Software for Assisting High-School Students in the Spatial Perception of Geological Structures

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ABSTRACT

Spatial abilities are required in the study of structural geology. However, relatively few learning aids for teaching spatial topics in structural geology have been developed. *Geo3D* is a software that was designed to assist high-school earth-science students in perceiving geological structures and in envisioning cross sections through these structures. *Geo3D* provides the student with manipulative animated visual illustrations of three-dimensional fold and fault structures. The illustrations are used for "spatial investigation" of structures in the first module of *Geo3D* and as "hints" for solving "structural tasks" in the second module. The interaction period required for working with the software varies from one to three hours.

The design process for *Geo3D* included investigating perceptions of geological structures; developing the first version of *Geo3D*; evaluating the early version; and developing an expanded improved version of the software.

Keywords: Education – computer assisted; education – precollege; structural geology.

Introduction

The study and understanding of structural geology involves the cognitive ability of multidimensional thinking – investigation of three-dimensional structures that change with respect to time. As Chadwick (1978), a geologist and psychologist, has claimed,

> ... For efficient and geologically adaptable thinking, one prerequisite is probably of universal value, whatever the nature of the geological content. This is the skill for thinking in three dimensions, for visualizing shapes in the mind's eye, rotating, translating and shearing them, and for imagining complex changes over time in the form of a cinematographic visual image (p. 144).

The skill mentioned by Chadwick, that of thinking in three dimensions, is related to a specific type of ability known in cognitive science as "spatial ability." Linn and Petersen (1985, p. 1489) described spatial ability as "skill in representing, transforming, generating and recalling symbolic, nonlinguistic information."

Spatial abilities or skills are required in fields including natural sciences, geometry, engineering and architecture. However, large parts of the population have considerable difficulty dealing with spatial tasks and problems (McGee, 1979). This difficulty is often manifested in the study of structural geology, in which high-school and university students often have difficulties in solving problems that require spatial abilities.

A considerable contribution to curriculum development has been made by studies that investigated the role of experience and the effect of instruction on spatial skills. Many of these studies indicated that spatial skills could be improved through learning experiences (Lord, 1985, 1987; Smith and Schroeder, 1981; Ben-Chaim, Lappan and Houang, 1988; Baenninger and Newcombe, 1989; Kiser, 1990). Evidence exists that instructional programs induce similar improvement rates for males and females (Ben-Chaim, Lappan and Houang, 1988).

Curriculum materials that have been shown to improve spatial skills can be divided into two main categories: a) learning programs involving two- or three-dimensional manipulative objects (Mitchell and Burton, 1984; Lord, 1985; Smith and Schroeder, 1981; Seddon and Moore, 1986; Ben-Chaim, Lappan, and Houang, 1988) and b) learning programs that are based on computer graphics and include graphic representations of three-dimensional objects (De Paor, 1986; McEachran and Marshak, 1986; Seddon and Moore, 1986; Kiser, 1990; Rodriguez, 1990; Wiley, 1990; Bezzi, 1991). The question as to which of these methods is more efficient gave rise to many studies. Although there is a general opinion that concrete models are more easily comprehended than computer-graphic presentations, some authors have shown that this is not always true (Dyche, Mclurg, Stepans, and Veath, 1993). In some cases, concrete models can even lead to confusion, whereas the computer graphics are advantageous (Seddon and Moor, 1986). One of the difficulties encountered in spatial problems is the need to correctly interpret two-dimensional representations of three-dimensional objects (Ben-Chaim, Lappan and Houang, 1989). The computer provides a powerful tool for assisting in such interpretation, since its two-dimensional representations can be presented as animated manipulations like rotation and translation.

The advantage of animation in the perception of three-dimensional objects was known before personal computers became popular. Dorethy (1972) indicated that the depth perception of graphically presented spatial objects was significantly higher when they were shown as an animation rather than as the static pictures that composed the animation. Wiley (1990) added that animation is an even more effective tool in illustrating three-dimensional objects when it is controlled by the student. Lowery and Knirk (1982) postulated that even microcomputer video games which use such animation might improve children's spatial skills.

Learning materials that include spatial training have been developed for various disciplines including: geometry (Mitchell and Burton, 1984; Ben-Chaim, 1985), chemistry (Small and Morton, 1983; Seddon and Moor, 1986; Dyche, Mclurg, Stepans, Veath, 1993; Tuckey and Selvaratnam, 1993), biology (Russell-Gebbet, 1984, 1985), astronomy (Broadfoot, 1993), engineering graphics (Wiley, 1990; Rodrigeuez, 1990), and certain aspects of mathematics (Kiser, 1990). In the study of geology, and especially in structural geology, relatively few learning materials which deal with spatial topics have been developed. Some of these instructional materials are in the form of software which deal with advanced topics of structural geology, such as stress and strain analysis (De Paor, 1986; McEachran and Marshak, 1986). The authors of this software emphasize the advantage of a graphic rather than an analytic approach for solving quantitative problems. Thus, such programs deal with the difficulties in teaching abstract concepts by using graphical methods where the understanding of the methods themselves require spatial abilities.

The more basic difficulty, that is, the perception of spatial configurations of geological structures, is usually overlooked. Bezzi (1991) addressed this problem by developing a computerized program that tests students' spatial abilities, using problems in structural geology. He postulated that students might improve the spatial skills required for structural geology by working on abstract spatial-ability problems as well as structural-geology problems with a right/wrong feedback. To this end, Bezzi's program takes advantage of the computer mainly as an analytical tool for tracking student performance and for providing online feedback.

The next step is to use the graphic capabilities of the computer to provide assistance in the visualization of structures through realistic three-dimensional animation. This application of the computer is introduced in the present paper through the software *Geo3D*. The software was developed to assist high-school earth-science students perceive the spatial configuration of geological structures and to envision cross sections in these structures. To reach this goal, a pre-development research of student perception of geological structures was conducted. Based on this study, the first version of *Geo3D* was developed. Formative evaluation was then conducted, and an expanded version of the software is being developed.

Pre-Development Research

To develop a meaningful learning tool, it was necessary to answer the following questions:

- What is the distribution pattern of student performance in solving basic structural geology problems that require spatial abilities?
- What are the typical incorrect answers students give in solving such problems?
- How do students reason different types of answers?
- Can students overcome their difficulties using assistance?
- How can appropriate assistance be provided?
- What is the hierarchical order of various types of problems?

A pilot study using 64 students from three high-schools was conducted to provide data on the ability of high-school students in solving spatial problems related to geological structures. To obtain further insight into student perceptions and difficulties, the main study was conducted with 115 tenth-grade students from three classes randomly selected from eight classes in a comprehensive Israeli high-school. The study included the following research tools:

1) **Geologic Spatial Ability Test (GeoSAT).** This test was designed especially for the pre-development research. A pilot version of the test, which was used in the pilot study, was designed as a multiple-choice test. To obtain further insight into student perceptions, an open-ended test was designed for the main study. The test consists of 13 problems that require spatial perception of geological structures. Three types of problems are included, grouped in the following sub-tests (Figure 1):

    a) Cross-section sub-test, including four problems which require drawing cross sections of structures presented as block diagrams (Figure 1a).
    b) Completion sub-test, including four problems which require completing block diagrams that reveal only a single face (Figure 1b).
    c) Construction sub-test, including five problems in which two cross sections and their location on a very simplified geologic map are given. The students are required to draw a third cross-section at a specified location on the map (Figure 1c).

2) **Interviews.** Interviews were conducted after testing in both the pilot study and the main study. The students were chosen from the samples as representatives of different levels of performance in the tests. Interviews in the pilot study (four students) concentrated on student difficulties, and on the effect of assisting these students. Interviews of the main study (six students) concentrated on students reasoning for different types of answers given in the test. The interviews were conducted as conversations which lasted from 20 to 60 minutes with each student, depending on his/her level of cooperation.

Table 1 is a summary of the results and conclusions of the pre-development research and their implementation in *Geo3D*'s design.

A full description of the findings and their analysis are given in the article "Spatial abilities of high-school students in the perception of geological structures" (Kali and Orion, 1996).

Description of *Geo3D*

Hardware requirements and development tools

Geo3D runs on any Apple Macintosh computer with a color monitor. It requires five MB of disk space and

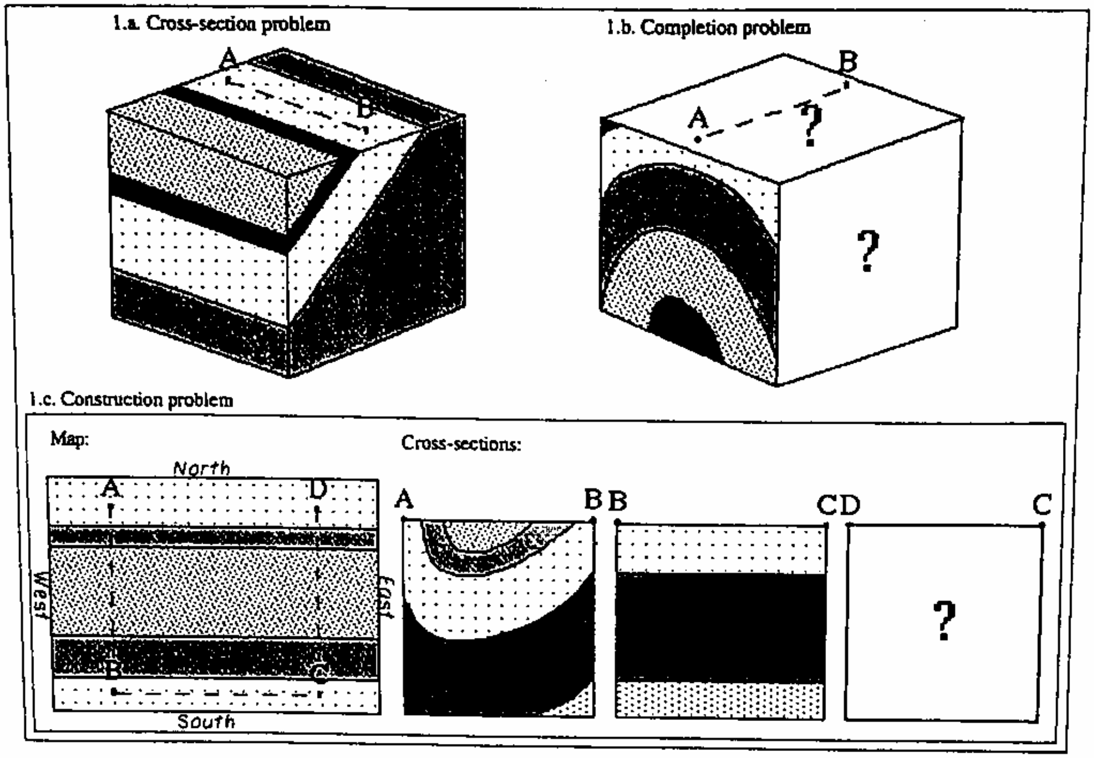

Figure 1. Examples of the three types of problems included in *GeoSat.*

three MB of RAM. A new version compatible with IBM *Windows* is under development. The software was written on a Macintosh computer using *SuperCard 2.0* (Allegiant) and *Swivel 3D*Professional 2.0* (Paracomp). *SuperCard* was used for all the programming and the interface design. *SuperTalk*, the powerful language of *SuperCard*, enabled sophisticated programming as well as creation of a colorful and friendly interface. *Swivel 3D* was used for creating three-dimensional figures and animation which were imported into the *SuperCard* document. *Swivel 3D* enabled construction of representations of three-dimensional objects and their presentation with the effects of perspective in space and illumination, through the use of color shading. These effects, together with the capability of *Swivel 3D* to create rotational and translational animation of those objects, enabled creation of visual illustrations of geological structures which can be perceived easily by the human eye.

General structure

Geo3D includes two modules:

1) Spatial investigation of basic structures – deals with various types of fold and fault structures which are taught in introductory earth-science courses at the high-school level (Figure 2).
2) Structural tasks – deals with solving spatial problems related to the type of structures illustrated in the first part (Figure 2).

Each of these parts can be accessed from the main menu of the software in an order which is determined by the student. Switching between the two parts can be done either through the main menu or directly through buttons which are available at the solution of each structural task.

The "spatial investigation of basic structures" module

This module includes two categories of structures (folds and faults) and twelve different structures which the user can investigate (Table 2). For each category of structures, the user is provided with the following options:

- Generation process – An animated illustration of the generation processes of structures included in the category.
- Examples – Scanned photos and maps of structures of the category.
- Investigation of the structures through two options: definition and visual illustration.

The visual illustration option includes three types of animated manipulations for each structure (Figure 3).

Results and Conclusions	Implementations in *Geo3D*
Interviews with students in the pilot study indicated that students who had difficulties managed to complete problems after being provided manipulatable visual illustrations. This finding indicates that with the appropriate means, solving of such problems is a skill that can be acquired.	With this finding in mind, an approach which is based on improving students' skills by providing them with an assistance system for solving such problems was used.
Significant differences were found in the performances of students within different problem types. These differences indicate that the difficulty levels of the problems form the following hierarchy (starting from the least difficult): a. Cross section problems based on simple structures. b. Cross section problems based on complicated structures. c. Construction problems based on simple structures. d. Construction problems based on complicated structures.	This hierarchy was used for designing problems which provide students with appropriate levels of difficulty.
It was found that two obligatory independent factors are required for solving GeoSAT's problems: a. The ability to perceive the spatial configuration of the layers comprising a structure. b. Visual penetration ability, defined as the ability to envision internal cross sections of structures.	In order to assist students in the perception of geological structures and in acquiring "penetration" skills, all the block-diagram representations are appended with the following types of manipulative animated visual illustrations: a. Rotation of block diagrams and exposing individually each layer comprising the structure. b. "Cutting" operation of block diagrams.
Student performance in solving the three types of problems included in the test showed bimodal distributions rather than normal curves. Therefore, the following points were concluded: a. Great heterogeneity in students' abilities should be encountered in the development of the learning tool. b. Large parts of the population which showed poor performances should be provided with assistance in solving such problems.	In order to provide assistance and prevent overloading on the less able students and, on the other hand, to provide challenges to the more able students, an individual learning approach was developed. This approach is implemented in the following manner: a. Constructing individual learning paths that are determined by student performance. b. Providing an optional assistance system for solving problems. This system can be used while solving problems as many times as necessary for each student. c. Deciding upon learning settings which are not time restricted as regular classroom lessons. Instead, parts of the software can be given as homework assignments which can be completed wherever a computer is available.
Two general types of incorrect answers were found in the attempts to draw cross sections of geological structures: a. "Non-penetrative" incorrect answers. These answers were based on external patterns exposed on the visible faces of the block diagram. b. "Penetrative" incorrect answers. These answers indicated attempts for representing interior elements of the block diagram but without having a clear perception of the spatial configuration of the structure.	This finding was used in order to design conflict-bearing distracters in multiple-choice problems within the software.

Table 1 - Summary of results, conclusions and implementations of the pre-development research.

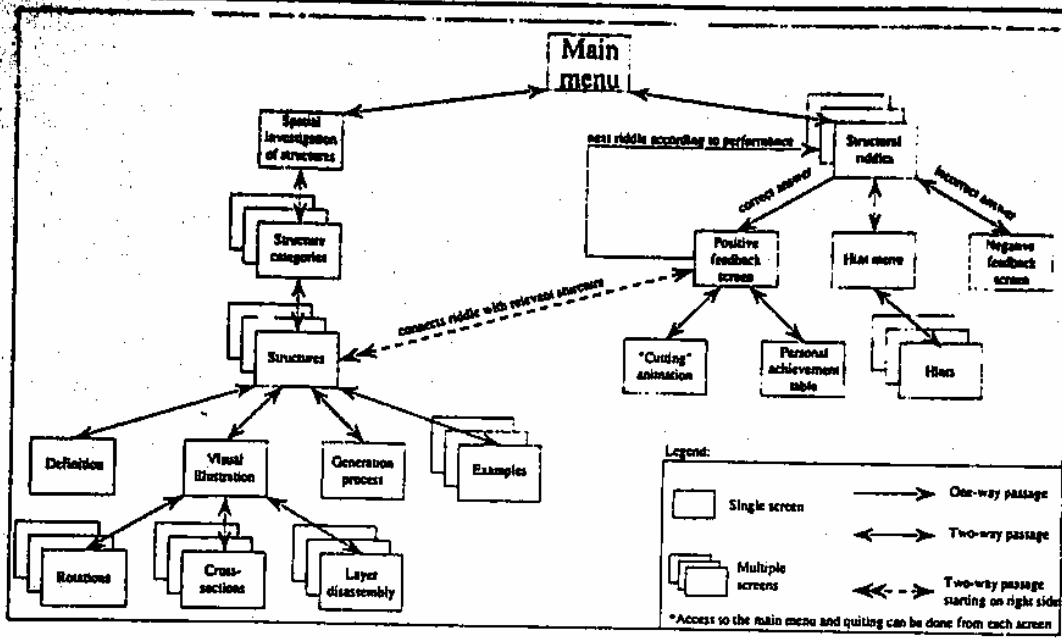

Figure 2. Branching options in *Geo3D*.

Fold structures category		Fault structures category		
simple folds	complex folds	dip-slip	strike-slip	oblique-slip
syncline	synformal-anticline	normal	right	normal right
anticline	antiformal-syncline	reverse	left	normal left
				reverse right
				reverse left

Table 2. Geological structures included in the software.

1) Rotation – a manipulation which provides four options of rotating the structure: right, left, up and down (Figure 3a).
2) Cross sections – a manipulation of "cutting" the structure across variously oriented planes, exposing characteristic cross sections. Three options are provided for creating cross sections: two perpendicular vertical cross sections and one horizontal cross section (Figure 3b).
3) Layer disassembly – a manipulation showing the spatial configuration of each layer. The number of options provided depends on the number of layers comprising the structure (Figure 3c).

The "structural tasks" module

This part consists of fifteen tasks which are divided into five categories of increasing difficulty. Each category covers three tasks of a similar difficulty level, including different structures. The level is defined by the type of assignment and the complexity of the structure. The categorization of the tasks is as follows:

1) Simple structure "cross section" assignment with topography.
2) Simple structure "cross section" assignment with truncated topography.
3) Complicated structure "cross section" assignment with truncated topography.
4) Simple structure "construction" assignment.
5) Complicated structure "construction" assignment.

An example of a task from the fifth category is given in Figure 4.

Each task contains three hints that can be repeatedly accessed by the user in any order and with no time limitations. The hints correspond to the specific structure of the task and the type of assignment involved in it. The hints for the "cross-section" tasks are visual illustrations of a similar sort to those provided in the "spatial investigation of basic structures" module, that is, rotation and layer disassembly. A third kind of hint illustrates the location of the cross section within the topography of the structure. The

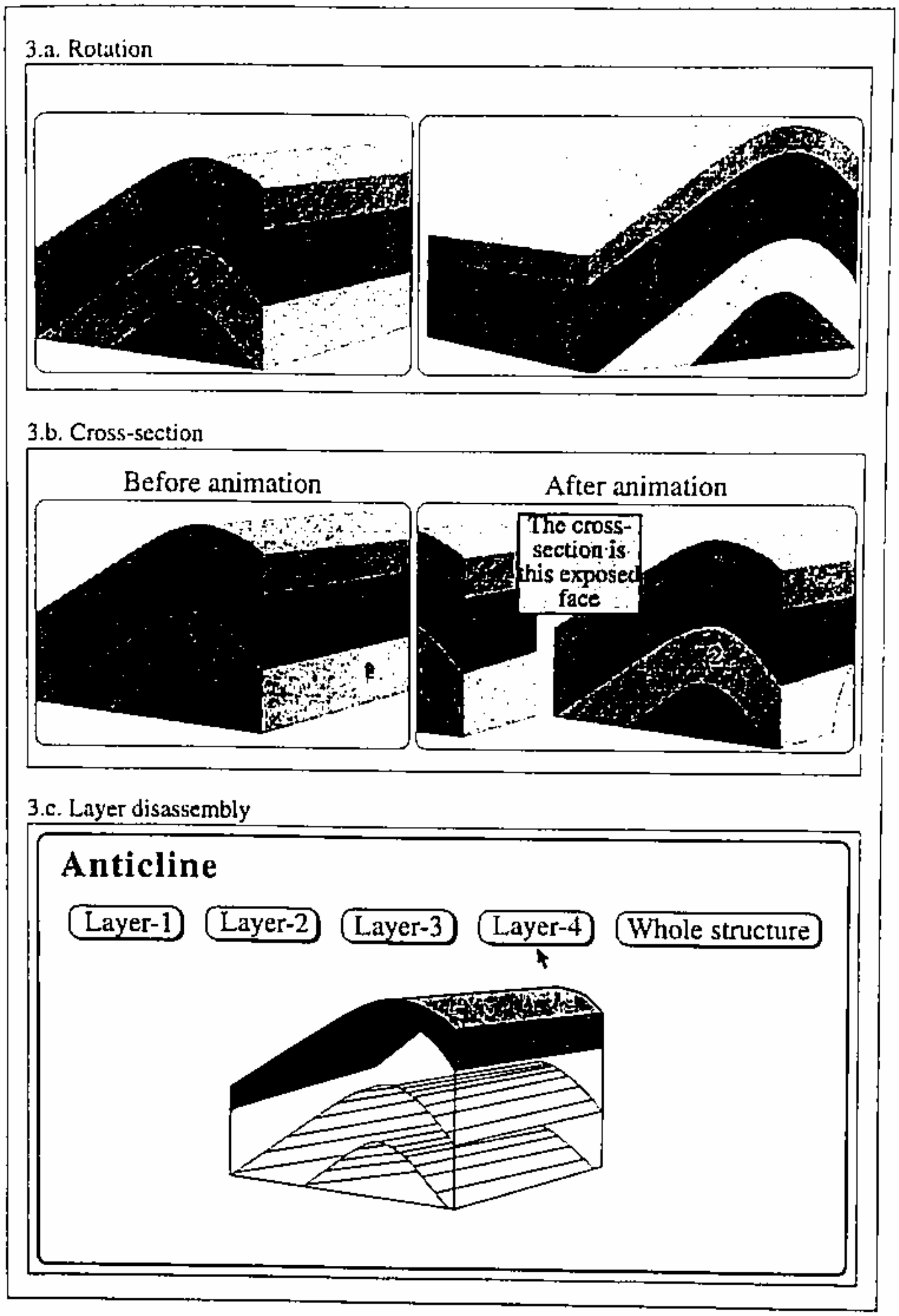

Figure 3. The three types of animated manipulations for geological structures.

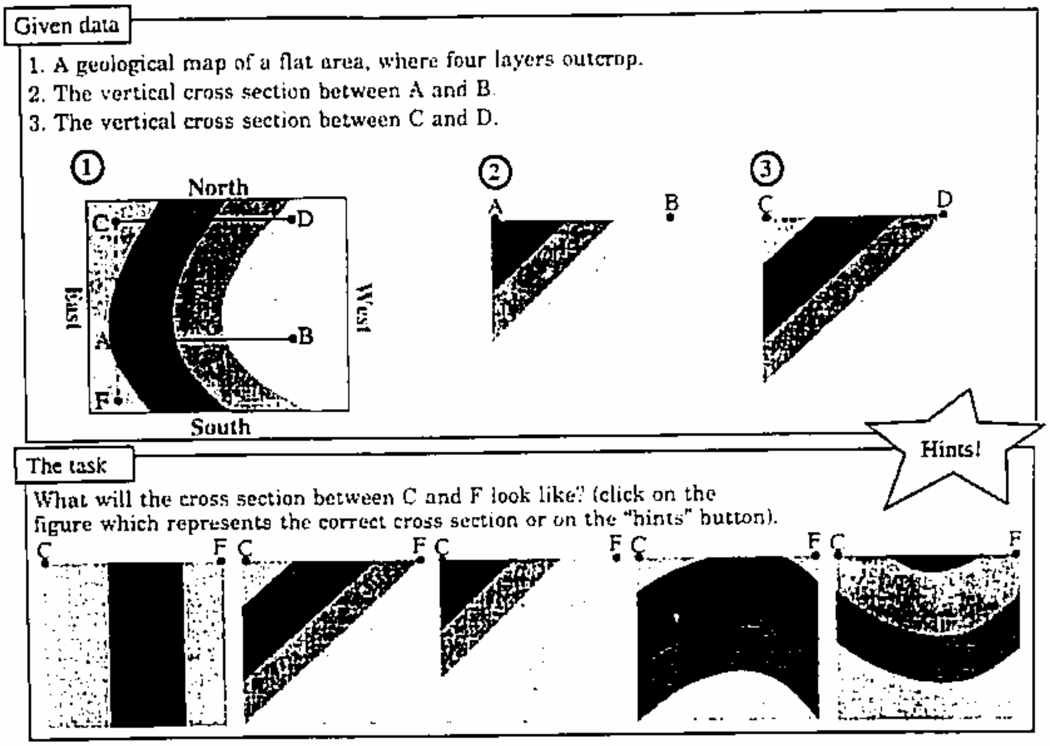

Figure 4. A task of the fifth category.

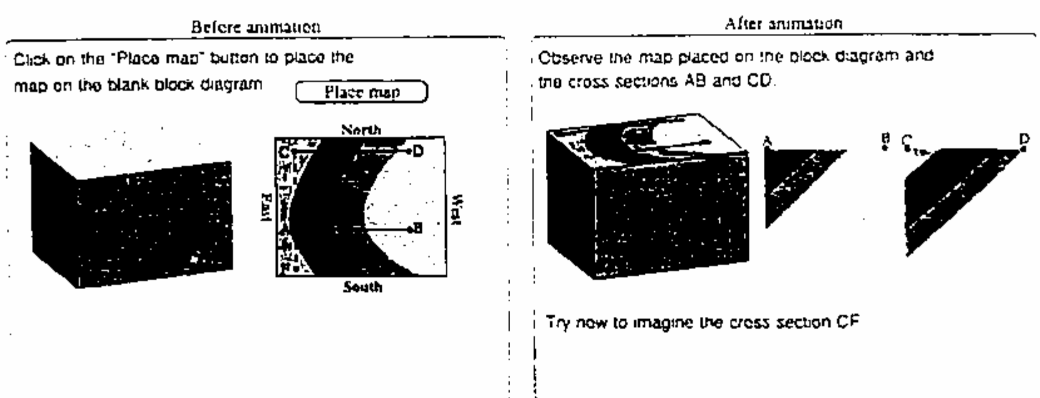

Figure 5. The first hint of a "construction problem."

hints for the "construction" tasks illustrate the mental process of constructing a block diagram from the map and the cross section. The first hint shows an animated process of placing the map on a blank block diagram (Figure 5). In the second and third hints, the cross sections are added one by one to the map on

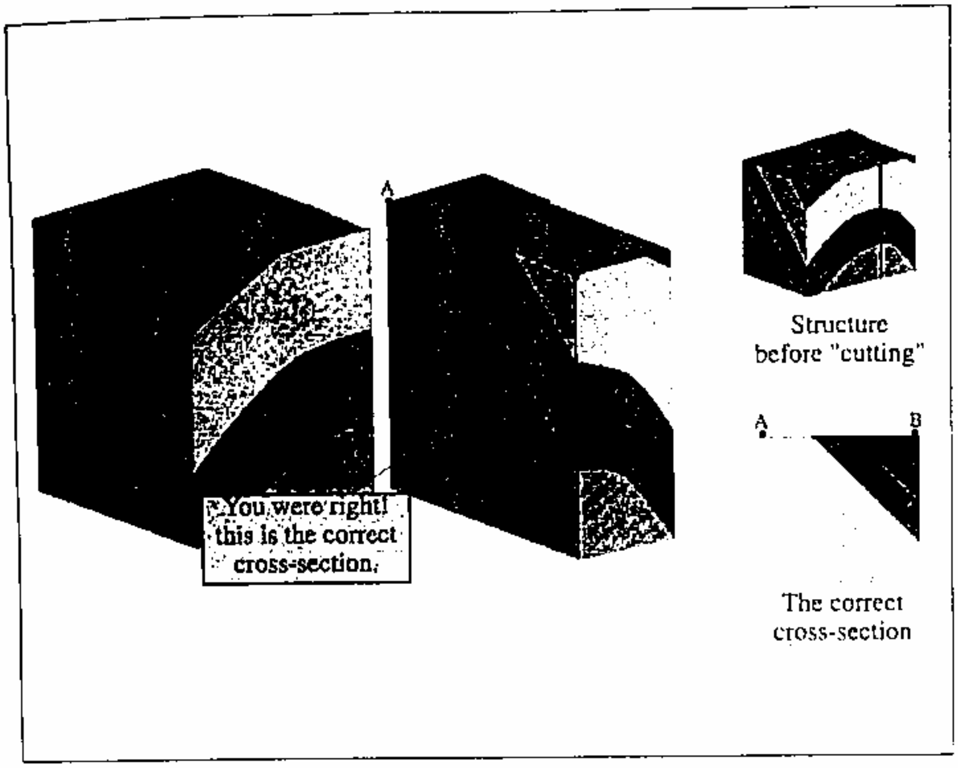

Figure 6. The "cutting" animation.

the block diagram, gradually creating a full block diagram representing the structure in the task.

The feedback for the user is as follows: Clicking on any of the wrong cross sections opens a dialog box with the words "Wrong answer. Try using a hint before the next attempt." Clicking on the correct cross section opens a screen that flashes the words "correct answer!" and provides an option to watch a "cutting" animation, which illustrates how the cross section is revealed from "cutting" the block diagram (Figure 6).

Formative Evaluation

Evaluation of the first version of *Geo3D* was based on four case studies of 11th-grade earth-science-major students towards the end of the first year of their studies. The students were chosen by their earth-science teacher as representatives of diverse ability levels present in their class. The case studies were mainly based on observations of the students while working with *Geo3D*. Additionally, the following information was collected about each student (Table 3):

- The opinion of the earth-science teacher about the students' performances in the classroom and in the field.
- Final grades on the introductory earth-science course.
- Performance in a spatial visualization test (Ben-Chaim and others, 1985) which was given to all the students at the beginning of the year.
- Performance in a short version of GeoSAT (The first few problems of the open-ended spatial ability test in geology) which was given only to the four students who participated in the evaluation study. This test was given twice: the first time before working with the software, and the second time afterwards, with an opportunity to reexamine the former answers. (A control group of a similar size from the same population showed no improvement of performance in encountering this test twice, without working with the software).

The observations were conducted in the school's laboratory where our computer was set. The students worked by themselves with the software. Participation of the observer was made only when students asked questions or when the observer stopped the students and asked questions about their actions.

As can be seen in the description of the case studies (Table 3), three of the four students improved their performances in the short version of GeoSAT after the interaction with *Geo3D*. Especially outstanding was Yosi's improvement, who not only corrected his wrong answer but also managed to answer correctly all the "construction" problems of the long version

1	2	3	4	5	6	7
Avi	A below-average student who is generally quiet and somewhat restrained.In the field, had difficulties in imagining large structures which can be observed only partially.	75	Below the average of the class.	Avi could not answer any of the problems.	Avi answered correctly three out of the four problems.	It seemed that Avi had difficulties in envisioning cross sections of the structures even when he seemed to perceive the spatial configuration of the layers. Avi had problems in visualizing, and therefore understanding the hints. Consequently, he did not use many hints. In some cases, Avi answered correctly, but was not sure that he understood why. However, each time he solved a riddle, he was very eager to see the animation presenting the "cutting" manipulation of the block diagram and exposing the cross section. After the animation was shown, he had the feeling that the answer was intuitively obvious.
Yosi	An above-average student. Usually understands what is taught in the class, but since he is extremely quiet, he prefers not to ask any questions, even if he does not understand.	95	Above the average of the class.	Yosi answered correctly three out of four problems.	Yosi was able to identify the wrong answer and to correct it. Asked to complete other problems of GeoSAT and managed to answer correctly all the "construction" problems of the test.	Yosi worked in a very systematic manner. In each screen he activated each of the optional buttons. The open branching possibilities of the "spatial investigation of basic structures" seemed to confuse him. Yosi solved the problems very fast while making an effort to answer correctly using a minimum number of hints. After solving each riddle, he always chose to see the animation of cutting the block diagram, even when he was very confident of his answer. At one occasion where he was not confident, he asked to go back to the riddle in order to watch the hints.
David	An average student who is very persistent in understanding what is taught in the classroom, and therefore asks many questions.	80	Above the average of the class.	David answered correctly two of the four block-diagram problems.	David identified his mistakes and corrected one of them.	David's interaction with *Geo3D* was characterized by a somewhat investigative approach. In the "Spatial investigation of geological structures" module, he read every text and examined each illustration very carefully. In the "structural riddles" module, David tended to answer the riddles only when he thought that he knew the correct answer. For this reason, he usually took his time in examining the data, and used many of the hints provided with the riddles.
John	A student who is a very quick thinker and performs well both in the classroom and the field.	97	Similar to the average of the class.	John answered correctly three of the four problems.	John was able to identify his mistake but could not correct it.	At the beginning of the observation, John showed very low motivation and had many cynical remarks. It seemed that he made an effort to impress the observer. As he went on working, he began to be more serious and did not have patience to answer the questions of the observer because he was so eager to go to the next riddle. Finally, after solving the last riddle, it seemed that his cynical attitude was changed, and he showed disappointment that there were no more riddles. John worked very quickly and even hastily. He did not read all the instructions provided with the riddles and guessed what the task was. Only in the fourth riddle he noticed that he could use hints. His rashness caused him to choose incorrect answers where he could undoubtedly answer correctly. John's very low motivation gradually changed to enthusiasm.

Legend
1. Student's name
2. Teacher's opinion
3. Final grade on earth-science course
4. Performance in a spatial visualization test (Ben-Chaim and others, 1985)
5. Performance in the short version of *GeoSAT* prior to working with the software (the four block-diagram problems of the test)
6. Reexamination of answers given to the short version of *GeoSAT* after working with the software *Geo3D*
7. Description of the student's interaction with *Geo3D*

Table 3. Description of students' interaction with *Geo3D* and additional information about each student

test. It should be mentioned that only five percent of the students tested in the pre-development research managed to do that. Another outstanding improvement was that of Avi, who was not able to answer any of the questions before working with *Geo3D* but solved three out of the four problems after this interaction.

The dramatic improvements of the students are evidently a consequence of their interaction with *Geo3D*. A question which might be raised is, "What are the precise sources of improvement of each student in his interaction with the software or lack of improvement in the case of John?" To answer this question, let's examine each of the students' interactions with the two elements that provide assistance in visualizing structures: the hint and the "cutting" animation of the positive feedback.

Avi's path through the software is characterized by using only a few hints and by manipulating the "cutting" animation after solving each of the tasks. This type of path might be explained by Avi's poor spatial perception, which was mentioned by his teacher and indicated by his low performance on the spatial visualization test and by his low confidence in answering the tasks. His difficulty to fully understand the hints, as indicated from his remarks, was probably caused by his poor spatial ability and was the reason for his secondary usage of the hint system. However, the secondary function of the hints in Avi's case was accomplished by his consistent manipulation of the "cutting" animation. This is apparent in his eagerness to watch the "cutting" animation at the end of each task. Avi's remarks indicate that his desire to see the animation was based on a desire to understand "what I did," and that this interaction assisted him in the perception of the internal properties of the structure in such a manner that he felt that the task is "actually obvious." Evidently, Avi's improvement resulted mostly from his consistent manipulation of the "cutting" animation.

Yosi's path through the software is also characterized by a minor usage of the hint system and by consistent manipulation of the "cutting" animation. However, this type of path in Yosi's case was induced by his motivation to solve the tasks using a minimum number of hints. As an above-average student with high spatial abilities, he was able to carry on with such an approach, as indicated by his high self confidence in the selection of the correct answers to the tasks. Nonetheless, at one occasion, when Yosi arrived to a point where he solved the task correctly but was unable to visualize the geological structure, he went back to watch a hint that helped him to understand the spatial configuration of that structure. Yosi's determination to visualize the structure even after solving the task demonstrates another function of the hints not only as assisting tools but as convincing affirmation tools as well. However, it seems that Yosi's improvement lies more on the "cutting" animation that he chose to watch after each task than on the hint system which he used only once for affirmation of his answer.

David's path is characterized by using both the hint system and the "cutting" animation of each task. His serious "investigative" approach, which was revealed through the observations, agrees with his persistence in understanding what is taught in the classroom, as was indicated by his teacher. His remarks after manipulating some of the hints' illustrations indicate that these hints comprised meaningful assistance for him. David's type of path, which included many manipulations of both assisting elements of the software, indicates that his improvement probably lies in both the hint system, and the "cutting" animation.

From the observation of John's interaction with the software, it seems that he put more effort into trying to impress the observer than in working seriously with the software. Although he began unmotivated and became more and more enthusiastic while working with *Geo3D*, his efforts to impress made him work hastily and he made foolish mistakes. This behavior caused him to go through a path that did not include many manipulations of either the hints or the "cutting" animation. It is therefore not surprising that John hardly improved his performance in GeoSAT after using the software. His path, which included only minimal manipulation, did not offer him an opportunity for such an improvement. However, it should be remembered that John is a high-performing student, as indicated by his teacher and by his performance on the spatial visualization test. Perhaps the software is not as helpful for him as for the other students. Nonetheless, his benefit from the software was substantial – a change in attitude and an increase in motivation.

The above analysis shows four types of students who interacted through different paths within the software. The type of path taken by each student was a consequence of his character and abilities. However, each of the path types induced positive impacts on the students at either the cognitive or the affective levels or both. In the pre-development research, it was concluded that the software should act as an individual learning tool. The case studies demonstrate that the implementation of this conclusion, which enabled the students to determine their individual characteristic path, was effective in inducing the positive impacts discussed above.

According to the analysis of the case studies, the first version of *Geo3D* was positively evaluated. Thus, the changes suggested for the next version are mostly extensions of the first one. Additionally, some interface improvements which were indicated from the observations were made. For example, an option to go back to tasks that were already solved was added. This option was included to provide students like Yosi an opportunity to study the hints after solving each task. Another example is an additional text explaining what each of the visual illustrations does. The textual explanation was added in order to assist students with low spatial perception, like Avi, in perceiving these illustrations.

Evaluation of the learning settings is more speculative than the cognitive and affective issues. Since the settings include individual interaction with the software, the presence of the observer can not be ignored. Still, it seems that the large differences in the duration of interaction that are induced by the different path types indicate that the individual-learning settings are advantageous. On the other hand, the interaction of the students with the "spatial investigation of basic structures" module revealed that not all students are able to utilize this part beneficially through individual interaction. An example is Yosi's confusion about the open-branching possibilities and his wish to be guided. Considering this finding, and to provide students like Yosi with appropriate tools for maximum benefit from of the software, it may be helpful to develop a guiding booklet for the "spatial investigation of basic structures" module. Nonetheless, the observations indicate that illustrations of the type used in this part are effective visualization tools. Therefore, in addition to the individual mode, this module can be used without any additional development as a powerful demonstration tool for teaching structural geology in the classroom.

Overall Conclusions

1) The findings of the evaluation support those researches which argue that the computer is an appropriate tool for illustrating three-dimensional concepts even though its screen is two dimensional.
2) *Geo3D* enabled students to choose a path type that was suitable to their own abilities and characters. This capability of the software enhanced learning both at the cognitive level and the affective level. At the cognitive level, *Geo3D* assisted students of various ability levels in their spatial perception of geological structures and in solving related problems. At the affective level, students were challenged and motivated by the software, and evidence for positive attitude change was indicated.
3) The positive evaluation of the software supports the method of a three-stage development process, including a pre-development research stage, a designing stage, and an evaluation stage.
4) Further research with larger populations is still needed for summative evaluation of an expanded version of the software and for a deeper understanding of types of learners, like the ones revealed in the above discussion. In order to analyze the interaction of large populations and to remove the interference of the observer, a follow-up system that records every step made by the user, including time intervals between steps, was developed. With the aid of this system, quantitative methods could be combined with the qualitative methods described above.

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the duration of interaction that are induced by the different path types indicate that the individual-learning settings are advantageous. On the other hand, the interaction of the students with the "spatial investigation of basic structures" module revealed that not all students are able to utilize this part beneficially through individual interaction. An example is Yosi's confusion about the open-branching possibilities and his wish to be guided. Considering this finding, and to provide students like Yosi with appropriate tools for maximum benefit from of the software, it may be helpful to develop a guiding booklet for the "spatial investigation of basic structures" module. Nonetheless, the observations indicate that illustrations of the type used in this part are effective visualization tools. Therefore, in addition to the individual mode, this module can be used without any additional development as a powerful demonstration tool for teaching structural geology in the classroom.

Overall Conclusions

1) The findings of the evaluation support those researches which argue that the computer is an appropriate tool for illustrating three-dimensional concepts even though its screen is two dimensional.
2) *Geo3D* enabled students to choose a path type that was suitable to their own abilities and characters. This capability of the software enhanced learning both at the cognitive level and the affective level. At the cognitive level, *Geo3D* assisted students of various ability levels in their spatial perception of geological structures and in solving related problems. At the affective level, students were challenged and motivated by the software, and evidence for positive attitude change was indicated.
3) The positive evaluation of the software supports the method of a three-stage development process, including a pre-development research stage, a designing stage, and an evaluation stage.
4) Further research with larger populations is still needed for summative evaluation of an expanded version of the software and for a deeper understanding of types of learners, like the ones revealed in the above discussion. In order to analyze the interaction of large populations and to remove the interference of the observer, a follow-up system that records every step made by the user, including time intervals between steps, was developed. With the aid of this system, quantitative methods could be combined with the qualitative methods described above.

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