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Impact of Simulator-Based Instruction on Diagramming in Geometrical Optics by Introductory Physics Students

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We examine the conceptual development resulting from an instructional experiment with an interactive learning environment in geometrical optics for introductory high school physics. How did teaching-learning processes come to change the ways in which students depicted various everyday optical situations in paper and pencil graphical representations? We view conceptual development as a process resulting in part from increasingly aligning one's practices to a target community by means of participating in a community of practice that uses the target concepts. For formal science learning, this participation requires changes in concepts, epistemological attitude, and in the development and use of representational tools, including diagrams and technical language, as a means of communication. Results of our instructional experiment indicated that students went through major conceptual developments as reflected in the diagrams they constructed and supported by other representational tools and as judged in terms of several perspectives: in identifying the formation of shadows and images, in recognizing the eye as a participating factor in the optical system, and in changing the types of justifications they provided in their optical reasoning from presuppositional to causal.

KEY WORDS: Simulator-based instruction; physics students; conceptual development; optics; diagrams; computer learning.

INTRODUCTION

The Optics Dynagrams Project is a classroom-based research and development project that investigated the use of diagrams in science learning and how computer technologies might enhance the roles of diagrammatic representations. The curriculum topic was introductory geometrical optics, particularly image formation with mirrors and lenses. Understanding the nature of light has been a major preoccupation of physical science for centuries. Fundamental physics breakthroughs during the 20th century have emerged from deep investigations of light's electromagnetic properties. The special case of geometrical optics—in which light is treated as traveling in straight lines called rays—is a standard unit in introductory physical science. Historically, the scientific community found new ways of reasoning about light and explaining light behavior only when new graphical representations about light were constructed (Toulmin, 1953). Explaining the formation of shadows was completely shifted when the "ray" was accepted as a legitimate representation of light. This means that the representation of light is a necessary but not sufficient tool for understanding and communicating about light. Therefore, the ways in which students construct diagrams in optics provide a major means for depicting their conceptual development with respect to light.

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Geometrical optics is also a diagram-dense subject. Texts for this subject are replete with diagrams of physical situations: point light sources emit rays of light; rays are reflected off of plane or spherical mirrors; light is refracted as it passes from air into water or glass. Iconic diagrams comprised of line drawings representing light sources, lenses, light "rays," and reflective surfaces are widely used, particularly since such conceptual relations as the ratio of image size to object size are common graphical illustrations. How do students reason about these topics, and how can their preexistent conceptual schemes for reasoning about optical situations and events be transformed by instruction to more closely align with expert scientific knowledge? These issues of conceptual change are central to constructivist accounts of science learning (e.g., Clement, 1982; DiSessa, 1982; Driver *et al.*, 1985; Hewson, 1981; Hewson and Hewson, 1984; Posner *et al.*, 1982).

Such topics in geometrical optics typically represent targets of student difficulty in understanding (e.g., Goldberg and McDermott, 1986, 1987), and several reports have documented students' preconceptions about light before formal physical science instruction (Anderson and Smith, 1984; Guesne, 1985; Jung, 1981). Using interviews with children about phenomena that for the physicist involve light (such as shadows, vision, mirror reflections, or use of a magnifying glass), they find that students of age 10–11 tend to represent light as its source, its effects, or as a state. By age 13–14, many students conceive of light as an entity distinct from its perceptible effects, something that propagates outward from a source and interacts with objects it encounters in its path. However, the physicist's notion of conservation of light seems a difficult one for the older children to grasp, as they confound light with its visible effects. They may feel that light "gives out" over long distances, even though there is no interaction with a material medium, or that light can be "multiplied" by a magnifying glass, or that there is no light when they look at objects or pieces of paper which do not reflect intense light (Guesne, 1985). Fifth graders recognize light as necessary for vision but do not see the light as reflected by the objects seen (Anderson and Smith, 1984). They thus do not appreciate that light travels from an object to the eye, which will cause problems during instruction:

> Often a teaching course will start by establishing the propagation of light in a straight line. To accomplish this, it will show pupils that they cannot see a candle's flame through a series of holes punched in a card unless the holes are aligned. Children cannot appreciate this demonstration; they cannot interpret the experiment in terms of the path of the light from the object to the eye, when they do not link the vision of the flame to a reception of light by the eye (Guesne, 1985, p. 29).

This older group also has a very difficult time with the concept of a virtual image of an object seen in a mirror. Guesne attributes this to the typical explanatory model offered, which rests on the idea that an object is seen because light coming from it penetrates our eyes after propagating in a straight line through the intermediate space.

We are not aware of any cognitive research on the nature of students' understanding of light and geometrical optics at the age level of our interest, 10th–11th grade (15–17 years), at which time students receive their first systematic and extended introduction to the physics of light.

The Optics Dynagrams Project

The Optics Dynagrams Project addressing these issues was organized in three phases. In the first, we studied the ecology of diagram use and understanding for geometrical optics in two exemplary high-school classrooms. This included videotaping expert teachers' use of diagrams for science education and individual students' use of diagram problem representation and topic understanding as they thought aloud and solved optics problems with diagrams at a chalkboard (for details, see Pea, 1992; Pea *et al.*, 1995). In the second phase, we used these results to influence the design and implementation of the *Optics Dynagrams* technology-enhanced teaching and learning activities (Jul, 1991; Pea, 1992). Central to these was a set of challenge activities integrating learning with an optics simulator we created, which includes a dynamic diagram (Dynagram) construction kit, hands-on optical tools, and videotape with optical situations and related explanatory animations for scientific visualization. These small-group activities involved continual mapping between real-world experience of optical situations and formal representations of optics concepts and relations (ray diagrams). In the third phase, for four weeks during an academic year, we examined how the use of *Optics Dynagrams* changed the nature of instructional practices and resultant student learning outcomes in a classroom whose previous practice and learning outcomes had been documented for this science topic during the first phase.

Goals

This paper is primarily aimed at identifying specific details of conceptual developmental shifts that resulted from students' interactions within the new computer-enhanced dynagrams learning environment. How did Dynagrams teaching–learning processes lead students to "see" world situations differently, in terms of their paper-and-pencil diagrammatic depictions of various optical situations and the inferences they make with them in answering questions about predicted optical phenomena? To address this issue, we designed a conceptual change instrument, presented below, which sought to elicit student's verbal and diagrammatic reasoning about everyday situations involving key optical phenomena and concepts. In this paper, we report analyses of the conceptual developments demonstrated by changes in students' patterns of responses from pretest to posttest.

The changes we examine derive from convergent perspectives on conceptual change. One is *content-focused*, identifying the development of conceptual understanding of the interaction of light and matter. It considers evidence from students' uses of multiple representations concerning: formation of fuzzy shadows; formation of images (real and virtual); and vision and the nature of light. A second perspective is *representation-focused*, and seeks to identify changes in students' representations of objects, light sources, and physical phenomena such as images and shadows, particularly in causal relationship to one another. A third focus is *explanation-focused*, and examines structural changes in the epistemological nature of students' explanations of optical situations and their justifications for such explanations using various representations. All three perspectives are analyzed through the diagrams students constructed and the supporting written evidence accompanying their diagrams.

As noted, to study and promote conceptual development in optics, an interactive learning environment called Optics Dynagrams was designed to provide students with tools to communicate and reason about light behavior. Before presenting results, we will describe this environment.

DYNAGRAMS LEARNING ENVIRONMENT

"Dynagrams" is our shorthand for "dynamic diagrams," a new kind of symbolic representation we have created as a rapid and highly interactive communication medium for students' *conceptual learning conversations* about geometrical optics. Visual representations such as diagrams play a more important role in the reasoning and problem-representation processes of scientists than educational practices and learning theories acknowledge (Miller, 1986). Diagrams can represent concepts and conceptual relations and provide a "language of thought" that exploits the visual processing capabilities of the human mind (Larkin and Simon, 1987). From our perspective, diagrams also provide conversational artifacts better enabling learners and teachers to become coordinated in activity, including talk, regarding their conceptual content, and to negotiate differences in their beliefs.

Lave and Wenger (1991) developed a perspective of situated learning that views learning as increasingly central participation in "communities of practice." This view influenced our conceptualizations of the nature of science expertise and the role of the school in initiating students into a community of science practice. In this view, learning is engaged by participation in the practice of a community. In the physics community, for example, practice is comprised of specific ways of talking and acting, shared beliefs about what a problem is, how to work on it, and which tools and representations are useful for what conditions of inquiry (Lemke, 1990). A community of practice for science includes quests for certain kinds of knowledge and understanding and certain kinds of processes and symbolic forms of legitimating and establishing new understandings and ways of knowing. The notion of learning as the incremental joining of a community of physics practice was directly relevant to the design of the Dynagrams classroom. Learning science would mean opportunities to participate in the practices of the community of science, during which peripheral participants (students) collaboratively make sense of natural phenomena with more central community members (teachers) by organizing their knowledge to resolve emergent dilemmas (also see Hawkins and Pea, 1987).

If participation in the talk and actions of a community of science practice is central to learning about nature, then being part of sense-making conversations is essential for students. Being a listener or onlooker to a community, as in the common lecture and demonstration-centered science classroom, is rarely enough. Participation in activities and conversations is the vehicle for sense-making in the concerns and ways of science as well as the way learning is accomplished. Learning is generated by communication, and it is the interactions among persons and materials in the world that gives them the opportunity to generate a phenomenon and to use representational tools such as words and diagrams for observation, reflection, and interpretation to make sense of why it occurred.

By these standards, the physics classroom had to become an environment where students would have opportunities to engage collaboratively in inquiries that required and challenged them to have conversations about what was happening while pacing themselves through the procedures of the science (hypothesizing, observing, experimentation, explanation). The tasks would have to be structured to encourage the students to seek out and use the terms, tools, and representations of the physics community to accomplish their work. Such an approach also required an altered role for the teacher, who needed to move from dispenser of other peoples' physics to expert facilitator of students' new uses of representational tools for reasoning in the domain and constructing new conceptual understandings.

Pea (1992) presented a social framework on learning that highlights the role of *conceptual learning conversations* as a major source of learning resources that have been unreasonably neglected in cognitive science. Learning is fundamentally built up through conversations between persons, involving the *creation* of communications and efforts to *interpret* communications. Creation and interpretation are the reciprocal processes of human conversational action, through which meaning of talk, diagrams, formulas, and actions gets established and negotiated (Goodwin and Heritage, 1990; Heritage, 1984; Schegloff and Sacks, 1973). Communication is thus not viewed in terms of one-way meaning transmission and reception, but as two-way transformational, changing both students and teachers (Pea, 1994).

Meaning is progressively constructed through successive turns of symbolic action and talk. Such conversational interactions allow persons to collaboratively construct the common ground of beliefs, meanings, and understandings that they share, as well as articulate their differences. In this publicly available space, rich opportunities exist for speakers to determine how they were understood, often leading to meaning negotiation and cognitive change. Meaning negotiation takes place using interactional procedures such as commentaries, repairs, paraphrases, and other linguistic devices for signaling and fixing troubles in shared understanding (Schegloff, 1991).

Our global pedagogical objective is to have students become better able to engage in appropriate conversations about the conceptual content they are investigating through their collective activity and symbolic action. We reasoned that their conversations should be inquiry-focused, sense-making conversations including authentic tasks in science practice such as making conjectures, designing experiments to test them, and revising conjectures in light of their observations. To pursue these objectives, we worked to create a learning environment, so that students might achieve competency in the language games of geometric optics, including verbal, physical, and diagrammatic representations. This design involved complex choices involving both technological and social dimensions.

The 2-D Optics Dynagrams simulator we created (for details, see Jul, 1991; Pea, 1993) allowed users to easily create and manipulate one or more scenes made up of optical entities such as spherical,

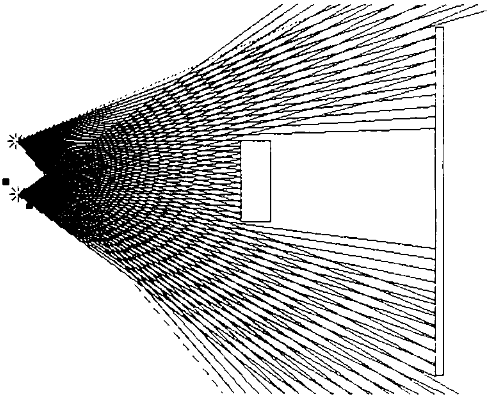


Fig. 1. Optics Dynagram representing ray tracing from two light sources in a situation constructed of a reflecting rectangle and a plane mirror.

triangular, and rectangular objects (that have assignable properties and/or materials; reflecting, absorbing, refracting). One could also emit single light rays, or ray sprays over an angle range, from one or more point light sources (Fig. 1). Users may create geometrical entities such as tangent lines, grids, and angles, and measure distances and angles.

Dynagrams is most centrally an optical-rule-based "microworld" related to the interaction of light and matter. We focus mainly on the phenomena of the refraction and reflection of light rays and deal with absorbance without any relation to temperature. In the Dynagrams software environment, the students can collaboratively construct objects with various shapes of transformed spheres. These objects have certain properties: absorption and/or reflectance and/or transmission of light. Numerical values of the variables are easily varied by the student. The range of the values is not restricted by the range of these variables possible in the natural world. Thus, students are allowed to construct imaginative setups in which visualization of hypothetical situations is made possible. Examples of such situations are depicted in Figs. 2 and 3.

The software allows three modes of interaction. The first is mainly a "getting familiar" mode, in which the student browses freely to get a sense of the symbol manipulation, interface, and general structure of the software. The second is a more directed learning environment, in which students carry out guided activities designed to lead towards learning a specific piece of scientific knowledge. This mode of interaction includes a set of tasks that are the basis of a set of activities generated by the Dynagrams research team and teacher. The third mode is a problem-solving task in which the students can use any of the previous modes to solve problems.

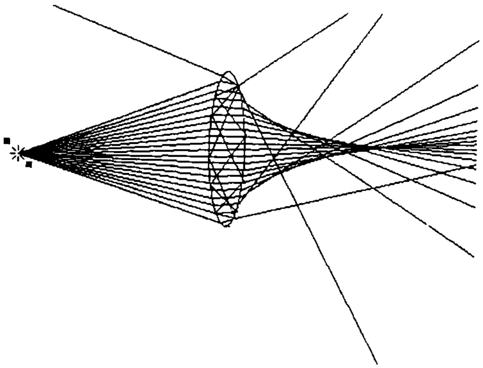


Fig. 2. Optics Dynagram representing ray tracing from a light source in a situation constructed of a lens.

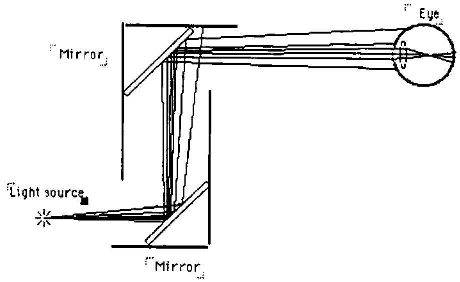


Fig. 3. Optics Dynagram representing ray tracing from a light source in a situation constructed of two plane mirrors, a lens, and an "eye."

We largely focused on promoting *qualitative* understanding of relations in geometrical optics (e.g., to define shadows, find image location, find lines of sight for mirrors), rather than formal quantitative principles and formulas. We used the Dynagrams simulator to create a set of challenge activity structures of increasing complexity (e.g., single to multiple light sources for making shadows; single mirrors to multiple mirrors; simple lens refraction to a coin-in-pool situation) for small group work in the classroom.

Student groups observed real-world optical situations (or video depictions), used our dynagramming tools to build scenes that make predictions and developed arguments to justify them based on scientific principles, definitions, or prior experiences. The Dynagrams bypass many difficulties students have in constructing paper-and-pencil or chalkboard diagrams. By comprising Dynagrams representations, students in a group can graphically express predictions and then use these representations as indexical support for narrative explanations of light behavior in the situations they have modeled. Rays of light, angles, shapes, points of contact between the lens and a ray, hypotheses about possible outcomes, argumentations—all are created by means of the software representation, for communicating with the teacher and other members of their groups. The representation on the screen turns into a tool that is less subject to the imprecision of everyday words for the representation of scientific phenomena. Since the simulator knows how light rays depicted will propagate in the situation students have modeled, students can then run their simulation models and discuss how well each of their graphical conjectures fits the actual results. Through learners' creation and interpretation of these representations in sense-making activities, the dynamic diagrams become symbolic vehicles for expressing students' conjectures about light behavior, and the topic for negotiating group and individual understanding of technical language, concepts, procedures, and skills.

Many learning situations can be constructed in this environment. Students, according to their needs, can create situations on the screen. These then provide communication tools that allow collaborative reasoning for solving the problem stated in the task. Thus, the software is not a specific curriculum dominated by the beliefs of the developer but rather is dominated by the scientific user who creates situations in an environment according to their discussions and the specific context. This environment serves as a tool that allows groups of teachers and groups of students to build tailored conceptual learning sequences free of ordering constraints.

Dynagrams supports a collaborative effort in a teacher–student group. The teacher, like the students, and to some extent like the scientist, faces a new world in which extreme cases can be constructed. The teacher faces a new virtual world, understandable, observable, explicit, based on known rules, yet different from the everyday world and from formalistic presentation of scientific rules. Situations created in this virtual world do not necessarily exist in the natural setup.

The screen is used for students to express ideas about the interaction of light and matter in a dynamic representational medium. The representation on the screen turns into a tool that is less subject to the imprecision of every day words for the representation of scientific phenomena. Once the communication tools are set, the ground for collaborative efforts for problem solving are established, and students proceed through a group activity, negotiating one situation against the other to construct a piece of a possible explanatory framework.

METHOD

The learning experiment took place over a period of four weeks in the 11th grade of a renowned high school in California. The participating teacher was an award winning teacher of physics, with over 20 years of teaching experience. The students who participated chose the course to fulfill their state science course requirements, and as a group, were described by the teacher as "mathematically reluctant." The teacher participated in the development of the activities based on the software and helped in designing the research.

In practice, the physics classroom teaching period had some regularized sequential patterns. Class started with an attendance check and the teacher's introduction to the day's topic and activities. Occasionally, assignments were collected, and the introduction was often supplemented with announcements. The segment was teacher directed, and often utilized a computer setup in front of the classroom, which the teacher used for discussing the goals and concepts for the day, for presenting demonstrations, and then to raise questions that were to be pursued in collaborative group work with eight Macintosh computers on the classroom tables. This introductory segment was followed by "the lesson or activities" segment of the class. It took different forms, depending upon the day's goals, with the possibilities of teacher-directed activities such as lecture, demonstration, and class discussion, or small group work at the lab tables. The lesson segment of the activity usually lasted the most time during the 48-minute period, lasting anywhere from 12 to 40 minutes. The third and final sequence was the wrap up, in which main points were restated, assignments and due dates confirmed, the next day's lesson introduced, and "things to think about" mentioned. This final segment included formal class dismissal. The middle segment of main lesson activities is when we found our students conversing and collaborating at tables around Dynagrams computer tools. Students separated freely into self-selected groups of roughly three students each, the teacher moving among them on an as-needed basis or in terms of his judgments of when groups needed to be guided in their work and conceptual growth. The basis for the activity was a daily activity sheet collected after each class, along with homework sheets.

Students worked in groups more often and had many more conversational opportunities than they had in the pre-Dynagrams classroom. Students used diagrams regularly as the basis from which they were asked to observe and describe optical phenomena. Rather than just know the definition of terms and properties, students were asked repeatedly to use and experiment with them in their modeling activities (e.g., light sources, rays, focal points, virtual and real images, normals). They made reference to terms and/or properties in more varieties of ways and in more instances. The simulator provided an exploratory environment where students were asked to reason about optics. Student activities and conversations became focused on making projections and conjectures, and then testing out their ideas of how light would react. The Dynagrams classroom activities provided students with more opportunities to ask questions of each other and an environment within which to test their answers. When questions emerged out of a group's activities, the teacher used the simulator with students for exploring questions before giving answers and explanations. Interactions surrounding classroom activities became more discovery-oriented.

The Dynagrams instructional experiment began in the first day of the academic year in September. Prior to the instructional experiment all students were asked to respond to a paper-and-pencil questionnaire: of the 21 students in the course, 15 participated in the pretest, and 12 in the posttest (others were ill or absent, and several declined participation in the study). Since not all students who returned the questionnaire answered all items, pre–post comparative analyses are reported as percentages. The pretest was administered in the first days of school, and the posttests were administered during the last several weeks of the school year period, during which geometrical optics was taught.

Test Items

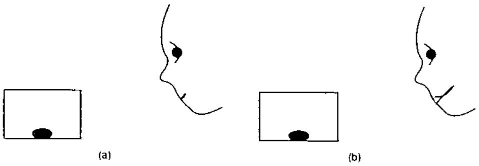
The test items used are listed below. Students were asked to use words and a diagram to answer each question. The number of students providing any answers in the pretest and posttest groups are reported after each question.

(1) Sometimes shadows seem clear and sometimes they seem fuzzy. Why? Show with a sketch what causes this to happen. (14/12).

(2) Imagine yourself in a dark room lit by a candle. Why is it that you can see not only the candle but also other objects in the room? Show with a sketch what causes this to happen. (15/12)

(3) Explain what happens when you see yourself in a mirror. Show with a sketch what causes this to happen. (15/12)

(4) In diagram (a) below, a bucket contains a coin which is just hidden from your view by the bucket walls. In (b), the bucket has been filled with water, and suddenly, though you did not change your position, you can se the coin. Why? Use the diagrams to explain, or draw a diagram of your own. (10/10)



(5) Draw a diagram of yourself looking at this page. Explain how it is that you can read these words. (14/12)

(6) If you stand in a lighted room and look through the window to a dark street outside, you can see your own image. Why can't you see your image if you stand at the same place during the day? Show with a sketch what causes this to happen (14/11)

(7) Explain how it is that something looks bigger when you look at it through a magnifying glass. Show with a sketch what causes this to happen. (dropped)

(8) Make a short list of the most important things that you know about light. (14/12)

(9) What are three things you'd like to know about light? (13/11)

(10) Why is it that you can use a magnifying glass to burn a piece of paper on a sunny day? Show with a sketch what causes this to happen (12/12)

(11) Assume that you are comfortable swimming under water with your eyes open. If you wear goggles or a mask, you can see much more clearly. Why? Show with a sketch what causes this to happen. (15/11)

(12) Does light from a TV travel the same distance at night and during the day? How far does it travel in each case, and

how do you know? Show with a sketch what causes this to happen. (dropped)

(13) Which would be a better approach to brightening a room, putting up mirrors or painting the walls white? Why? Show with a sketch what causes this to happen. (dropped)

(14) You are locked in a room which has identical white walls, except for a mirror which covers the door. The room is completely dark. Using a flashlight, how would you recognize the mirror? Show with a sketch what causes this to happen. (12/12)

(15) Descartes (a philosopher who lived in the 17th century) claimed that light has an infinite speed. He based his claim on the following reasoning: if you go outside at night with your eyes closed, and then open them, you immediately see the stars. The fact that it is immediate proves that light has infinite speed. Was he right? What do you think about his explanation? (dropped)

(16) If you watch the bottom of a clear wavy pool on a sunny day, you can see changing patterns of light. What creates them? Show with a sketch what causes this to happen. (10/11)

The items were designed so that use of a number of major concepts (e.g., the role of the eye; virtual images; nature of light) would be elicited by several different questions. None of these specific questions were directly used as topics of course instruction, so changes in student's patterns of response are of interest as indices of learning from the Dynagrams instruction. For the purposes of this paper, we will examine student responses to questions 1-6, 10, 11, 14, and 16. (The open-ended questions 8 and 9 were used for the teacher's purposes, and questions 7, 12, 13, and 15 were beset with methodological problems and dropped during administration.)

Analytic Method

Protocols for each of the students were analyzed according to their general features, their written explanations, and characteristics of their diagrams. General features to all the problems included categories such as: no answer, written explanation present, correct explanation, diagram present, diagram follows explanation. Categories of the analysis of written explanations and the diagrams were specific to the situation described in the problem. For instance, the analysis of the written explanations of fuzzy shadows was based on these categories: the shadow is fuzzy because: (a) intensity of the source is too low; (b) distance of the source from the object is too great; (c) multiple light sources are present. Students' diagrams for this problem were analyzed according to whether: (1) the light is represented by (a) a single ray, (b) diverging rays, or (c) a colored area; (2) the number of light sources present in the diagram is either (a) none, (b) 1, or (c) greater than 1; (3) the rays hit the object and (a) define a shadow, (b) define a sharp shadow, or (c) define a fuzzy shadow; (4) the rays are reflected (or not); (5) the rays enter the eye (or not); and (6) perfect explanation and diagram are provided.

The second and third parts of the analysis of students' responses are based upon the situation described in the problem. The basic constituents are similar—analysis of the representation of light, the role of the eye, and the relations among the various components of the optical system. Yet the content, since it is based on the situation, may differ.

The results were coded by two independent judges, whose agreement was near 100%. Comparison of the pre-post results below are used to describe the changes within the various categories for each problem in terms of the following considerations: (1) the changes in the content of the concept; (2) the changes in the conceptualization of the behavior of light as an integrative mechanism which relates the components of the system to each other to create a causal story; and (3) the role of the eye.

RESULTS

We are particularly concerned with understanding specific differences between pretest and posttest profiles of student responses to the battery of questions presenting problem situations for reasoning about optics. This section presents findings from a variety of analyses of students' diagrams and explanations on geometrical optics. In three subsections, results are characterized in terms of different indices of students' conceptual change: (1) aspects of the *development of conceptual understanding* of the interaction of light and matter; (2) developments of *verbal and diagrammatic tools* that represent related scientific ideas; (3) developments in the *epistemological structure of explanations* involving central concepts in geometrical optics.

Development of Conceptual Understanding of Interaction of Light and Matter

Patterns of responses on the pretest indicated some of the students' prescientific ideas related to light-matter interactions. These ideas drastically differ from the scientific ideas expressed in their explanations after the Dynagrams learning experiences. In the three parts of this subsection, major changes are identified in students' postinstructional conceptualizations of: (1) the formation of shadows, especially fuzzy shadows (i.e., shadows with different intensities of darkness); (2) formation of images by optical devices such as mirrors, lenses, glass and water; and (3) vision as related to the role of the eye.

We next describe changes in the understanding of each of these ideas from pretest to posttest, presenting first the question and problem situation, and then patterns of students' responses and how these changed, if at all, from pretest to posttest.

Formation of Shadows

In the pretest shadow question (Q#1), only 13% of our students explained correctly how a shadow is formed; 79% explained the formation of shadows in terms of one of three physical properties of the system, rather than by the interaction of light with these properties (percentages are broken out below; numbers sum to more than 79% since some students used multiple physical properties to explain shadow formation). Thus, in the pretest responses, students describe shadows as fuzzy because of either the relative distances of source–object–shadow (43%); the intensity of the light source (29%); or physical properties of the object such as "sharpness" of the object's shape, "smoothness" of the wall, or motion of the objects or sources (21%). S# stands for student number for all examples.

(1) *The relative distances of source–object-shadow* (43%). For example:

S13: " . . . as the distance increases between an object and its shadow, the clarity decreases. The closer a shadow gets to the exact size of an object, the shadow will become more detailed. This is caused by gases of the atmosphere which scatter the light . . ."

S2: "the farther away from the object the light is, the less fuzzy it is [i.e., the shadow]"

The diagrams support the written explanation, e.g., the diagram following S13's explanation shows both far-away and nearby shadows of an object situated between a wall and the sun. The first shadow is depicted as fuzzy, and the latter is sharp.

(2) *The intensity of the light source* (29%). For example:

S12: "It depends on how strong the sun or light is shining"

S12's diagram depicts a fuzzy shadow when the sun is blocked by clouds, and a sharp shadow when the sky is clear.

(3) *Physical properties of the object such as "sharpness" of the object's shape, "smoothness" of the wall, and motion of the objects or sources* (21%). For example:

S20: "perhaps the surface that the shadow is lying on is not a smooth surface"

This distribution of mistaken conceptions changes significantly in the posttest: 92% of the students in the posttest correctly account for the fuzziness of shadows with explanations in terms of multiple light sources. The diagrams in the posttest, although not always correct, explicitly recognize the structure of the light source in the formation of a shadow (Fig. 4). Only 17% of the posttest students still explain fuzziness in terms of relative distances, and none of them explain fuzziness in terms of light source intensity or object properties. An answer that was not given in the pretest, and is now reflected in 8% of the posttest responses, accounts for fuzziness in terms of the size of the light source. Physics treats an extended light source (e.g., a light bulb) equivalently to multiple light sources. We have no way of knowing whether students equated extended light sources with multiple light sources.

Light was recognized by students in the pretest as playing a necessary role in shadow formation. All students produced some representation of light in their diagrams—either a light source or some rep-

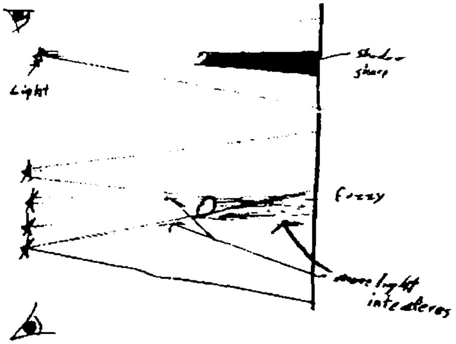


Fig. 4. S8 posttest diagram for shadows question 1.

resentation for rays. Yet none of our students, even those who accounted for fuzziness in terms of more than one light source, went on to explain *how* light accounts for shadow formation. In contrast, students in the posttest commonly used relational reasoning to describe the central role of light rays in the formation of the various boundaries of fuzzy shadows. All 75% of the students who answered the shadow question correctly described the relations between light sources, objects, and shadows by using light sprays to project the boundaries of the shadows, and the boundaries of the various levels of darkness of shadow are explained in posttest responses in terms of the overlapping illuminated areas by each light source interacting with the object casting the shadow.

In summary, while in the pretest students treated light sources, objects, and shadows as isolated entities, in the posttest they are predominantly treated as an integral system linked by the light rays. Some of the posttest students (21%), although correctly stating that multiple light sources cause fuzzy shadows, were unable to support their answer by a diagram including the causal relations between the multiple light sources and the structural properties of the shadow. These students drew light sprays, as well as the locations of the object, wall and shadow, yet the light sprays did not link these together into an integral causal relation. Although some of the instructional activities dealt directly with modeling a shadow created by a single source, two sources, and finally multiple sources, students' application of an understanding of the way a shadow is created by one source was not extended to multiple sources. The integration of multiple ray sprays into multiple shadows (fuzziness) was not evident. It seems that the strategy of the diagram was learned, the actual correct answer was also learned, yet the relation between the two was still weak.

The nature of the shadow as the surface of a material object that reflects less light or no light, is hardly addressed by students either in pretest or posttest. It was addressed by 14% of the students' diagrams by including an eye that looks at the shadow (e.g., Fig. 4). This response reflects a deep understanding of the shadow as a reflectance phenomenon. For the shadow to be seen, there must be a surface to reflect the decreasing flux of light and an eye to detect it. This is probably the deepest understanding of shadow formation represented by geometrical optics, and from the results we can see that this is hardly achieved.

Formation of Images: Real and Virtual

In this section we portray pretest–posttest changes in students' conceptions of the formation of real images, and the formation of virtual images.

Real Images. Students' conceptions of the formation of real images are revealed in their answers to questions 10 (magnifying glass for burning paper), 11 (wearing goggles in a swimming pool) and 16 (patterns of sunlight in a wavy pool). We present first results concerning the development in students' concepts of real images and then move to the development of the concept of virtual image.

The situations described in the questionnaire are not necessarily associated to the "classical" lens and real images introduced in a typical physics class. Our aim was to avoid a simple recognition of "real image" type of problems for the posttest, to which standard classroom answers could be given. For this reason, the questions did not include the phrase "real image," although the situations required reasoning about real-image phenomena. This phrasing of questions thus increases their degree of difficulty. The student needs to recognize the problem situations as depicted in the question to be associated with refraction phenomena, and then as calling for the applications of the concept of real image learned in different situations in the classroom.

Question 10 (Magnifying Glass for Burning Paper). None of the students, either in the pretest or posttest, explained the burning paper situation as an image of the sun which falls on the paper when it is placed at the focal distance from the lens. A majority (53%) explained it correctly in the pretest as the result of the focused rays, which increase the heat of a specific area on the paper (e.g., S8, Fig. 5). This percentage of correct answers increased in the posttest to 73%, but just as important were the changing components of the students' explanations in the posttest, which better justified their answers. The components of improved explanations, both diagrammatic and written, that changed from pretest to posttest were: (1) light is represented as straight lines (post) rather than wavy lines (pre); (2) these straight lines are represented as parallel because of the distance of the sun (post), instead of convergent (pre); (3) each symbol is explicitly assigned a role in the causal story (post), instead of symbols without such roles (pre); and (4) the representation of the lens is functional (post) rather than a photograph-like drawing of the everyday shape, such as a magnifying glass with a handle (pre).

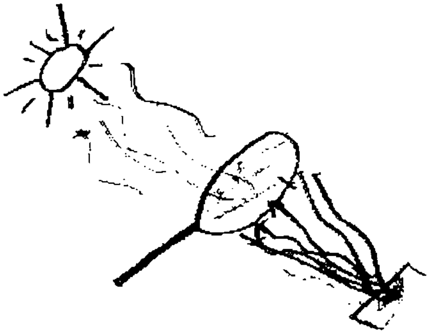


Fig. 5. S8 pretest diagram for burning paper question 10.

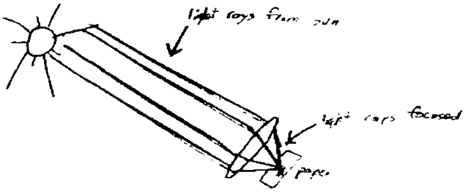


Fig. 6. S8 posttest diagram for burning paper question 10.

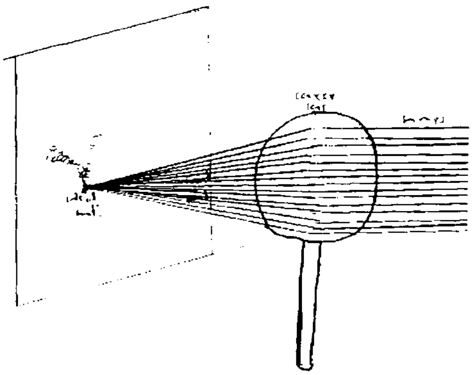


Fig. 7. S11 posttest diagram for burning paper question 10.

The remaining 27% who responded incorrectly sometimes mentioned the intensity of light in their answer, yet did not explain it as resulting from refraction of light through the lens in a converging manner; 8% of students in the pretest and 25% in the posttest mention or graphically depict the focal point of the lens (e.g., Fig. 6). It thus appears that students acquire a phenomenological understanding of burning a piece of paper with a lens, which is refined by classroom learning with Dynagrams, yet they still encounter difficulties explaining the event in terms of the image of an infinitely far object, formulated at the focal point of the lens (e.g., see S11, Fig. 7, which depicts a "focal point" and the label "lots of heat!" at the paper surface, but not the sun's image).

Question 11 (Wearing Goggles in a Swimming Pool). The role of the goggles while swimming under the water is somewhat tricky to understand. It relates to a real image formation on the retina, by the lens that is part of the eye. For the eye to create an image, it needs to refract the rays of light. It also presupposes understanding of the index of refraction as a normative rather than an absolute concept. Therefore, to answer this question one needs to understand that each transparent substance has multiple indices of refraction, determined by the materials of the surrounding environment (see Fig. 8). The closer the relative index of refraction is to 1 (the lowest possible value is 1), the less refraction occurs, and the more blurry the sight becomes. The role of the goggles is to create an "air lens" which

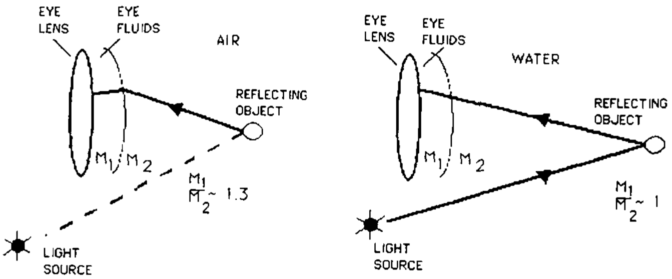


Fig. 8. Explanatory diagram for goggles question 11.

diverges the rays before convergence by the lens of the eye.

We found some difference in the distribution of correct responses to this problem (0% in the pretest, 17% in the posttest). The content of the answers distributed differently: 50% of the responses in the pretest and 11% in posttest were based on the properties of the water/goggles/eyes. For example: S6—"water takes up part of the light"; and S18—"water pressure on the eye."

Another 50% of students for the pretest (67% in the posttest) based their answer on phenomenological accounts: S2—"because there is air between you and the water"; S16—"eyes are irritated by chlorine"; S17—"there is friction between eyes and the water" (also S14). Only one student mentioned that goggles have the role of a lens, but went no deeper in explaining the phenomenon beyond this observation.

Though minimal changes appeared in the frequency of correct responses overall, more posttest students (67% vs. 0% in the pretest) explained the need for goggles as a tool to create a layer of air. The precise role of the air layer for the image formation on the retina was still missing in their explanations, however.

Question 16 (Patterns of Sunlight in a Wavy Pool). The wavy pool question deals with images of the sun created by the wavy surface of the water. Correct explanations went up from 20% on the pretest to 58% on the posttest. A major difference between the two groups was in the posttest group's ability to not only write a correct explanation relating the interaction of light and water, but to construct a causal explanation in the diagram representation: 92% of the students constructed a diagram after instruction, while only 58% had constructed a diagram in the pretest.

In answering all three of these questions related to real images an overwhelming majority of the students show an important conceptual shift in their understanding of what an image is. In the pretest, a real image is not described as a light-related phenomenon, but as something that is present when light is present. In nearly all of the posttest responses to the burning paper and wavy pool problem situations, students relate the real image phenomenon to light refraction, rather than presenting the image as a phenomenological assertion. This more advanced pattern, however, occurs only for a fifth of the students' responses (21%) and to a more shallow depth of understanding in posttest responses to the goggles question.

Virtual Images. Students' conceptions of the formation of *virtual* images are revealed in answers to questions 3 (looking at a mirror), 4 (coin in the water), 6 (window as a mirror), and 14 (dark room with one mirror). The understanding of a virtual image presupposes the understanding of the role of the eye as a detector in the formation of the virtual image. The eye sees the virtual image because it is deceived to interpret the rays of light as originating from the direction from which they hit the eye. The eye cannot sense the changes of direction of the light rays prior to their hitting the eye. As a result, the eye creates an image in the direction sensed by the eye, which, in the case of reflection from a mirror, is not the actual original direction. Rays of light do not cross each other at the virtual image, as happens in the case of a real image. Therefore the image is considered to be virtual and it does not actually occur unless there is an eye to "see" it. Obviously then, the role of the eye is central to the understanding of the formation of a virtual image.

Therefore, we analyzed students' responses to questions concerning phenomena of virtual images from three perspectives: (1) the location of the virtual image on/out of the surface of the reflecting/refracting surface, (2) interaction between light and reflecting/refracting surface, and (3) the essential role of the eye in forming and monitoring the virtual image. Since the consistency of the responses for each student varied, we separately analyzed their responses to each question. A unified view is presented in the concluding analysis and discussion.

Questions 3 (Looking at a Mirror). The responses to the classical mirror situation indicated that the changes in students' conceptualization of the location of the virtual image after Dynagrams instruction were massive. While in the pretest the full 83% of the students who drew an image at all positioned that image *on* the mirror's surface (Fig. 9), in the posttest none did so. Instead, 83% of posttest students correctly positioned the image *behind* the mirror's surface. Only a few pretest students (7%) used a ray spray to justify the image formation, but 42% used a ray spray to do so in the posttest. The role of the eye was not mentioned at all in the pretest, and just 33% of the posttest students included it either in the diagram or noted it in their written explanations.

Question 4 (Coin in the Water). In this problem situation, the coin becomes visible to the observer only when immersed in water because of a virtual image due to light refraction. The percentage of students who verbally explained the viewer's ability to see the coin as a result of refraction in the water increased from 20% in the pretest to 89% in the posttest. When we examined students' diagrams only, we found a shift from 7% pretest to 67% posttest correct answers. For example, see S8's pretest in Fig. 10 and posttest in Fig. 11. In the posttest, the coin is represented as visible because light bends, but in the pretest the coin itself is represented as higher up, and the light is not depicted as refracting. This written–diagramming response difference indicates that some students who responded correctly in the written explanation did not describe the process of light refraction in their diagram. For example S10's posttest diagram did not show the rays refracting to hit the coin, but his written explanation correctly described the bending of the light rays to hit the coin: "The rays now hit the water and bend in towards the normal and can reach the coin, therefore illuminating it and making it appear within our line of vision." As in the earlier results for explaining shadow formation, the students' over-

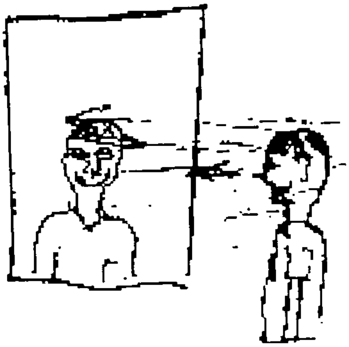


Fig. 9. S11 pretest diagram for looking in plane mirror question 3.

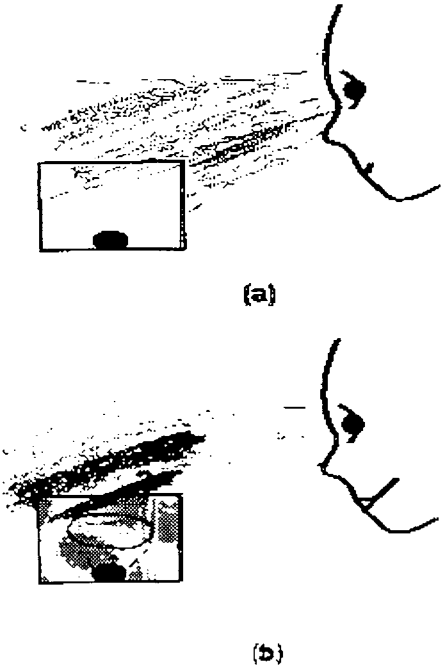


Fig. 10. S8 pretest diagram for coin-in-water question 4.

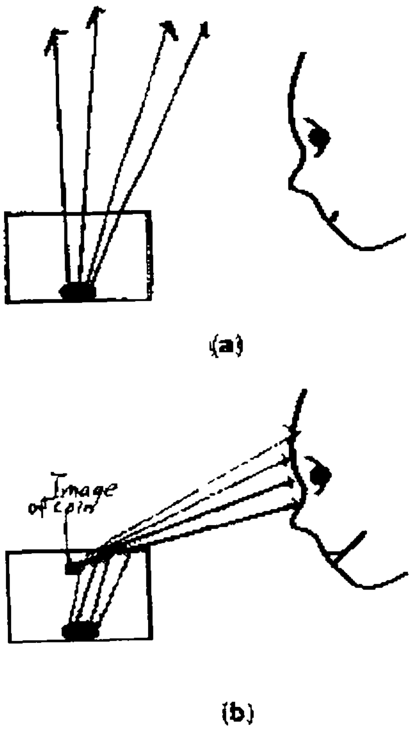


Fig. 11. S8 posttest diagram for coin-in-water question 4.

all explanatory accounts were lacking the causal linkages between the coin, its image in the water, and the "deceived" eye, as explained by the interaction of light, water and the eye.

A major pre-post change detected, as in the problem looking in the mirror, was in the percentage of students who traced rays backwards to show the location of the virtual image created by the eye: 11% in the pretest vs. 40% in the posttest. Yet the eye (drawn by the researchers as part of the question) was linked to the light rays and water in all the diagrams drawn by students, either by a single direct ray, or by an attempt to describe the field of vision. These rays mostly originated in the eye in the pretest (56%), but were directed from the coin to the eye (60%) in the posttest (see pre-post developments revealed in Figs. 10 and 11). After instruction, pretest responses based on magical properties of the bucket/water/coin system (40% of pretest students), such as "water carries the light," completely disappeared.

Question 6 (Window as a Mirror). From the physics point of view, an explanation of the window serving as a mirror is identical to the previous two situations. There is one additional factor here: The amount of light reaching the observer's eye from the inside of the room relative to the amount of light reaching the eye by transmission through the glass from the outside. However, once the image is detected by the eye, the basic structure of the physical explanation of the image formation is identical to the previous cases. This additional factor may have contributed to our finding that the students' responses to this question seemed to be completely different to those of the previous two situations. The dominant response was that the glass changes its properties and behaves differently during the night (71% in the pretest vs. 55% in the posttest). About 14% of students in both pretest and posttest groups conceptualize darkness outside the lighted room as a dark materialistic background. For example: S14—"dark does not absorb light while light colors do."

We found little change in the response that the image is hard to see during the day, and that "it is easier to see bright against dark." More diagrams in the posttest presented the image behind the window (0% pretest vs. 80% posttest for those who drew the image at all; see, e.g., pretest-posttest changes from Fig. 12 to Fig. 13). Hardly any responses explicitly included the role of the eye in their graphical accounts of the formation of the virtual image.

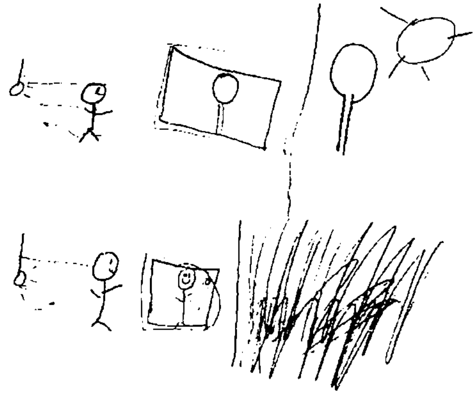


Fig. 12. S8 pretest diagram for window-as-mirror question 6.

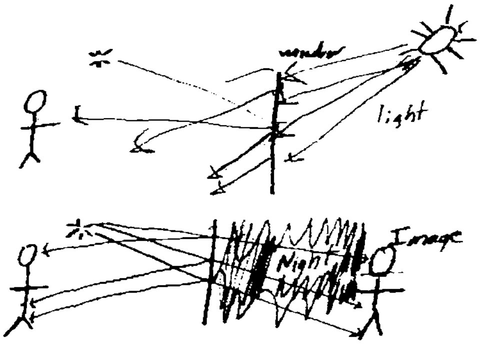


Fig. 13. S8 posttest diagram for window-as-mirror question 6.

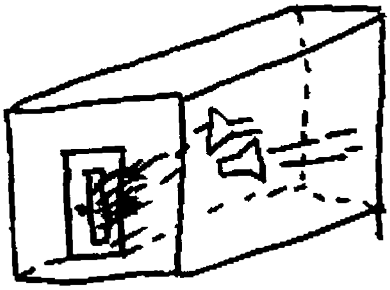


Fig. 14. S9 pretest diagram for mirror-in-dark-room question 14.

Question 14 (Dark Room with Mirror). Students were asked in this question to identify a door that is hidden behind a mirror in a dark room by using a flashlight. In order to correctly and fully answer this question, they needed to answer its two parts: (1) identify the wall with the mirror; and (2) identify the precise location of the door from the position of the image. Since the position of the image is twice the distance from the student than the mirror, one needs to roughly divide the distance in half to locate the door.

Most of the students (73% in the pretest and 83% on the posttest) answered correctly on the first part of the question. Interestingly, though, students assumed that just locating the mirror was sufficient in order to locate the door. No student indicated either in the written explanation or in the diagram an understanding of the fact that the door is positioned at half the distance between the flashlight and its image. It seems that the students assumed that once one knows which wall the mirror is on, one also knows the distance to the door. The underlying student assumption that would seem to make such an inference reasonable is a belief that the image is located at the mirror, which one finds in examining their diagrams.

Student diagrams for this question, though, changed significantly from pretest to posttest. They used rays in the posttest to justify their answers, when they did not commonly use them in the pretest (55% vs. 18%, see S9's pretest in Fig. 14 and posttest in Fig. 15). We found that 27% of students located the image behind the mirror in the posttest, in contrast to no students on the pretest, but a more surprising result was that more posttest students (64%, e.g., S9 in Fig. 15) put the image *on* the mirror (vs. 18% in the pretest). This is consistent with the fact that all students ignored the image distance as a factor for determining the exact location of the door. While more students are aware of the fact that an image is present for the eye to detect, they do not infer the correct distance, even though 83% did

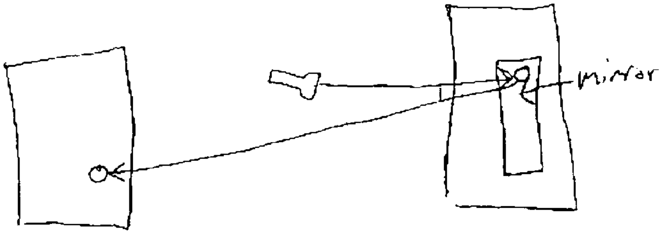


Fig. 15. S9 posttest diagram for mirror-in-dark-room question 14.

so in the posttest on the simple looking-in-a-mirror question. This question clearly presented a more demanding problem than the basic case of looking at a plane mirror.

In summary, across the three questions involving virtual images, overall responses to the three mirror questions revealed a strong reconceptualization after Dynagrams instruction of the position of the image relative to the surface of the mirror. However, there were considerable differences in the rate of posttest success across the set of problems: for the simple plane mirror question (Q#3), 83% of posttest students vs. 0% of pretest students correctly positioned the image *behind* the mirror surface, while 100% of pretest students drawing an image at all (80% did so) placed it *on* the mirror surface. For the more intricate two-step dark room and mirror question (Q#14), 64% of posttest students appeared to regress to their pretest performance, placing the image on the mirror. Posttest responses to the window-as-mirror question (Q#6) were more advanced, with 80% of students placing the image *behind* the mirror (vs. 0% pretest).

Some dramatic progress was made by students in considering light rays as the causal mechanism accounting for the virtual image formation, especially evidenced in their diagrams depicting a person looking into a plane mirror or at a coin underwater, both problem situations in which roughly half the posttest students came to successfully trace back ray sprays to justify image location, in contrast to one in ten students in the pretest.

We found less prevalent a conceptual shift in student responses toward the idea of light as an integrating link between the object, source, virtual image, and eye. The role of the eye was almost totally ignored, especially in the problem situation of the window as mirror at night. One situation in which students came to recognize the fundamental role of the eye in virtual image formation was in the quite basic case of a person looking into a plane mirror, where we see a small improvement (0% vs. 30%) in the understanding of the role of the eye as an essential factor in the system as evidenced in diagrammatic and textual explanations.

Vision and the Nature of Light

Consider question 2: "Imagine yourself in a dark room lit by a candle. Why is it that you can see not only the candle but also other objects in the room?" A correct answer to this candle question, which deals with vision, includes recognition of multiple steps in the propagation of light: Light is emitted by the candle in all directions, hits objects, is then reflected off of them, and then travels into the observer's eye (Fig. 16). More students in the posttest than in the pretest realize that light hits the objects (83% vs. 33%) and that objects need to be reflective as a necessary condition for vision (75% in the posttest vs. 47% in the pretest). However, only 13% realized in the pretest that light needs to hit the observer's eye for vision, while 67% mentioned the eye and each previous step in the process of light travel from candle to eye in the posttest. Figures 17 and 18 illustrate these developments for S9. In the posttest, S9 realizes the role of reflected light that hits the eye as necessary for vision. The posttest diagram for S9 also shows light emitted and reflected in all directions. This is a major new understanding achieved through Dynagrams instruction of the role of the eye in the process of vision. Prior to the classroom learning, half the students had an idea of reflectance as a necessary condition for visibility, but the causal link between light source and rays, the objects in the room as reflectors, and the eye was missing. Over two thirds of the students came to provide this multistep causal account after Dynagrams instruction.

Development of Representational Tools

This section focuses on learners' development of representational tools, both verbal and diagrammatic, for reasoning about and explaining optical situations. We look at pre–post changes in students' representation of objects, light sources, and light

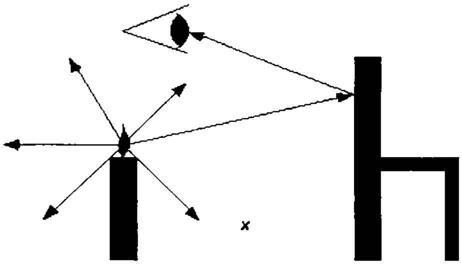


Fig. 16. Explanatory diagram for dark room lit by candle in question 2.

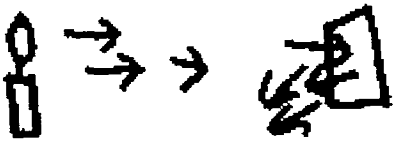


Fig. 17. S9 pretest diagram for dark room lit by candle in question 2.

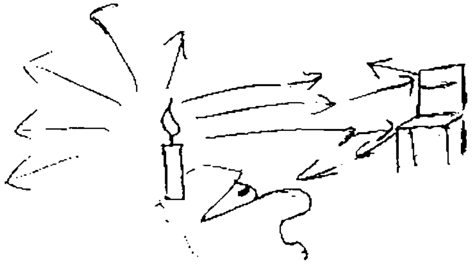


Fig. 18. S9 posttest diagram for dark room lit by candle in question 2.

and physical phenomena such as shadows and images. Then, we analyze the development revealed in their representations of the *relations* between the light source, physical objects, and natural phenomena.

Recall that students were asked to draw diagrams both in the pretest and in the posttest. There was no significant difference between the number of diagrams drawn prior to and after the Dynagrams instructional process. In these terms, students seemed equally confident that they had the tools for diagram construction both before and after instruction.

The five parts of this subsection of our analysis are concerned with capturing the richness and diversity of different aspects of students' diagrams: (1) representations of entities such as light sources, objects, and the physical phenomena such as shadows and images; (2) representations of light; (3) representations of shadow; (4) representations of an image; and (5) representation of temporal or causal links, as in how light-image connections depict the behavior of light as interacting with matter (such as objects and eyes).

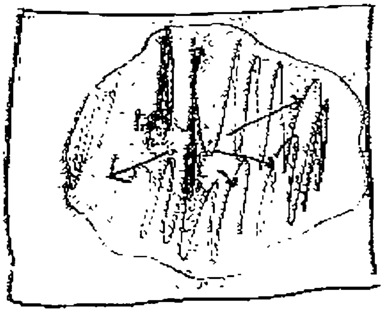


Fig. 19. S8 pretest diagram for dark room lit by candle in question 2.

Representations of Entities

Most of the diagrams created by students in the pretest across all questions are of a *photographic nature* (76%). By photographic, we mean that the students draw the situation in roughly the same way that it would appear in a picture taken by a camera (e.g., Figs. 9 and 19). The objects are represented by their shape, the light source is represented by traditional symbols of light such as a glowing candle, glowing sun, or bulb, which for our purposes is also considered to be a photographic representation of a light source. A lens is represented by its contour (sometimes with a handle) and the shadow is a darkened area. The image is represented also by its shape.

Representations of Light

Light creates a special problem, for it can hardly be represented by its shape, as can other components of the system. We found that students chose to represent light through three different representational symbols: (1) rays (one or more, parallel), (2) ray sprays (one or more divergent rays), and (3) fully painted/colored regions. In S8's pretest diagram in Fig. 20, light is represented both as rays and as a painted region, and in a posttest diagram in Fig. 7, light is represented as parallel ray beams. In S11's posttest diagram in Fig. 21, light is represented as ray sprays.

We may now consider the full set of diagrams produced for all questions in which light was represented. The 15 pretest students produced 60 such diagrams in total, and the 12 posttest students pro-

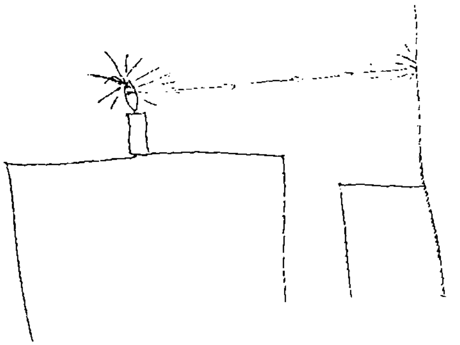


Fig. 20. S20 pretest diagram for dark room lit by candle in question 2.

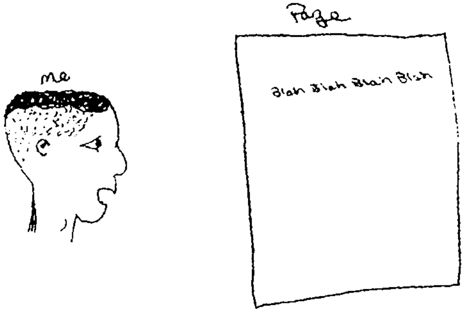


Fig. 21. S13 pretest diagram for reading paper question 5.

duced 85 such diagrams. When we compare the frequency distributions of pretest and posttest students' representations of light across all questions, the following differences emerge. For both groups, the most commonly used tool is a single ray or a two-ray beam: 73% of all pretest diagrams representing light did so in this manner, but only 50% of posttest diagrams did so. The reason for this drop was a major development for the posttest group. The percentage of diagrams that represented light by means of ray sprays—the representational tool highlighted throughout the Dynagrams software and instructional activities—increased strongly from 17% in the pretest to 45% in the posttest.

The pretest–posttest improvements in the representation of light were most dramatic for specific questions representing basic shadow and virtual image situations (Q#1, 3). These questions are more explicit in their demand to construct an image, while other questions such as the mirror in a dark room (Q#14) are but indirectly related to image formation. When we combine the diagrams students produced for these two questions, we find that the use of diagrams depicting divergent rays increased from 15% to 60% while those using the single ray/beam decreased from 60% to 25%. Use of a colored area to represent light was relatively constant for the combined Q#1 and Q#3 responses, accounting for 25% of the pretest and 15% of the posttest responses.

A halo is often drawn around the light source of a glowing candle for question 2, although most of the time (98% of the light sources drawn), it is constructed of small lines that are not related to light rays, beams or sprays. When a ray is drawn, it is not a continuation of the halo around the light source, but is drawn separately as emerging directly from the light source (for example, S20's pretest diagram in Fig. 22). Thus the halo appears to be depicted as a symbol of the state of the source—active/on—rather than the function of the source—emitting light. The function of the source as the origin of light rays is not present. It is more frequently represented in the posttest (e.g., S11's diagram in Fig. 21) through the ray spray tool (17% in the pretest vs. 45% in the posttest), which, by its very definition, has to emerge from the light source. A fully painted area is rarely used to represent light (10% pretest, 5% posttest). In these cases where such a graphical convention is used, the rays are superimposed on the fully painted area, separating the ray of light from the fully lighted space.

Representations of Shadows

Shadow was represented as a darkened area on the surface of a plain object by all students in the pretest and posttest groups (e.g., see Fig. 4). This depiction corresponds to their verbal representation: e.g., "no light is reflected," "no light hits the wall," and "no light gets there." Some students represent a shadow as a darkened space, not just a two-dimensional piece on the surface, but rather all the space behind the object, on the far side of the light source (20% pretest, 5% posttest). This difference suggests an increasingly common representation of the idea that a shadow is not a dark space but a surface that reflects less light. Reflection is impossible when the shadow is a dark space.

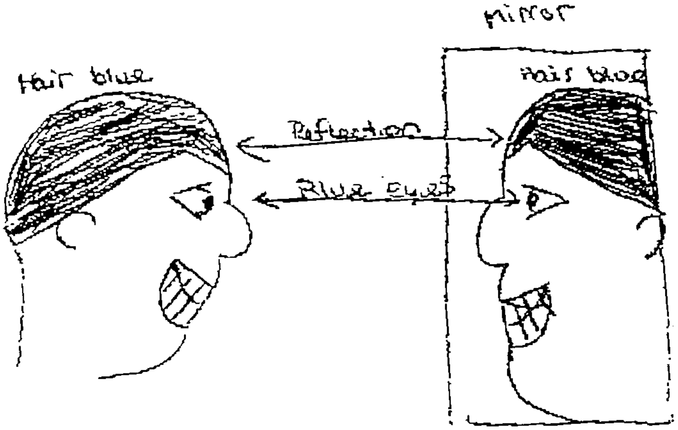


Fig. 22. S13 pretest diagram for plane mirror question 3.

Representations of Images

We now describe students' representations of an image and characterize the restructuring of these representations after learning with Dynagrams. We first discuss the shape of images, then image locations, then depiction of causal relations in students' diagram symbolization.

An overwhelming 87% of the students' pretest responses (with completed diagrams) presented an image in its photographic form by drawing the shape of the image, as in S13's diagram for the reading process question (Q#5), shown in Fig. 19, where no role is depicted for light in image formation.

Only one of 21 pretest students related image formation to light behavior, and this connection was not from light behavior to image location, but only to image existence and shape. Parallel lines were drawn in S13's pretest diagram (shown in Fig. 23) between the image and the object, but were not explicitly referred to as light. These lines had the role of corresponding lines that related each feature of the object to its symmetric feature in the image.

The location at which students depict the image of an object undergoes profound changes from pretest to posttest. Whereas for Q#3 the image location in the pretest is represented *on* the mirror surface (80% pretest, 0% posttest), we find students in the posttest to predominantly display the image as an imaginary construct (the virtual image) formalized by continuing the reflected rays *behind* the mirror (0% pretest, 83% posttest).

A further development in the concept of the image depicted in diagrams was that of relating it to the behavior of light in the identification of image location. As noted, one may best recognize an image in the pretest based on the recognition of its *shape*. In explanations, sometimes light is characterized as a carrier of the image, e.g., "light passes around your face, bounces off the mirror and back to your face and illuminates your features. These light particles bounce back to the mirror where they display an image of you."

In the posttest, students represented *image position* by locating the point at which the extension backwards of light rays crossed each other. They developed the recognition of the image as a phenomenon that exists at the point where all the rays cross each other, rather than as a mere photographic representation. Eighty percent of the pretest students drew an image without relating it to the interaction of light and the mirror in reflection (e.g., S11's pretest diagram in Fig. 9). None of them represented in their diagrams that the image was related to imaginary lines constructed by the eye which go beyond the surface of the mirror until they cross each other. This is supported by the literature which points at this notion, the virtual image, as one of the most complex in all of geometrical optics to understand (e.g., Goldberg and McDermott, 1986). By contrast, we found that for at least the simplest virtual image problem (Q#3), 66% of the posttest students constructed an imaginary trace back either of rays or a ray spray in order to correctly locate the image, although only 17% of the posttest students drew an image while justifying its formation by tracing light rays.

This posttest improvement in depicting trace back of rays to account for a virtual image was strongest in the plane mirror question (Q#3: from 0% to 66%) and the coin-in-the-water question (Q#4: from 11% to 44%) but substantially weaker in students' responses to questions that did not relate directly to formation of an image, such as the window-as-mirror question (Q#6: from 5% to 10%), and the mirror-in-a-dark-room question (Q#14: from 0% to 9%).

The relation between the light and the image described in the verbal component of students' responses was fragmented in the pretest, but becomes more coherent in the posttest. Commonly used expressions in the pretest are: "you see your reflected image" and "the image of the flashlight is reflected" (70% average across all image questions, i.e., Q#3, 4, 6, 14). In contrast, the verbal characterization of the situation in terms of the association of "reflected image" is rarely used in the posttest (20% average across all image questions). Instead, conjunctive phrases of the type: "light is reflected and you see the image of . . . "are more frequently used.

We also identified large interproblem differences in this improvement by students in dealing with virtual images, between such simple situations as the plane mirror question (Q#3) and more demanding ones such as the mirror in the dark room (Q#14). As previously mentioned, the position of the image is mostly diagrammed *on* the mirror before instruction and appropriately *behind* the mirror afterwards.

It is quite interesting that posttest students' diagrams and verbal explanations for the mirror-in-the-dark-room situation do not reveal the same change. Posttest students unexpectedly tend to keep on describing the image as *on* the mirror. This is perhaps because more students are aware after in-

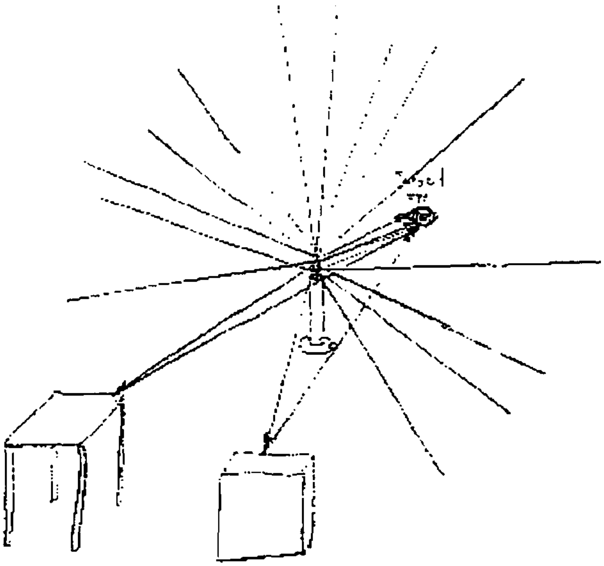


Fig. 23. S11 posttest dagram for dark room lit by candle in question 2.

struction of the necessity to draw an image somewhere in the diagram, but they still do not correlate this unusual situation to the traditional mirror situation with which they presumably have more everyday experience. Yet overall, the dominant pretest concept of the image as a reflected instance is reconstructed into the dominant posttest concept of the image as associated to reflected light rays.

Finally, we found an interesting inconsistency in verbal terminology and diagrams for the differentiation of reflection and refraction, which appeared mainly for the posttest questions. In some situations, students write that light is *reflected* by the water and yet the diagram drawn shows a *refracted* pattern of light. For instance, in their written textual answers to the wavy pool question, some students explain the patterns of light by the reflection of water. Yet their diagrams show a change in the direction of the rays from the sun, after they hit the water.

Representations of Temporal and Causal Aspects of Optical Situations

The previous part of this subsection reviewed evidence regarding the development of the concept of the image from a representation of the shape on the surface of the mirror, towards a representation which includes light rays as tools for providing justifications for image formation. Light rays also may be viewed as providing event-oriented causal linkages for integrating the behavior of a light source, the optical device(s), any objects, and finally the image formed or shadow cast. In contrast, the photographic representation commonly found on students' pretest diagrams does not represent the causal relations among these components of optical situations.

The major shift from the pretest to posttest responses was the increasing tendency of students to use the ray spray or single ray to construct a causal linkage among the various components of the optical situation. For instance, the formation of the shadow in the pretest is represented as a dark area on the ground, shaped similarly to the object. The pretest diagram typically does not explicate what mechanism is responsible for the size and shape of the shadow, nor does it explain how the shadow is related to the light source. An example is provided by S13's response to the question: "Sometimes shadows seem clear and sometimes they seem fuzzy. Why?" He writes in his verbal explanation: "Shadows seem clear or fuzzy depending on the distance between the object and the surface in which the object's shadow is reflected upon [sic]. As the distance increases between an object and its shadow, the clarity decreases. The closer a shadow gets to the exact size of an object, the shadow will become more detailed."

In the pretest, light rays are not used as an explanatory tool that could help in efficiently representing the relations between the number of light sources and the number of intensities of the darkness of the shadow (previously defined as *fuzziness*). The relative number of the overall situations where light rays are used to construct causal links in the pretest diagrams is negligible—less than 5%. That is not to say that light rays are not drawn. They do appear as entities in the diagram but are not constructed in a manner accounting for the shadow cast or for the image formed.

The presence of both the image and the trace back of reflected rays reflects an understanding of light rays as a strategy for constructing a causal link between the rays and a virtual image. None of the pretest students constructed an image by using trace back of ray sprays (for a typical pretest diagram, see Fig. 9). Yet 50% of the posttest students' responses to the self-in-mirror question (Q#3) included the image and the ray trace-back strategy. Such trace-back improvements from pretest to posttest were barely evident, however, in responses to the more demanding window-as-mirror (Q#6: from 0% to 10%) or dark-room-with-mirror questions (Q#14: from 0% to 9%). These two questions were harder generally as well, in that the pretest percentage of students that provided *any* representation of the image in their diagram at all (Q#6: 38%; Q#14: 18%) was far lower than for the self-in-mirror question (Q#3: 80%).

Overall, we have identified three representational models for rays and ray sprays as causal linkages integrating the various components of the image formation and shadow casting situations. The most advanced representational model includes all three of the following causal components: (1) Light originates at the source, hits the object, which reflects, refracts or absorbs the light. (2) As a result, a shadow or an image is formed, depending on the situation. (3) Reflected rays hit the eye and an image, shadow, or an object is detected by the eye.

We will now examine students' pretest and posttest attainment of different levels of the three-component representational model in terms of their responses to there questions: the shadow, candle, and mirror questions (questions 1-3). The third component, the inclusion of the eye in the causal story, was clearly the most demanding to achieve, and a significant advance resulted from Dynagrams instruction. For the *shadow* question, 50% of the posttest students had acquired the full model versus 14% in the pretest, 75% of the posttest students had acquired a model that included the first two components, but not the eye. (The eye was less crucial as a component for explaining the shadow situation than for the candle and mirror situations.) Responses to the *candle* question revealed 58% of posttest students using full models (e.g., S11 in Fig. 21) versus only 13% in the pretest. For the same question, 67% of posttest students versus 53% in the pretest had a partial model of one or two components that did not include the eye. For instance, S1's posttest only reveals one component in his diagram—light emitted from the source, and for the *mirror* question, 50% of the posttest students versus 13% in the pretest used the full model, while 58% of the posttest students and 47% of the pretest students had acquired a model lacking only the eye.

We must note that the ray-spray representational "game" has its own rules and that these are violated in diagrams even by some posttest students. A ray spray is supposed to originate at the light source, hit objects, then reflect or refract according to Snell's laws. At a broader glance, aggregating across diagram responses to the shadow, candle, and mirror questions (Q#1-3), we found that light rays represented in 10% of the posttest students' diagrams did not originate at a light source or a reflection from an object. Rays in these cases were either lines coming from the eye in the diagram (5% of total), or from some other, apparently arbitrary, direction (5% of total). In one class of diagrams, rays are drawn correctly from a light source but then the rays are not related to the objects or to the natural phenomenon discussed. For instance, in some cases, rays do not hit an object but pass *through it* as if it was not there. For example, for S10, the light rays hit the object correctly, the fuzzy shadow is correctly drawn, but the projection is a right-angle projection, drawn by parallel lines, instead of a diverging angle projection.

Development of Epistemological Structure of Explanations

In this final results subsection, we examine a meta-level of learning by characterizing changes observed in what counts for students as a sufficient explanation from pretest to posttest and in terms of what the developmental differences are in students' construction of diagrammatic and written justifications for their explanations. These shifts provide evidence for development as a result of Dynagrams instruction in the epistemological structure of explanations of optical situations. The perspective taken here is that verbal tools are not sufficient to construct a causal explanatory argument in the case of geometrical optics. We base this claim on the historical necessity that drove the construction of diagrammatic tools for reasoning and communication in physics generally (e.g., Miller, 1986). Therefore, the following analysis is based on an integrative view of explanations, which are represented *both* by verbal means and by diagrammatic tools.

We consider the development of argumentation and justification of explanations of an optical situation from two points of view: (1) presuppositional versus causal explanations, and (2) the presence of single-layered versus multilayered accounts, that is, those in which single versus multiple elements of knowledge are used to justify the same phenomenon.

Presuppositional versus Causal Explanations

We define presuppositional explanations as based on an assumption that the observed or predicted state of affairs is how things happen naturally, and thus there is no need for justifications. In contrast, causal explanations account for the event by using a rational, causal linkage between the components of the system observed. Thus all accounts of image formation based on the representation of light interactions with optical devices are considered to be causal in nature, not presuppositional. The following cases are examples of presuppositional explanations:

- On the formation of fuzzy shadows: "the shadow grows clearer as the flashlight moves towards the wall" (S2 pretest, shadow question #1).
- On the observation of an image in a lighted room window: "Dark outside does not absorb

any light" (S14 pretest, window-as-mirror question #6).

- On the formation of images: "When looking into a mirror, you observe a reflection of yourself . . . light makes the image visible" (S3 pretest, mirror question #3).

These examples share a presuppositional belief that what is observed is just how nature behaves, and so an explanatory account is not needed. We observed a strong restructuring of the types of explanations offered from pretest to posttest: most explanations offered on the pretest are of a presuppositional type (61%). The frequency of students offering presuppositional explanations decreased after the learning experience to about 30%, and the causal explanations increased to 67% (from 37% on pretest). Some of the questions yielded bigger pre-post increases in the frequency of causal explanations than others—shadow formation Q#1 (21% to 92%), vision with a candle Q#2 (13% to 58%), image formation in a mirror Q#3 (7% to 83%), reading process Q#5 (45% to 82%), and the wavy pool Q#16 (56% to 82%). This result is convergent with results presented earlier on students' adoptions of causal models represented by the ray sprays. After Dynagrams instruction, students adopted the ray tools they learned to use in order to construct causal explanations involving the optical system components, even with a paper-and-pencil medium.

Single versus Multiple Knowledge Elements Used for Explanations

In most pretest explanations, students provided a single element of knowledge to justify their responses. This is sufficient to construct a legitimate justification; 75% of the justifications in the pretest are based on such a single element of knowledge. Only 24% explicate more than one element of knowledge: this is sometimes logically layered, meaning that one statement is justified by another one, which again can be justified by a third statement. A justification can be wrong and yet layered: e.g., "As the distance increases between an object and its shadow, the clarity decreases. The closer a shadow gets to the exact size of an object, the shadow will become more detailed. This is caused by gases of the atmosphere which scatter the light . . . " (S13). This account consists of three layers: a phenomenological observation (shadows are fuzzy), a physical property which explains the reason why shadows are fuzzy (distance), and a possible abstract explanation to account for the reason that the distance is a factor in the sharpness of the shadow. Conceptually, it seems to be structured through three logical relations accounting for each other.

We find that the dominance of fragmentedness in pretest protocols, considered to be one of the characteristics of naive knowledge, decreases in posttest responses. A layered justification reflects logical linkages that the student constructs between different elements of knowledge. An increase in the number of students who conducted layered justifications was found—24% of the pretest justifications were layered, while 53% are layered after instruction. The single-element justification is the predominant strategy in the pretest (75% of students), and is less frequent in the posttest (47% of students).

DISCUSSION AND CONCLUSIONS

Fundamental Roles of Physical Representations

Hanson (1958) recommends using the Wittgensteinian concept of "seeing as" to describe the process of enculturation in the physics community. Objects and events come to be seen and represented differently when a physics approach is taken. Arrow symbols are not seen as beams of light, but as a representation of direction of propagation of light. Likewise, rays of light are viewed as representational tools that enable one to reason about and explain the behavior of light for the purposes at hand.

Familiarity with the physics communication tools that such representations as terminology, diagrams, and mathematical symbols provide is crucial for participating in a community that deals with physics. Knowing physics means both differentiating between everyday reasoning and scientific reasoning and at the same time seeing how physics can help one understand the natural environment. It does not mean creating an imaginary world of theoretical abstractions only, but rather understanding the surrounding nature by means of physics reasoning. Producing causal accounts using representational tools to explain observations of physical situations is central to the development of physics reasoning.

The concept of representation is related to the empirical definition of "students' knowledge." Our view is that students' current understandings are indexed by their uses of representations in relation to situations. By representations, we include what they verbally say in a conversational process and what they symbolically represent by means of their communication tools, including diagrams and written language. Our analysis of students' knowledge in this paper is thus an analysis of conceptual change in terms of changes in the nature of representations they use to account for physical situations involving optics.

Throughout our analyses we have presented an integrative view of learning—looking at changes in diagram and verbal constructions as evidence for conceptual development, developments in representations used, and for epistemological development in terms of explanation structures. Across these perspectives, we found that student performance after instruction reflected important new developments. We now offer an integrative discussion of the primary student achievements.

Development of Conceptual Understanding

We may generalize from the details of our results a few examples of levels of conceptual development, in terms of the example topics of shadow formation, and virtual images.

Example 1: The understanding of *shadow formation.*

Level 1: Students use verbal representation of multiple sources to account for fuzzy shadows. Yet they still do not support their answer by a diagram that includes the causal relations between light sources and level of darkness of a shadow. Sometimes they explain fuzziness in terms of relative distances, light source intensity, or object properties.

Level 2: Students' verbal representations are full and correct. Light ray sprays are drawn and so are the locations of the other components of the system—the light sources, the object, and the wall. Yet the light rays do not link these together into a causal explanation.

Level 3: A full account is constructed by linking the components in the system, and the verbal and diagrammatic representations into a causal chain that explains how these components interact to create a shadow.

Example 2: The understanding of *virtual images.*

Level 1: The virtual image is located behind the mirror. The image distance is equal to the source distance.

Level 2: Light rays illuminate the object, reflected light reflects from the object, hits the mirror, and reflects back to hit the eye. The eye creates a virtual image of the object.

Level 3: Level 1 is verbal, and the level 2 uses a different representation—through diagrams. The deeper understanding includes both.

The first level for each example could have been judged as correct in a sense. It is only the necessity to construct multiple representations that reveals the weakness of the shadow and virtual image conceptualization. Therefore, it seems that conceptual understanding needs to be tested through multiple representational tools, as we have in this conceptual change instrument and set of analyses. Based on the same argument, we see that understanding has to be developed through uses of multiple representational tools in the instructional context.

Toward a Causal Model

The single most important development revealed across the students' performances on the posttest items was a major movement toward understanding the interrelation of the components of the optical system that produce shadows and image formation. We see better understanding of the propagation of light from source to object to the eye as image detector and of multiple light sources as the causal foundation of differences in shadow fuzziness. Few students realized in the pretest that light needs to hit the observer's eye for vision. Most posttest students mentioned the eye and each previous step in the process of light travel from candle to eye. Prior to the classroom learning, half the students had an idea of reflectance as a necessary condition for visibility, but the causal link between light source and rays, the objects in the room as reflectors, and the eye was largely missing. Indication of the model-based nature of students' understanding in the posttest patterns of response was provided by their greater use of full models in accounting for optical events. We looked at three components of these events as defining a full model: (1) Light originates at the source, hits the object, which reflects, refracts or absorbs the light; (2) as a result, either a shadow or an image is formed; and (3) reflected rays hit the eye and an image or shadow is detected by the eye. When we examined students' pretest and posttest attainment of different levels of the three-component representational model in terms of their responses to three questions: the shadow, candle, and mirror questions, we found that the third component—inclusion of the eye in the causal story—was clearly the most demanding to achieve, and it represented a significant achievement for those students who came to use it.

Deeper Understanding of Image Formation

For questions relating to the phenomenon of real images, a large majority of the posttest students demonstrated an important conceptual shift in their understanding of what an image is—from something present when light is present—to a phenomenon causally related to the propagation of light, whether reflected or refracted in the particular situation.

Offering a greater challenge is understanding a virtual image, which presupposes understanding the role of the eye as a detector of the image. After Dynagrams instruction, a strong reconceptualization was found of image position relative to the mirror surface when responses were analyzed to virtual image questions from three perspectives: (1) the location of the virtual image on/outside of the surface of the reflecting/refracting surface, (2) interaction between light and the reflecting/refracting surface, and (3) the essential role of the eye in monitoring the virtual image. Posttest responses to simple plane mirror questions and the window-as-mirror question led this developmental advance. Nearly all posttest students but none of the pretest students correctly positioned the image behind the mirror surface, while pretest students drew the image on the mirror. For the more intricate two-step dark room and mirror question, two thirds of the posttest students still placed the image on the mirror. Dramatic progress was made by students in considering light rays as the causal mechanism accounting for the virtual image formation, as shown in their diagrams for a person looking into a plane mirror or at a coin under water.

Students developed models of light behavior on various levels of complexity and using different systems of external representation (written language and diagrams). The diagramming representations fostered a deeper understanding of optical phenomena than the verbal medium alone, and an advanced understanding of light behavior is not possible without these multiple representational tools. Therefore, the process of acquisition of the representational tools is crucial for students to attain a full understanding of the optical phenomena. Furthermore, lack of multiple representational tools limits a student's ability to represent ideas to others, either on paper or for discussion with others. The ability to communicate physics ideas, especially in optics, is determined by the student's reserve of representational tools.

Appropriating Powerful Diagrammatic Representations

We have seen how the initial stage of the development of representations for students in our study was a very concrete one—a *photographic* form of representing a physical optical system. The only entities that need to be represented, according to this initial stage, are the observed objects. Students depicted in a diagram what they saw literally, not in terms of processes and causal relations. Therefore, the mapping function between the diagrammatic representation and the observed physical entities is based on the shape of the objects. This raises a major difficulty for students when they need to construct a representation for abstract entities such as *light.* A new diagrammatic "language" is necessary to allow students to represent ideas that cannot be represented otherwise. Such representations are also crucial to the construction of explanations of more complex optical phenomena, as we have seen.

For both pretest and posttest groups, the most commonly used tool is a single-ray or a two-ray beam. Most pretest diagrams represented light in this way, but only half of the posttest diagrams did. The reason for this drop was a major development for the posttest group, as the use of ray sprays came to far greater use instead. The more powerful representation, a diverging ray spray, is partly developed by most posttest students and fully by some.

Whereas students evidence a mapping function from diagrammatic representations to what they depict in both the pretest and posttest, the mapping function changes. It becomes less photographic, which means the shape of objects is not the function students continue to use after instruction. They expand or restructure the mapping function to represent the abstract concept of light and its relations not only to light sources, but to the eye as a detector of images and shadows, and as the generator of virtual images. The joint inclusion of these aspects is reflected in the construction of causal explanations. When students successfully construct such explanations for the problems we presented, it means not only that they recognized the role of each of the optical system components, but also recognized how each acts as a causal link in the overall optical process. The major shift from the pretest to posttest responses was the increasing tendency of students to use the ray spray or single ray to construct a *causal linkage* among the optical situation components. The posttest use of both the image and the trace back of reflected rays reflects an understanding of light rays as a strategy for constructing a causal link between the rays and a virtual image.

This representational tool of model-based ray tracing is a new convention they developed during Dynagrams learning, and it brings them closer to the communication tools accepted in the scientific community. For example, the location at which students represent the image of an object underwent profound changes from pretest to posttest. Whereas for a plane mirror question the image location in the pretest is almost always represented on the mirror surface, we find students in the posttest almost always displaying the image as an imaginary construct (the virtual image) formalized by continuing the reflected rays behind the mirror, and never representing it *on* the mirror. For the posttest, students came to represent image location by locating the point at which the continuations of light rays crossed each other, thus recognizing the image as a phenomenon existing at the point where all the rays cross each other, rather than as a mere photographic representation. Appropriate uses of ray tracing provided evidence of the development of the image concept from a representation of the shape on the surface of the mirror towards a representation that includes light rays used as tools to provide justifications for image formation.

Construction of Better Explanations

Students developed an important attitude toward and methodology of causal explanations. This result is consistent with the result just described: students adopted ray tools to construct causal relations among the optical system components to account for optical situations. As we note in an earlier section, the nature of their explanations shifts from presuppositional to causal—justifying temporal and causal links in terms of a model rather than alluding to "the ways things are." Furthermore, the fragmentedness of their explanations decreases in the posttest, i.e., there are layers to their physical accounts of optical situations in causal terms.

Limitations of Students' Improvements

We have been struck by the complexity of profiles of understanding that students bring to reasoning about optical situations. Overall, the primary limitations were in students' greater difficulties in use of representational tools and the full three-component causal model outlined earlier when they were challenged by less prototypical situations. Such atypical situations included explaining the problem situation of the window as mirror at night, or the mirror in a dark room, or the clarity of images when wearing goggles under water. In these situations, we found less prevalent a conceptual shift in student responses toward the idea of light as an integrating link between the object, source, virtual image, and eye. The role of the eye was commonly ignored, especially in the case of the window as mirror at night. For the goggle question, although minimal changes appeared in the frequency of correct responses, more posttest students explained the need for goggles as a tool to create a layer of air. Yet they omitted an account in their explanations of the role of the air layer for the image formation on the retina. While, as noted, students' posttest improvement in depicting trace back of rays to account for a virtual image was considerable for the plane mirror and the coin-in-the-water questions, it was far weaker in students' responses to questions that did not relate directly to image formation, such as the window-as-mirror question, and the mirror-in-a-dark-room question. It is provocative that posttest students' diagrams and verbal explanations for the mirror-in-the-dark-room situation do not reveal the same change. Posttest students unexpectedly kept on describing the image as on the mirror with reasonably high frequency for this question, maybe because, while aware after instruction of the necessity to draw an image somewhere in the diagram, they still do not correlate this unusual situation to their new learning about how to use the fuller model for explaining the traditional plane mirror situation (with which they presumably have more everyday experience).

One finding of particular interest for teaching is that most of these changes from pre- to post were larger for a few identifiable questions and smaller for others. Specifically, the conceptual restructuring process resulting from students' learning was stronger for situations analogous to those covered in the Dynagrams activities, such as the plane-mirror problem, and not as strong in others, such as in the case of observation of one's image in a lighted room window.

CODA

Through our analyses, we have sought to broaden the notion of conceptual change—and what counts as evidence for it—by treating what it means to know a concept as involving the use of multiple representations of that concept and coordinating the meanings of the representations and strategies used for applying the concept in diverse problematical situations. In preparation for the instructional experiment, computer tools for geometrical optics were developed to provide for the easy construction by students of representations for augmenting their sense-making capabilities and learning conversations concerning optical situations. Specific features of the Dynagrams simulator tool were designed to overcome specific conceptual difficulties students are known to have, such as the use of single rays or beams rather than ray sprays and the lack of a causal model linking light sources, reflection or refraction of light by objects, and the eye as image detector (Pea, 1992; Pea *et al.*, 1995). While future work teasing out contributing factors will need to take place with control and comparison groups, we believe that several of our main successes may be reasonably linked to the design features of the instructional tools and tasks—students' increasingly common uses of light sprays for explaining shadow formation and virtual images, and the more common use of the eye as image detector in their causal accounts of optical situations.

The construction of learning environments is a challenging task that becomes all the more demanding when examined from a social framework. The issue for science learning from this perspective is not so much one of coming to master the component skills of manipulating scientific symbol systems and the problem-solving skills associated with their use in working on problems. What is most *centrally* "constructed" through experience in scientific activity is the disposition to engage in appropriate scientific conversations using representational tools. In the Dynagrams Project, computer tools served to augment students' sense-making capabilities and their learning conversations, and important conceptual developments in a difficult subject area resulted. While we expect many challenges to establishing conditions for "growth" of such communities of representational practice in school institutions, we are optimistic that an increasing focus on augmenting conceptual learning conversations with computer tools could go a long way toward improving science learning.

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