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ABSTRACT

This report describes a study that investigated the relationship between mental imagery and problem solving in physics, specifically in kinematics. A distinction is made between visual imagery and spatial imagery used in solving physics problems. The results of this study indicate that while spatial imagery may promote problem solving success, the use of visual imagery presents an obstacle to problem solving in kinematics. (Contains 23 references.) (WRM)

Students' Use of Imagery in Solving Qualitative Problems in Kinematics

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Objectives

Historically, there is much evidence that mental imagery plays a central role in physics conceptualization processes and in scientific discoveries. Research that analyzes the processes of physics discoveries such as Galileo's laws of motion, Maxwell's laws, Faraday's electromagnetic field theory, or Einstein's theory of relativity, emphasizes the extensive use of visual/spatial images and their crucial function in these discoveries (Miller, 1986; Nersessian, 1995; Shepard, 1996). This gives rise to the idea that mental images also play an important role in students' physics learning and problem solving. The main goal of this study is to investigate the relationship between imagery and problem solving in physics, specifically in kinematics.

The domain of physics chosen for the purpose of this study is kinematics, which describes the motion of objects without regard to mass. Kinematics was chosen because of its dependence on a diversity of visual/spatial representations, including graphical schematic representations (e.g., vectors of force or velocity or graphs of motion) as well as concrete physical representations (e.g., blocks, pulleys, or springs).

Theoretical Framework

In the physics education literature surprisingly little attention has been paid to understanding the role of imagery in problem solving processes. Research that investigates the differences between expert and novice problem solving in physics focuses mostly on verbal aspects of problem representation and semantic knowledge of physics laws (Larkin, 1982; Chi & Glaser, 1988; Ericsson & Smith, 1991). It has been noted that diagrammatic representations "can support extremely useful and efficient computational processes" (Larkin & Simon, 1987, p. 99) during problem solving, but this claim has not been tested empirically. Furthermore, the United States Employment Service includes physics in the list of occupations requiring a high level of spatial ability, i.e. the ability to perform spatial transformations with mental images or their parts (Dictionary of Occupational Titles, 1991). No attempts have been made in science education research, however, to understand how imagery contributes to learning and problem solving in physics.

Most of the previous studies that examined the relationship between imagery and problem solving were carried out in the field of mathematics education. The results of these studies are not entirely consistent. On one hand, extensive research has shown that there is a significant correlation between spatial ability and mathematical performance (e.g., Battista, 1990; McGee, 1979; Sherman, 1979; Smith, 1964). On the other hand, the research findings also suggest that persons who prefer to use imagery when processing mathematical information (so-called "visualizers") do not always do better on certain mathematical tasks than persons who prefer a verbal-logical processing mode (e.g., Lean & Clements, 1981).

In contrast to previous educational research that considers imagery ability to be a general mental skill, the current research differentiates between various imagery abilities. This approach to imagery is consistent with findings of cognitive psychology and neuroscience research: imagery is not general and undifferentiated, but composed of different, relatively independent visual and spatial components (e.g., Baddeley, 1992; Farah *et al.*, 1986; Kosslyn, 1995; Poltrock & Agnoli, 1986; Underleider & Mishkin, 1982). *Visual imagery* refers to a representation of the visual appearance of an object, such as its form, color, or brightness. *Spatial imagery* refers to a representation of the spatial relationships between parts of an object, the location of objects in space and their movements; it is not limited to the visual modality (i.e. one could have an auditory or tactile spatial image). Cognitive neuroscience studies (e.g., Farah *et al.*, 1986) provide strong evidence for a dissociation between these two aspects of imagery: following brain lesions, patients can be extremely impaired in tasks tapping visual aspects of imagery while showing normal performance in tests of spatial imagery. Furthermore, cognitive psychology research (e.g., Baddeley, 1992) also suggests that the nonverbal component of working memory should be divided further on its spatial and visual components: visual imagery tasks are impaired by concurrently viewing irrelevant pictures but not by arm movements, whereas spatial imagery tasks are impaired by arm movements, but not irrelevant pictures.

We suggest that dissociation between visual and spatial imagery also exists in individual differences in imagery ability, i.e., some individuals are especially good in the construction of vivid and detailed visual images, whereas the others may succeed in spatial transformations such as mental rotation of a complex three-dimensional image. In this research we refer to *visual ability* as ability related to constructing mental images of vivid color and detail. *Spatial ability* is considered here as a subset of imagery abilities, related to spatial transformations of mental images or their parts.

The focus of this research is to identify imagery abilities that affect problem solving in physics. We hypothesize that spatial ability is an important component of imagery ability in physics problem solving. This hypothesis is based on the fact that the majority of physical strategies involve schematic spatial representations in the forms of graphs, diagrams, or physical models. In contrast, visual ability may present an obstacle to problem solving processes, since it concentrates the problem solver's attention upon concrete pictorial details, and thus, makes it difficult to formulate necessary abstraction.

Integration of Quantitative and Qualitative Research Methods

This research makes use of both quantitative and qualitative research methods. First, we examined the quantitative relationship between the ability to solve different types of kinematics problems and spatial imagery tasks. The reason for starting with the quantitative approach is that spatial ability factors, being established and defined through psychometric research, can be more easily interpreted through quantitative measures. Second, in order to gain insight into the nature of statistical correlation found in the quantitative part of the research as well as to investigate the relationship between visual imagery and physics problem solving, we employed qualitative methods.

Quantitative Study: Method and Instrumentation

Sixty undergraduate psychology students, who had not taken any physics courses at the college level participated in this research. The students were presented with the following tests:

Spatial ability tests: Students' levels of spatial ability were assessed by means of the following questionnaire related to three main sub-factors of spatial ability:

- *Spatial Visualization* - the ability to manipulate or transform the image of spatial patterns into other visual arrangements. Students' levels of spatial visualization were assessed by a paper folding test and a form board test (from the KIT of Factor Referenced Cognitive tests by Ekstrom, French, & Harman, 1976);
- *Mental Rotation* - the ability to solve simple mental rotation problems quickly, without imagining the oriented self. Students' levels of mental rotation were assessed by a card rotations test and a cube comparison test (from the KIT of Factor Referenced Cognitive tests by Ekstrom, French, & Harman, 1976);
- *Spatial Orientation* - the ability to imagine how a stimulus array will appear from another perspective. Students' levels of spatial orientation were assessed by means of spatial layout test, developed for the purpose of this research. In this test, the subject is given a spatial layout of seven objects. Then, he/she is asked to take different perspectives in that layout and point to objects' location in space relative to each other. The internal reliability of the test is 0.83.

Physics Questionnaire: To classify kinematics problems into definite number of classes, whose solutions may require the use of spatial imagery, we reviewed qualitative kinematics problems typically presented in physics textbooks as well as in mechanics diagnostic tests aimed to assess students' understanding of the laws of mechanics (e.g., the Mechanics Diagnostic Test by Halloun & Hestenes, 1985; the Force Concept Inventory Test by Hestenes, Wells, & Swackhamer, 1992). Based on this pool, five different classes of kinematics problems were distinguished:

- *Extrapolation problems*, that require predicting the motion of an object from an observed to an expected path;
- *Speed problems*, that require the student to make a qualitative judgment about the object's absolute velocity (e.g., to determine if object's velocity is constant, increasing, or decreasing);

- *Graph problems* - that involve relating one type of graph to another, connecting a graph to the real-world situation, and matching verbal information with relevant features of a graph;
- *Frame of reference problems*, that imply the transition from one system of reference to another;
- *Comparison problems*, that require students to compare one object's motion (e.g., object's trajectory, velocity, or acceleration) to that of another.

The questionnaire included 19 kinematics problems, with 3-4 problems of each of the above types; all the kinematics problems involved visual-spatial representations in the form of graphs or diagrams. The internal reliability of the test is 0.81.

Cognitive Style Questionnaire: The students were also presented with a visualizer/verbalizer cognitive style questionnaire, which measured their preference to use imagery as opposed to verbal-logical codes when attempting to solve problems. This questionnaire was included in this study to clarify the ambiguity in mathematics education findings as to the relationship between spatial ability, problem solving performance, and visualizer/verbalizer style. The questionnaire includes five problems that may be solved either by visual or analytical methods. For each visual solution a score of 1 was allocated and for each non visual solution a score of zero, irrespective of whether the answer was right or wrong. The internal reliability of the test is 0.80.

Verbal Ability Test: In order to discriminate between the effect of general intelligence (e.g., composed of verbal ability and spatial ability) on physics problem solving from the effect of spatial ability on physics problem solving, the subjects' levels of verbal ability were assessed by means of the advanced vocabulary test (from the KIT of Factor Referenced Cognitive tests by Ekstrom, French, & Harman, 1976).

Quantitative Study: Results

The Relationship Between Cognitive Factors and Kinematics Problems To analyze the quantitative data, bivariate correlation analysis and factor analysis were carried out. The results of the bivariate correlation analysis between kinematics problems and the cognitive factors (spatial visualization (SV), mental rotation (MR), spatial orientation (SO), verbal ability, and cognitive style) are presented in Table 1.

Table 1: Correlations between kinematics problems and cognitive factors (N=60)

	Extrapolation	Speed	Graphs	Frame of reference	Comparison	All problems
Paper folding (SV)	0.35**	0.25	0.18	-0.11	0.29*	0.33**
Form board (SV)	0.34*	0.22	0.20	0.16	0.20	0.30*
Card rotation (MR)	-0.02	0.04	0.12	-0.07	0.16	0.07
Cube comparison (MR)	0.20	0.06	0.19	0.11	0.19	0.19
Spatial layout (SO)	0.18	0.16	0.26*	0.26*	0.18	0.29*
Cognitive style	-0.23	-0.07	-0.13	-0.12	0.18	-0.09
Verbal ability	0.02	0.15	0.38**	0.05	0.25	0.24

** Correlation significant at the 0.01 level (2-tailed)
* Correlation significant at the 0.05 level (2-tailed)

In general, students' overall scores on kinematics questionnaire correlate significantly with the paper folding test ($p = 0.01$), form board test ($p = 0.02$), and spatial layout test ($p = 0.02$). These results strongly suggest that spatial visualization and spatial orientation are important abilities in physics problem solving. In contrast, the mental rotation tests (card rotation and cube comparison) did not correlate significantly with any kinematics problems. It seems that the ability to solve mental rotation problems quickly is not as crucial as spatial visualization and spatial orientation ability in physics problem solving. As for verbal ability, it does not correlate with students' overall scores on kinematics questionnaire. This supports the conclusion that spatial ability is the most important component of general intelligence factor that contributes to physics problem solving.

In order to explore more thoroughly the relationships between kinematics problems and cognitive factors, a factor analysis was performed on the data set. The results of the factor analysis show that all kinematics problems can not be treated as a single factor: while some types of kinematics problems require a high level of spatial ability, other types of problems require semantic knowledge of physics laws. For instance, the evaluation of an object's speed is a type of problem whose solution primarily depends on a subject's knowledge of physics laws. In contrast, the types of problems whose solutions depend basically on spatial ability are extrapolation problems and frame of reference problems. Surprisingly, graph problems are found to be loaded on verbal ability factor. The results of the next qualitative part of the research have shown that the reason for this is that for most subjects, who have not studied physics, but have had several mathematics courses, it was easier to solve graph problems by applying purely verbal-analytical strategies.

Cognitive Style Questionnaire According to the results of the current study, the cognitive style questionnaire does not correlate with either kinematics problems or with any of the spatial ability tests. These results are consistent with other mathematical education education research that no positive correlation exists between visualizer/verbalizer style, spatial tests, and problem solving performance. However, the conclusion that visualizers' performance on spatial tests is no better than verbalizers seems inexplicable and doubtful. Although analytical strategies may be involved in the solution of some spatial tasks, there is a convergent evidence from a numerous cognitive psychology studies (e.g., Baddeley, 1992; Baddeley & Lieberman 1980) that spatial tasks primarily involve spatial transformations of visual stimuli.

To investigate this further, we examined the frequency distribution of visualizers and verbalizers with respect to their spatial ability levels: First, on the basis of a median split performance, we classified the participants into the following groups: *visualizers* (i.e., students who preferred visual methods) and *verbalizers* (i.e., students who prefer verbal-logical codes). Second, for each participant, we calculated his/her total standard score (Z score) for all spatial ability tests (i.e., paper folding, form board, card rotation, cube comparison, spatial layout). According to their standard scores, the participants were classified as low spatial (bottom 25% of the distribution), high spatial (top 25% of the distribution) or average spatial (others). Figure 1 presents the percentage of visualizers and verbalizers who scored low, average and high on spatial ability tests.

As is easy to see from the Fig. 1, the distribution of verbalizers across spatial ability levels is close to normal, that is, the majority of verbalizers are of average spatial ability. As for visualizers, their distribution is bimodal, in that it exhibits negative kurtosis with a pileup of cases to the left and the right tails. This implies that, in contrast to verbalizers, visualizers are not a homogeneous group; there are actually two contrasted groups -- visualizers of high spatial ability and visualizers of low spatial ability. In order to determine whether a systematic relationship between students' levels of visuality and their spatial ability levels does exist, a chi-square analysis was carried out. According to the results of the chi-square test, the relationship between visuality and spatial ability is statistically significant: $\chi^2 = 10.6$ ($p = 0.005$), df=2.

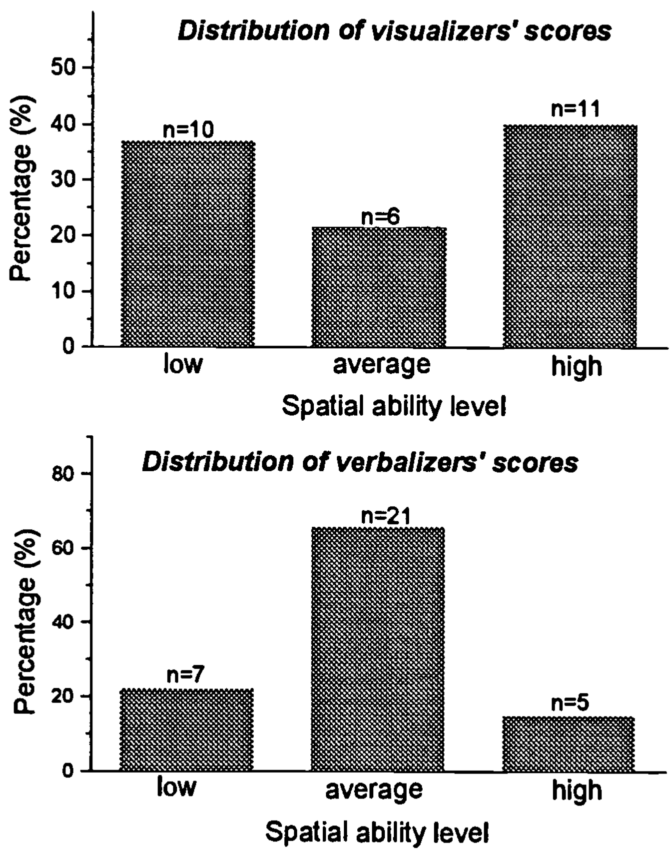

Fig. 1 Percentage of verbalizers and visualizers who scored low, average, and high on spatial ability tests

Other researchers (e.g., Lean & Clements, 1981) have not taken into account the fact that the distribution of visualizers' scores with respect to spatial ability is not normal. This led previous researchers to the misleading conclusion that verbalizers "outperform more visual students on both mathematical and spatial tests (e.g., Lean & Clements, 1981, p.296).

It should be noted that the distribution of visualizers and verbalizers with respect to their scores on verbal ability tests is normal for both groups, that is, the majority of verbalizers and visualizers are of average verbal ability. These results strongly support the conclusion that, in contrast to verbal ability, imagery ability is not simple and undifferentiated, but composed of different components. Some people may prefer visual strategies since they are especially good in the construction of vivid color images, yet others may succeed in spatial transformations such as mental rotation of a complex three-dimensional image.

Qualitative Study: Method

In order to specify the differences between visualizers of high and low spatial ability in solving problems in kinematics, interviews with 17 students were conducted. Students selected for the interviews were all "high visualizers", i.e. they showed a strong preference for the visual processing mode, but differed in their spatial ability level (8 were high and 9 were low spatial ability. During the interviews, students were asked to solve those types of kinematics problems, that were found in the quantitative study to be significantly related to spatial ability, namely, extrapolation and frame of reference problems. In order to gain further insight into the nature of the statistical correlation between this graph problems and verbal ability, found in the quantitative study, students were also presented with graph problems. The interviews with students were video-taped and analyzed. The students' use of visual images, drawings, and gestures, and verbal descriptions of mental schemes reported during problem solving procedures received the most attention in the protocol analysis in this study.

Qualitative Study: Results

The results of the protocol analysis show that characterizing students as "visualizer" and "verbalizer" is too ambiguous a categorization. In contrast, this study suggests that there are two contrasting types of visualizers that can not be pooled into one group: the spatial type, characterized by high spatial ability; and the visual type, characterized by low spatial, but high visual ability. According to the results of this study, visual and spatial types generate and use mental images in different ways while solving problems in physics. The main differences between students of spatial and visual types are the following:

Types of visual/spatial representations The visual type generates pictorial images that primarily encode the visual appearance of the objects. While solving problems in kinematics, visual types constructed visual representations of concrete physical objects, such as balls, cars, bullets, and so on. In contrast, the spatial type generates schematic visual-spatial images, in which unnecessary details are ignored and pure relationships are encoded.

Amount of spatial processing resources Spatial types are characterized by high spatial processing resources. These subjects are able to integrate successfully multiple motion parameters, transform and reorganize spatially one problem representation to another. In contrast, visual types are not characterized by high spatial-processing resources. They are not able to process more than a single motion parameter at a time or perform dynamic spatial transformations. Instead, their mental transformations are limited to coloring an image and/or imposing excessive amounts of pictorial details.

Characteristic differences between the visual and spatial types in solving particular kinds of kinematics problems

Extrapolation problems - Students of the visual type were unable to process motion in horizontal and vertical directions simultaneously; they consistently neglected one of the motion components. All students of the spatial type, in contrast, consistently referred to both motion components.

Graph problems - Students of visual type interpreted the graph as a literal picture of a situation. They expected that the shape of the graph should resemble the path of the actual motion and did not see any reason for the appearance of a graph to change, even though, the ordinate variables changed. While explaining the situation depicted on the graph, students of visual type reported vivid, spontaneously generated images of concrete objects (e.g., hill, ball, car, elevation, bullet, table, and so on) and were unable to abstract any relevant information form the graph. In contrast, students of spatial type gave a purely schematic description of the situation and did not ascribe any concrete features to the object, whose motion was depicted on the graph. They consider the graph to be an abstract spatial representation; none of them referred to the graph as a concrete duplication of the motion event.

Frame of reference problems - Visual type students viewed the same problem as two different ones, while perceiving it from different frames of reference. Their multiple-view representations of the same problems were isolated from, and often at odds with each other. These subjects were more likely to accept and encode problem representations as it presented without reorganizing, restructuring, or revision. In contrast, students of spatial types were able to reorganize and restructure spatially the problem representations to suit their needs. They dynamically transform the problem representation from one frame of reference to another.

Scientific and Educational Significance

In this study, the distinction was made between two types of imagery used in solving problem in physics: visual imagery, involving visual representations of the objects' appearance in terms of form, vividness, or color; and spatial imagery, involving representations of the spatial relationships between parts of an object, and the location of objects in space. The results of this research clearly shows that while spatial imagery may promote problem solving success, the use of visual imagery presents an obstacle to problem solving in physics. Instructing students to use mental imagery as a cognitive strategy will probably not be effective. In order to make the optimal use of the strength of visual/spatial processing, physics instructors should encourage students to construct spatial representations of the relations between objects in a problem and discourage them from generating concrete pictorial images. Interactive computer graphics, to be used effectively, should primarily involve schematic visual-spatial representations and not call students' attention to vivid color details. This is especially relevant for teaching low-spatial students, who are particularly susceptible to focus their attention on irrelevant elements of the problem.

This study also helps to clarify why previous studies found no statistical relationship among "verbalizer-visualizer" dimension, spatial ability, and problem solving (e.g., Lean & Clements, 1981). It also explains the results of previous educational studies (e.g., Presmeg, 1986) why the group of visualizers did not benefit from teaching by visual methods. Visual and spatial types are very different types of visualizers that can not be pooled into one group, nor taught by the same methods. Students of the visual type have much more difficulties in learning physics than students of high spatial or verbal abilities. Recognizing the source of their difficulties and modifying our approach towards physics education accordingly will lead to a more successful educational experience for both the student and the teacher.

The current research also specifies those types of kinematics problems whose solutions primarily depend on the use of spatial imagery. This leads to some important instructional implications regarding the relative emphasis on verbal processes and spatial imagery during physics instruction. Regardless of students' spatial ability, it might be possible to teach them effective ways to solve these types of problems by placing emphasis on spatial imagery processes. Having students memorize formulas and use them to obtain numerical results may not be the best way to follow. Evidence presented in the research clearly indicates that teachers are very unlikely to impart to low spatial students an understanding of kinematics topics by giving only a verbal explanation about the independence of the horizontal and vertical velocity components and Newton's First Law.

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