3. Engagement—the experience and the empowerment brought to students by virtual environments is unique. Learners can control the computer to do their bidding in sophisticated ways, and may be intrigued by well designed virtual environments.

Static visuals have been studied by Gabel and Bunce (cited by Williamson and Abraham, 1995), who reported increased understanding at all levels. However, they fail to depict the dynamic nature of many chemical and physical processes (for example, phases of matter and phase transitions). Positive effects using animations were reported by Zeidler and McIntosh (cited by Williamson and Abraham, 1995), when coupled with conceptual change strategies, by Williamson and Abrahm (1995), who analysed the effects of computer animations on the mental models of college Chemistry students, and by Escalada and Zollman (1977), who investigated the effects of interactive digital video in a Physics classroom.

Goal of present work

More research has been called for to explore the relationship between instructional strategies via visual learning platforms and cognitive processing (Crosby and Iding, 1997). And several pilot studies have been performed to examine virtual reality's potential in education:

- *ScienceSpace* (www.vetl.uh.edu/ScienceSpace/ScienceSpace.html) is a series of virtual environments to assess the potential impact of virtual reality in science education (Physics, Chemistry and Biology);
- *VriChEL* (www.engin.umich.edu/labs/vrichel/) is a virtual environment to explore Chemical Engineering;
- *Chemistry World* (www.hitl.washington.edu/projects/learning_center/) is a virtual environment in Chemistry. Some of them are under development or evaluation.

Although the results point to some usefulness of virtual environments, recognition of what is essential and how it can be exploited is still missing.

Learning style, particularly the visual-spatial learning style, should be an interesting factor for improving virtual environments. Virtual environments should clarify the difference between spatial learners and the others.

Our study was designed to address two questions:

a) How students who do not have very strong backgrounds in Physics and Chemistry, but have high spatial aptitudes (reasoning and comprehension abilities), respond to virtual environments with and without stereoscopic visualization?
b) Does the conceptual understanding acquired with virtual reality vary with spatial aptitude?

In our opinion, the criteria for selecting the sample (pattern of low grades and indications of high spatial aptitude) should help to better understand whether the use of 3-D virtual environments, which stimulate space reasoning, benefits the students with potential for higher achievement. A similar procedure was used by Williamson and Abraham to study the influence of computational animations in the understanding of atomic and molecular models in college students of Chemistry (Williamson and Abraham, 1995).

In this work we want to analyse whether 3-D virtual environments are more useful for students with higher spatial reasoning and comprehension abilities. Since virtual environments are characterized by immersion, interactivity and 3-D perception, we are particularly interested in correlating 3-D perception with conceptual understanding. We did a comparative study between stereoscopic virtual environments (using appropriate glasses) and virtual environments restricted to the screen. Figure 1 shows schematically the relations between our variables.

Our program, *Virtual Water*, deals with molecular dynamics and atomic orbitals, at the final year high school and first year university levels. In the molecular dynamics

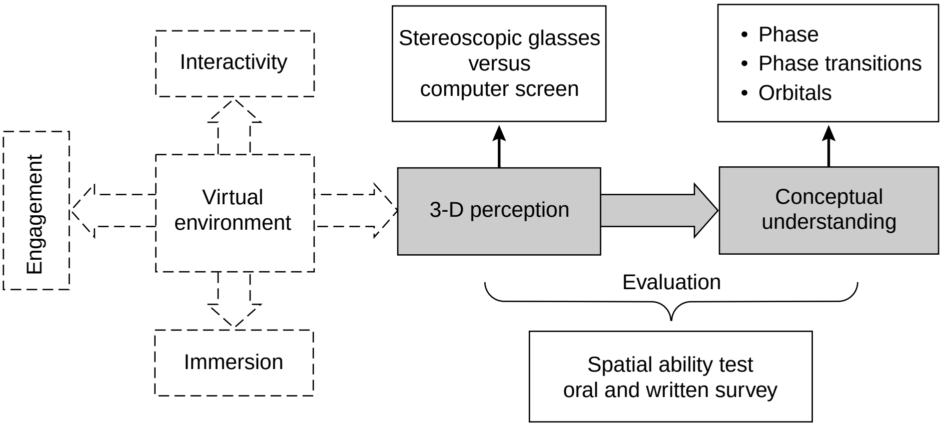

Figure 1: Schedule diagram of the descriptive research

environment we aim at the better understanding of water properties by simulating the molecular motion (Figure 2). The student may explore the liquid, gaseous and solid phases and the respective phase transitions. In the quantum mechanics environment we focus on hydrogen atomic orbitals. Students may visualize orbitals and study their symmetry.

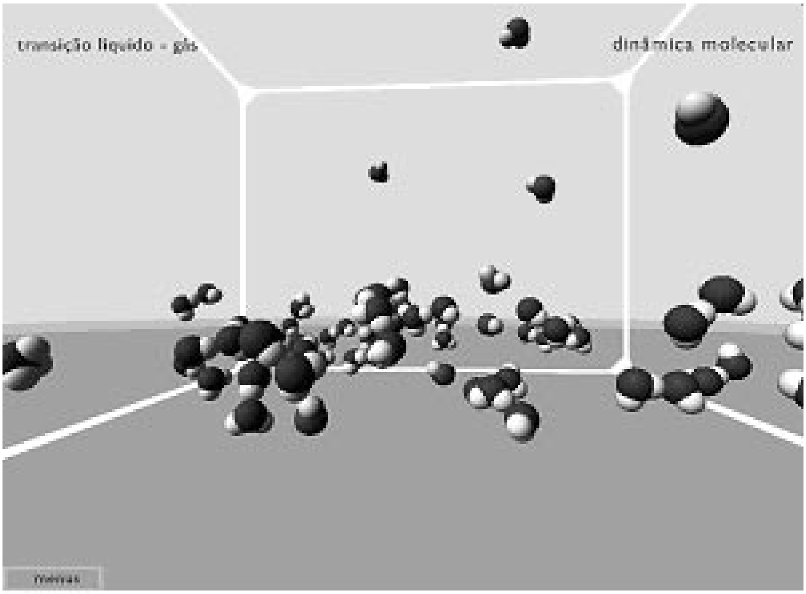

Figure 2: Virtual water snapshot showing the liquid-gas phase transition in the molecular dynamics environment

Sample

Twenty first year university students (twelve male and eight female) volunteered to participate in this study. These students came from Chemistry, Industrial Chemistry, Physics, Engineering Physics, and Engineering Civil courses in which atomic structure and phases and phase transitions had been taught. The majority (80%) were in courses of their first choice. Also the majority (80%) were attending Chemistry and Physics university classes for the first time.

Variables and instruments

Spatial aptitude is our independent variable. Spatial comprehension ability and spatial reasoning ability were measured by the tests *Provas de Avaliação da Realização Cognitiva* (PARC) designed and validated by Iolanda Ribeiro and Leandro Almeida for use with university students (Ribeiro, 1998). This test is similar to the Test of Logical Thinking (TOLT), which measures controlling variables, proportional reasoning, combinatorial reasoning, probabilistic reasoning and correlational reasoning (Tobin and Capie, 1981). PARC is a package of nine multiple-choice questionnaires. PARC's spatial ability section contains 25 items of spatial comprehension (rotation 2-D figures), while its spatial reasoning tests include tasks of perceptual orientation with 3-D figures (ability to rotate, orient, and realign a mental image).

Attitude towards instruction (which was separated into conceptual comprehension and motivation) is the dependent variable. Conceptual comprehension is the degree to which the student's understanding of a concept corresponds to the scientific explanation. Understanding was determined by student's oral explanations in a guided interview (each interview took about 45 minutes and was tape-recorded) and by a written questionnaire. The Particulate Nature of Matter Evaluation Test (PNMET) and the interview guide developed by Griffiths and Preston (1992), for studying final year students' misconceptions of atoms and molecules, were adapted to our study. Satisfaction was also determined by a questionnaire.

Some items were based on the Attitudes toward Computer Technologies (ACT) to measure students' perceived usefulness of and comfort/anxiety with computer technologies (Delcourt and Kinzie, 1993). The ACT, which was developed and validated for use with teacher education students and practicing teachers, was employed by Escalada and Zollman (1977) to investigate the effects of interactive digital video in Physics student learning and attitudes. Our variables were not made known to the students.

Coverage of concepts

All concepts considered in our study are microscopic. Although atomic and molecular structures and behaviours explain a plethora of chemical and lot of physical phenomena, students have difficulties understanding many concepts related to gases, liquids and solids (Krnel *et al*, 1998; Mullet and Gervais, 1990; Lee *et al*, 1993; BouJaoude, 1991; Domenech *et al*, 1993; Novick and Nussbaum, 1978; Benson *et al*, 1993; Krnel, 1994; Pereira and Pestana, 1991) and quantum concepts (Styer, 1996; Petri and Niedderer, 1998; Griffiths and Preston, 1992). For example, some drawings of high-school students show different forms of particles for different states of matter: gas molecules are round, molecules of liquids have irregular forms, molecules of solids are shown as cubes (Haidar and Abraham, 1991, cited by Krnel *et al*, 1998). Other studies have shown misconceptions of high school students related to the shape, size, weight, and animism of atoms (Griffiths and Preston, 1992).

Procedures

Traditional learning requires students to master symbolic systems before they may understand content. Our expectation was that by allowing students decide about how their "world" was to appear, and then having them visit their virtual environment, would help students who do not do very well with a symbol-oriented pedagogy.

First we evaluated students' spatial ability: they were given the PARC test for spatial ability. The subsequent interview included a translation of the problem into the microworld and a raising of hypotheses to be tested. Before entering the simulation, they had to respond to several questions and were given the opportunity to modify their responses after the virtual exploration. The *Statistical Package for the Social Sciences* (SPSS version 10 for Windows) was used for data analysis.

Results and discussion

The grade point averages of our Physics and Chemistry students lie between values of 11 and 16 (out of 20), with an average of 13.5, a median of 13.0 and standard deviation of 1.5. Concerning software, our sample students have a good knowledge of common computer applications (spreadsheets, word processor, browsers, etc) as well as with pedagogical software, eg, *Interactive Physics*, from *Knowledge Revolution*, and *Creative Physics*, from *Stewart Software*. None of the students had used virtual reality before the study. Regarding their spatial aptitude, spatial comprehension is more homogeneous than spatial reasoning, with ¾ of the data over 19 (first quartile), and an upper median (20). Spatial reasoning is less homogeneous, with ¾ of the data lower than 20, and a median of 16 (Figure 3).

With the Wilcoxon test we intend to detect differences between conceptual comprehension without the software and using the two visualization processes. For this purpose, the results from conceptual comprehension about phases, phase transitions and orbitals were analysed.

Figure 4 shows histograms concerning water phases. For both visualization methods the distribution curves deviate slightly to the right, with equal negative values (averages of –1.2 and standard deviation of 0.81), which denotes better results with equipment and software. In fact, the results of the Wilcoxon test denote that the differences between conceptual comprehension with screen and stereoscopic views are statistically significant ($p < 0.05$).

Concerning phase transitions, the histograms (Figure 5) also present negative values, denoting better results with the software, the stereoscopic view showing advantage

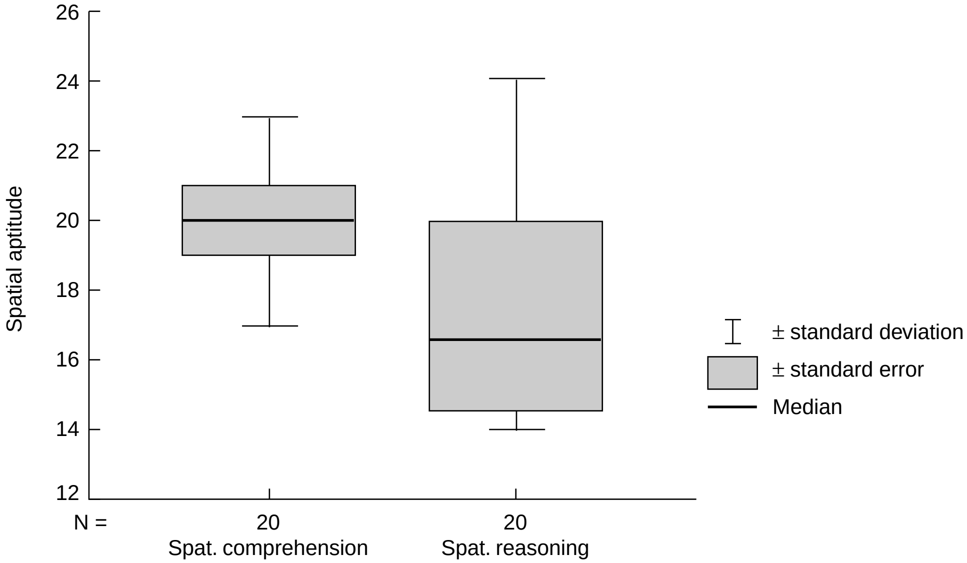

Figure 3: Box plots for spatial aptitude

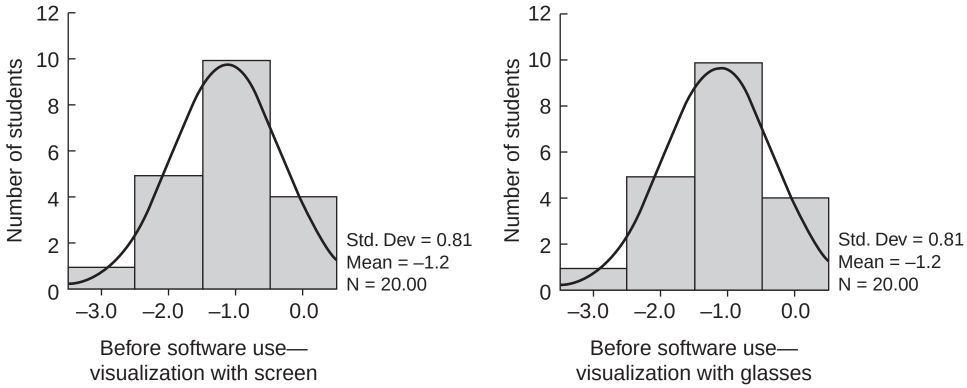

Figure 4: Water phases—histograms showing the differences between: a) results before software use and results with screen visualization; b) and results before software use and results with visualization through stereoscopic glasses

(high absolute average). In effect, the results of the Wilcoxon test indicate that these differences are statistically significant ($p < 0.05$).

For conceptual comprehension orbitals the results are different. Although the distribution curves (Figure 6) for screen and stereoscopic view indicate negatives average values (–0.5 and –1.0 respectively), the Wilcoxon tests denote that these differences are not statistically significant.

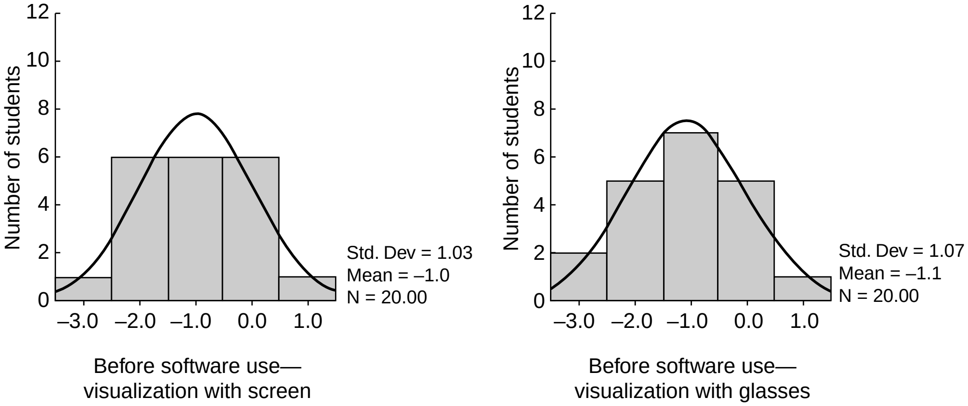

Figure 5: Water phase transitions—histograms showing the differences between: a) results before software use and results with screen visualization; b) and results before software use and results with visualization through stereoscopic glasses

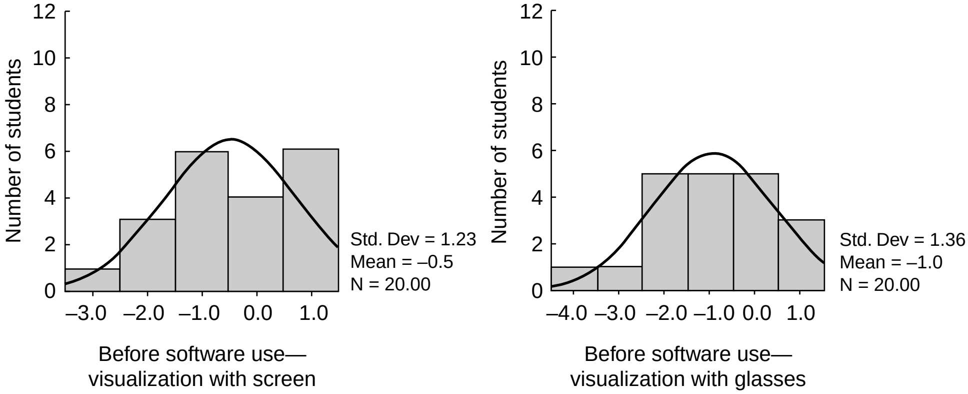

Figure 6: Orbitals—histograms showing the differences between: a) results before software use and results with screen visualization; b) and results before software use and results with visualization through stereoscopic glasses

These results are consistent with Spearman correlations between spatial aptitude (spatial comprehension and spatial reasoning) and conceptual comprehension, for the two visualization forms. Table 1 show the results (values in brackets indicate the significance level).

Correlations exist between spatial aptitude and conceptual comprehension of phases and phase transitions, but not with orbitals, for both forms of visualization. The statistical significance level is 5%, except for spatial ability and phase transitions correlations for both forms of visualization, which is higher (1%).

Table 1: Correlations between spatial aptitude and conceptual comprehension

	Phases		*Phase transitions*		*Orbitals*	
	Screen	*Stereoscopic View*	*Screen*	*Stereoscopic View*	*Screen*	*Stereoscopic View*
Spatial Comprehension	0.512 ($p < 0.05$)	0.593 ($p < 0.05$)	0.578 ($p < 0.01$)	0.626 ($p < 0.01$)	0.295	0.441
Spatial Reasoning	0.454 ($p < 0.05$)	0.501 ($p < 0.05$)	0.515 ($p < 0.05$)	0.557 ($p < 0.05$)	0.430	0.420

Assuming that these outcomes indicate good results for conceptual comprehension of phases and phase transitions, we should clarify which virtual environments variables are responsible for that, and why stereoscopic view is better than screen view for the conceptual comprehension of phase transitions. We also intend to explain why the results are not satisfactory for orbitals.

The scenery characteristics and the students responses to the free format questions allow for explanations. The main differences between the three types of sceneries are shown in Table 2.

Students refer to the differences of orbitals scenery characteristics in the free format questions:

- "The software is especially good for 3-D behaviours" (similar responses from various students);
- "The phases and phase transitions sceneries give a clearer picture of the molecular behaviour";
- "In the orbitals scenery the model really helped in the area of real versus mathematical";
- "There is no much difference between visualization with and without stereoscopic glasses in orbitals scenery" (responses from different students);

Table 2: Main differences between sceneries

	Sceneries Types		
Sceneries Characteristics	*Phases*	*Phase Transitions*	*Orbitals*
Dynamical behaviour	Water molecules behave dynamically according to their phase		All orbital models are static
3-D perspective	Yes, from any referential inside or outside the water box and from a water molecule viewpoint		Yes, but only in front of orbital model
Interactivity	Very high		Very low
Navigation	Yes		No

– "The stereoscopic view is more useful for phases and phase transitions" (similar responses from different students).

In order to understand these results we proceed with the analysis of virtual environment (proof) and conceptual comprehension (dependent) variables, identifying correlations between them.

We obtained three series of data concerning comprehension without software, with software and screen visualization, and with software and stereoscopic view (Table 3). For comprehension with software (with the two visualization processes) we obtained a higher average than for comprehension without software. Conceptual comprehension of orbitals showed the lowest averages, while phases and phase transitions yielded similar averages.

Concerning phases and phase transitions after software use, ¾ of the results are above 4 with 2 units of amplitude. Phase transitions have the lowest amplitude variation for conceptual comprehension without software.

These results confirm the existence of an association between spatial aptitude and conceptual comprehension only for phases and phase transitions. For phase transitions we have noted a special association with spatial ability. Since in a virtual environment, learning occurs in 3-D space, we suspect that technical differences between the phases and orbitals sceneries (for example, lack of some navigation features in the orbitals scenery) might have cancelled out any advantages arising from high spatial ability.

Concerning visualization (Table 4), the average is higher than 4 in all parameters, except immersion with screen (which is not surprising). For stereoscopic view the averages are all higher than for visualization with screen, except for 3-D perception (which is smaller, strangely) and interactivity (which is equal).

As shown in Figure 7 all boxes plots have ¾ of the data higher than 4, except for navigation with screen, for which the results are almost all equal to 4, and for immersion with screen, for which ¾ of the data are under 4.

Table 3: Averages and standard deviations for conceptual comprehension

	Phases			*Phase Transitions*			*Orbitals*		
	Without software	*Screen*	*Stereo glasses*	*Without software*	*Screen*	*Stereo glasses*	*Without software*	*Screen*	*Stereo glasses*
Average*	3.15	4.30	4.30	3.20	4.20	4.30	2.10	3.55	4.05
Standard deviation	0.93	0.66	0.57	0.70	0.62	0.80	1.25	0.94	0.60

* out of 5

Table 4: Descriptive statistics of the visualization processes

Three-dimensional virtual environment			*Average**	*Standard Deviation*
Visualization Process	Screen	Immersion	3.70	0.86
		Interactivity	4.25	0.64
		Engagement	4.35	0.67
		Navigation	4.10	0.55
		3-D perception	4.30	0.66
	Stereo glasses	Immersion	4.35	0.75
		Interactivity	4.25	0.64
		Engagement	4.40	0.68
		Navigation	4.20	0.62
		3-D perception	4.15	0.59

* out of 5

In fact, a computer with a screen (*window on world*, in virtual reality terminology) is not an immersive system. In an authentic immersive system the user should have the perception of being inside a scenery, which appears according to our movements (eg, it shows a new scene when the head is moved). Research conducted by Byrne (www.hitl.washington.edu/projects/learning_center/) on the use of virtual reality as an educational tool in Chemistry (*Chemistry World*) has indicated that immersion is not an important variable in learning through virtual environments, in contrast to interactivity. Regarding 3-D perception by stereo glasses we have verified, through students opinions, that it is useful for observing complex structures (like the structure of ice) and some dynamical behaviours (like phase transitions).

These results agree with the quality parameter variables (Table 5). Results on glasses ergonomics show that students have a favourable opinion about their use (average of 4.1 and standard deviation of 1.52), according to user preference variable (average of 4.15 and standard deviation of 0.93), in spite of the lower average about commodity (average of 3.55 and standard deviation of 1.1). The high values of standard deviations in opinion about utilization and commodity help to understand this result.

We are particularly interested in the associations between visualization processes and conceptual comprehension. With respect to the screen (Table 6) there are significant correlations between conceptual comprehension of all subjects and visualization process parameters, except immersion. Lower correlation values ($p < 0.05$) exist for conceptual comprehension of phases and interactivity and 3-D perception. Concerning orbitals, for which conceptual comprehension results were not good enough, correlation with navigation and 3-D perception was the only significant one found.

In relation to stereoscopic visualization (Table 7), we found strong correlations between immersion, engagement and phases, and, on the other hand, interactivity, engagement, 3-D perception and phase transitions. For the remaining variables we found significant

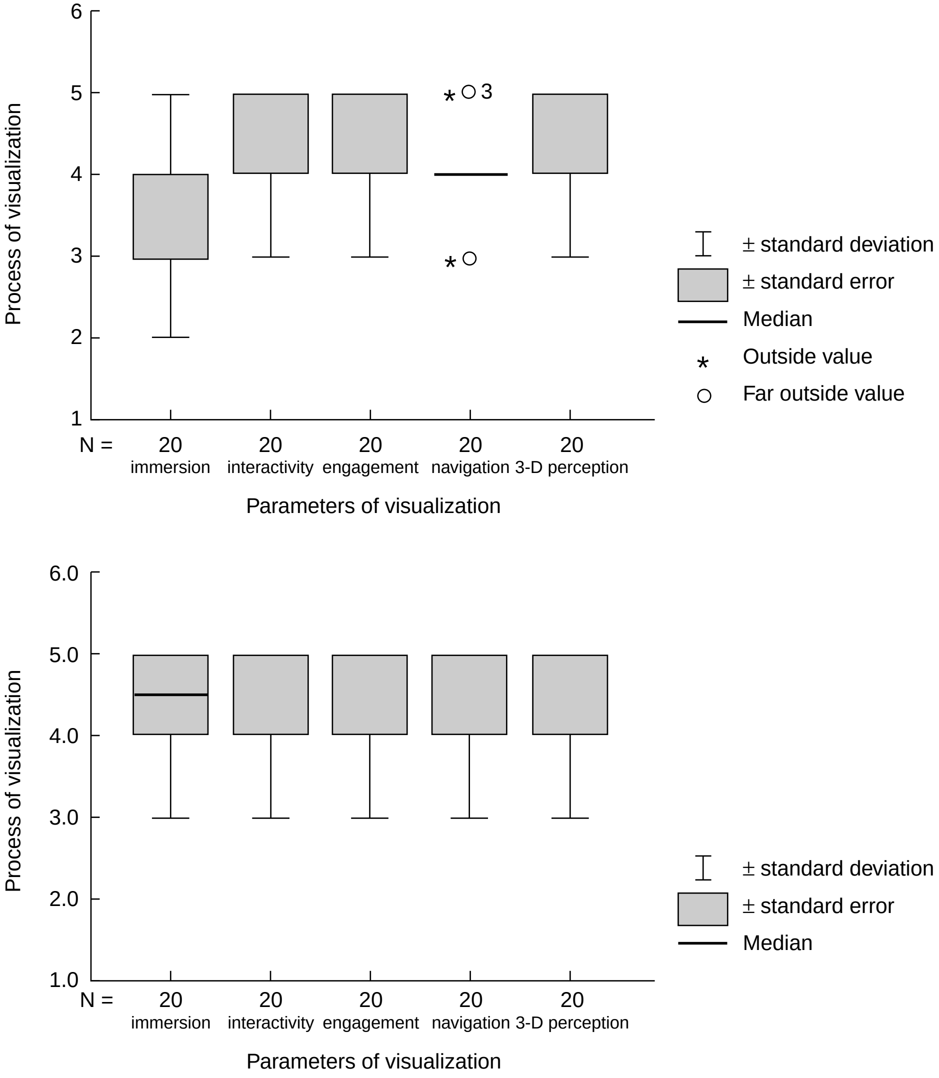

Figure 7: Box plots for the two visualization processes: a) visualization with screen; b) visualization with stereo glasses

statistical correlations of 5%, except for immersion, interactivity, engagement and conceptual comprehension of orbitals.

In response to the free format questions the students said that:

– "This visualization will stay with me";
– "This experience will stay in memory much longer than any notes or lectures" (similar responses);

Table 5: Quality descriptive statistics

Three-dimensional virtual environment			*Average**	*Standard Deviation*
Quality	Ergonomics (glasses)	Commodity	3.55	1.10
		User preference	4.15	0.93
		Opinion about utilization	4.10	1.52
	Software	Scenery transition	3.85	0.81
		Scenery rendering	4.30	0.57
		Students' expectations	3.85	0.67

* out of 5

Table 6: Correlations between visualization process and conceptual comprehension using computer screen

	Computer Screen Visualization				
Conceptual comprehension	*Immersion*	*Interactivity*	*Engagement*	*Navigation*	*3-D Perception*
Phases	0.154	0.473 ($p < 0.05$)	0.631 ($p < 0.01$)	0.578 ($p < 0.01$)	0.552 ($p < 0.01$)
Phase transitions	0.417	0.769 ($p < 0.01$)	0.653 ($p < 0.01$)	0.675 ($p < 0.01$)	0.707 ($p < 0.01$)
Orbitals	–0.125	0.198	0.128	0.459 ($p < 0.05$)	0.560 ($p < 0.05$)

Table 7: Correlations between visualization process and conceptual comprehension using stereoscopic view

	Stereoscopic View				
Conceptual comprehension	*Immersion*	*Interactivity*	*Engagement*	*Navigation*	*3-D Perception*
Phases	0.588 ($p < 0.01$)	0.459 ($p < 0.05$)	0.841 ($p < 0.01$)	0.536 ($p < 0.05$)	0.453 ($p < 0.05$)
Phase transitions	0.492 ($p < 0.05$)	0.579 ($p < 0.01$)	0.872 ($p < 0.01$)	0.499 ($p < 0.05$)	0.584 ($p < 0.01$)
Orbitals	0.441	0.256	–0.071	0.542 ($p < 0.05$)	0.504 ($p < 0.05$)

- "Very good form of learning, a good complimentary device";
- "Very good, a lot of potential";
- "It's easier to understand things when you can visualize them".

Conclusions

We conclude that the view of 3-D computer animations implies an increased conceptual understanding of some contents by students with high spatial abilities. The responses after observing *Virtual Water* were in general more accurate, more complete, and showed a better conceptual understanding than the previous responses given by the same students. The concepts which have shown to be better understood were those associated with phases and phase transitions (which had more interactivity). Interactivity, navigation and 3-D perception were the more influential visualization parameters for those concepts.

The main strength which we have found in virtual reality is, not surprisingly, the ability to visualize situations which can not be seen otherwise and, moreover, to immerse the student within them. A photo or movie may show students the internal geometry of ice, but only virtual reality allows them to enter inside and observe it from any viewpoint. An animation could illustrate the mechanism of solid-liquid phase transition, but virtual reality provides students with a much stronger sense of "being there". Students reported an increased motivation for the formalism behind molecular dynamics after having explored the 3-D motion and its relations to the physical properties.

However, stereoscopic visualization does not seem to contribute much to conceptual understanding. In spite of some sense of immersion provided by the stereoscopic view, results for screen and stereoscopic glasses were almost identical. The single stereoscopic feature which most students seemed to really appreciate was the 3-D structure of the ice structure. They generally reported that this gave them a more tangible grasp of a solid state structure. One of the values of virtual reality is precisely its ability to give substance to abstract concepts. As one student said, "when I work on a physics or chemistry problem for an hour, all I have to show for my efforts is a number, which doesn't always mean anything to me. This program gave me a chance to *see* water molecules behaviour for the first time".

Our findings will be non-generalisable without a method for evaluating the impact on learning, a work that goes beyond this descriptive study. We present some suggestions for further research: test students with lower reasoning ability; use more complex animations; examine other areas of Physics and Chemistry; examine long-term retention of concepts; and examine transferability of concepts to other subjects.

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