The influence of an historically oriented course on students' content knowledge in optics evaluated by means of facets-schemes analysis

Igal Galili and Amnon Hazan
Science Teaching Center, The Hebrew University of Jerusalem, Jerusalem 91904, Israel

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We report on an experimental course in geometrical optics which heavily incorporates historical models accounting for light, vision, optical images, and others. The design and contents of the course were guided by previously elicited knowledge of high school students regarding optical phenomena. We utilized the course in a year-long experiment. The content knowledge of students expressed in a facets-scheme structure was compared with the same under regular instruction. We made qualitative and quantitative assessments based upon facets-scheme frequencies. Clear differences found in students' conceptual knowledge may support the adopted rationale and teaching approach: using appropriately selected historical materials that address knowledge issues relevant for the students can significantly promote meaningful learning of the subject matter.

I. INTRODUCTION

The process of learning science, and the success of the learner, remain the focus of various research efforts. Classical science traditionally seeks understanding of natural phenomena by means of establishing structural knowledge and revealing the dynamic relationship of its components. It is believed that, given such knowledge, we better understand nature. Educational research practices a similar approach with regard to the knowledge of the learner. The subject of such research combines the complexity of the discipline with the no less difficult analysis of students' acquired knowledge. As in science, the progress manifests itself in determining new elements of knowledge and the establishment of their relationship within the structure. This perception implies determination of elements of adequate representative power, their identification and elicitation in an appropriate empirical study. The complexity of the subject motivates scholars to speculate about possible components in the structure of learner's cognition.[1] Such knowledge might facilitate not only our understanding of learning science but also suggest the objectives for remedial instructional interference, as well as to evaluate the efficacy of the applied educational activity.

Many science educators consider the incorporation of contents from the history and philosophy of science (HPS) in science instruction as powerful and beneficial.[2] At the same time, one could easily imagine several possible reservations regarding such an approach.[3] The present study tries, by means of elicited structural components of students' knowledge, to infer the influence of a historically oriented instruction in optics on the content conceptual knowledge of students in this science domain.

II. THE THEORETICAL BACKGROUND

A. Structure of knowledge in learners

The traditional requirement of parsimony of scientific knowledge,[4] and the devotion to positivist conception regarding human knowledge, inspired Mach to perceive science as a manifestation of the principle of ''economy of thought.''[5] Congenial to the idea of simplicity was the belief that nature can be understood in terms of structure, *viz*. well-defined elements interrelated within some wholeness. To know/investigate something was conceived as synonymous with to know/seek its structure. Following this perception, Bruner[6] insisted on the inclusion of a structure of knowledge in the teaching of any scientific discipline, even emphasizing such knowledge over that of factual contents. His arguments, as those of Mach, refer to an inability to grasp, remember, or manipulate a huge amount of complex contents without knowledge of structure. This belief in the central role of structure, expanded in the humanities (anthropology, linguistics) within the philosophical framework of structuralism.[7] With regard to learning, the issue of structure of knowledge was historically interwoven with the introduction of constructivism,[8] which replaced behaviorism that ignored the structure of knowledge. Starting from Piaget, the constructivist theory pursues picturing human cognition by its elements related in schemata, as they emerge in the sequential stages of cognitive development.[9]

Cognitive organization, emerging in individuals as a result of either personal experience or social interaction, became a subject of much research effort. Numerous cause–effect links and correlative rules of explanatory power were identified in the mental activity of the learner, and described in terms of schemata and mental models, which reflected and accounted for the regularities in daily perceived reality, forming our ''common sense.'' Common sense considerations of the learners were understood as a highly influential factor of their success in the science class.[10]

Following only one theoretical line, we mention here diSessa,[11] who argues for the existence of stable cognitive constructs spontaneously created in the form of fundamental self-explanatory patterns, which he calls phenomenological primitives (''*p*-prims''). *P*-prims establish relationships between a few general factors or concepts (e.g., ''maintaining agency,'' ''Ohm's *p*-prim''), and thus guide the individual activity of making sense of observed reality, perceptual experience, and problem solving. Within this view, a picture of spontaneously produced ''knowledge in pieces'' emerges prior to the formal instruction.

Minstrell[12] elaborated students' ways of making sense, striving for understanding of particular physical settings, in terms of *facets of knowledge*. Facets may represent consistently applied explanations manifested in a declarative knowledge, but not only. They can also express certain strategies, elements of students' characteristic behavior (procedural knowledge), when coping with particular questions and problems. Facets are more context specific, and thus less fundamental than *p*-prims. Facets may incorporate several concepts, related in such a way as to represent individual comprehension of the situation.

At first glance, facets may be reminiscent of the tendency to ''compartmentalize'' knowledge.[13] However, that tendency was elicited in knowledge accommodation resulting from formal learning. The presented-by-instructor knowledge is adopted by the learner, and modified by surface characteristics of the context of its initial application. Students separate the knowledge acquired in one context from that acquired in another, ignoring its universality. Knowledge compartments may remain isolated even when they are well developed. This can be observed, for example, when students who did well in mechanics fail to transfer ''mechanical'' scientific knowledge required in dealing with problems in electricity.[14]

Here, the topic is different, and we consider students' accounts for physical situations, making sense of them by means of conceptions they hold in the same area of knowledge. Some facets of knowledge might be due to the idiosyncratic interpretation of instruction; others, consciously or intuitively, may have originated in spontaneous *p*-prims held. Facets of knowledge can be grouped in clusters, which correspond to the same idea or physical mechanism, underpinning all the facets affiliated with that cluster. This core constitutes a *scheme of knowledge*, which is less dependent on the context, and hence, possesses a more inclusive meaning than a facet.[15] Unlike *p*-prims, which are elementary logical blocks, schemes can relate concrete entities (instead of abstract concepts), and evolve in course of formal learning rather than be spontaneous.

The two-level facets-scheme hierarchical structure of students' knowledge was applied to represent the collective knowledge of students regarding optics (images and other concepts),[16] seasons and illumination,[17] and other topics. In many cases, students' schemes of knowledge were found to be different than, and even conflicting with, formal scientific knowledge. Thus, they represent ''alternative knowledge,'' the naive conceptions of students. Free from the constraint of mutual consistency, schemes may coexist and complement each other in a variety of associations. Information about schemes held and their abundance in a particular student population may serve as a reliable indicator of the metamorphose (in constructivist perspective, conceptual change) of students' knowledge in the course of learning, thus revealing the impact of a particular instruction.

Another merit of knowing learners' schemes manifests itself in the design of instruction. There, it is reasonable to address schemes, thus aiming at the essence of the naive conception, rather than situational details. This could be of crucial importance in facing the great versatility of naive conceptions, proliferating in numerous research reports (e.g., 3500 publications listed by Pfund and Duit[18]).

Finally, a close look at scientific treatises at the dawn of science (Aristotle, Euclid, Archimedes), may provide additional clues regarding scheme-facets organization of nonmature knowledge. Namely, one can recognize cases when a number of claims and accounts about regularities, observed in specific situations (as facets are), were later represented by one inclusive proposition (law, or principle, in science).

How can the established schemes of knowledge be best addressed in instruction?

B. Using HPS learning materials

Since Mach and Duhem, many science educators have argued that history and philosophy of science can be used for improving success in learning.[19] Leaving aside cultural, social, and affective aspects, important as they are, one might start with questioning the influence of HPS on the students' content knowledge of the subject matter. The claim of Mach and Duhem was categorical:[20]

> The legitimate, sure and fruitful method of preparing a student to receive a physical hypothesis is the *historical method*. To retrace the transformations through which the empirical matter accrued while the theoretical form was first sketched; to describe the long collaboration by means of which common sense and deductive logic analyzed this matter and modeled that form until one was exactly adapted to the other: that is the best way, surely even *the only way*, to give to those studying physics a correct and clear view of the very complex and living organization of this science. [emphasis added]

This claim often remained a claim of value, being warranted by the high stature of its proponents. Many educators share this conviction, whereas others decisively rejected it (e.g., on the grounds of inadequacy of the old knowledge subsequently discharged in science, its misleading potential for the students aimed at mastering the ''accurate'' theory, and its appearance for the contemporary student as strange or unusual[21]). At the same time, the arguments in favor of HPS use in science instruction has been strengthened,[22] expanding on cognitive aspects.

First, the paradigm of a unique (in its form or content) scientific truth, so noticeable in history, has been substantially modified in modern culture. In science itself, the simplest aspect of this conception is manifested in the legitimacy of multiple representations of reality (e.g., geometrical and algebraic understanding of the concept of derivative, integrative, and differential representations of classical mechanics, matrix and wave-function formalism in quantum mechanics). Moreover, the *progress* of science is no longer perceived as linear, but a rich and complex stream, contributed to by a variety of resources. Thus, by likewise presenting ''unsuccessful'' attempts at conceptual development that nevertheless helped to attain present scientific knowledge, students are shown a realistic picture of the complex transformation of knowledge from old to new, arguments of conscious preference given to its presently adopted version. Regardless of the degree to which past hesitations and alternative solutions perserved in the new and more powerful theoretical contents, the refuted alternatives previously practiced by human minds, do not present extra elements, but an organic part of a body of science. This approach to learning science, considers HPS contents as essential and indispensable.

Second, philosophical and educational constructivist perspectives not known in the past shed new light on the nature of the relationship between the evolution of science and its learning, the collective and individual dynamics of knowledge. In this perspective, the goal of HPS-based teaching is not to display the chronicles of discoveries, but to reveal the conceptual evolution of human thought and ideas about nature. Many of the currently maintained scientific ideas, being traced back to the past, reveal conceptual alternatives similar to those ideas produced today by the naive common sense of students.[23] Although limited in extent the recapitulation of the science history in the growth of individual knowledge indicates similarities between the conceptual difficulties overcome by scientists in the past and by the learner of today. The arguments of reasoning employed by the great minds in the past can be reapplied today, helping numerous learners who face similar problems of comprehension. The solidarity that the learner often experiences in such cases, constructive responses to the old ideas, can be interpreted as a ''cognitive resonance'' between similar perceptions of the same subject.

Third, an exposure to competitive ideas and subjective perspectives in science humanizes scientific contents and removes the unnecessary rigidity of the instruction. This changes the image of science, making it appealing to a wider variety of minds. Too often, regular science instruction in high school is excessively focused on, and restricted to numerical problem solving according to the provided examples and/or mastering instrumental procedures. In this, many students fail and/or find it irrelevant. This reality contradicts the common view of school science as being preferably oriented to scientific literacy rather than professional training.

In our study, optics was chosen as a suitable area to test the impact of historical materials on the content knowledge of students. In fact, scientific knowledge of optics is highly anti-intuitive. This may explain the impressive abundance of naive conceptions with regard to optical phenomena[24] as well as the extremely rich chronicle of optical conceptions that replaced each other during 2500 years of documented history of science.[25] These conceptions can be examined in light of the schemes of knowledge students hold regarding optical phenomena.

III. EXPERIMENT

A. Teaching resource

A specially prepared textbook served as the main learning resource for both instructors and students in the year-long experiment. Though the course preserved the standard menu of topics of a regular curriculum, it differed greatly from the traditional in several aspects. The most pronounced difference was the parallel exposure of the learner to the historical growth in the understanding of vision, interwoven with discussions about the nature and behavior of light. These two trends created a constant focus on the relationship within the triad: object, light, and eye—the main participants in the vision process. The line of instruction followed historical progress,[26] which interwove the growth of knowledge about light with that of vision, topics of simultaneous and equal importance for learners. Duhem suggested that the history of science is an illustration of ideas and theories raised and refuted with no specific preference. We therefore, had to choose which particular historical contents to include. The schemes of students' alternative knowledge with respect to vision, nature of light, optical imaging, and shadow[27] guided us in this search. Among the materials incorporated into the curriculum were ancient Greek, medieval Arabic, and early modern theories of vision, ideas regarding the nature of light, ideas regarding light, its expansion light rays, shadows, reflection and refraction of light, mirror, lens and pin-hole images, the speed of light. Table I specifies examples of conceptual parallelism in optics knowledge used in the experimental course.

Table I. Examples of conceptual parallelism in optics knowledge used in the experimental course.

Historical conception (practiced in the past science)	Student's conceptions (practiced in course of learning)
Pythagorean conception of vision	''Active'' vision
Euclidean visual and light rays	Rays of sight, rays of light, (rays reification)
Atomists' conception of ''Eidola''	Image Holistic Scheme
Biblical–Medieval dichotomy of light as an entity and perception (lumen–lux)	Static light located in/around light sources, halos, bright sky, illuminated surfaces (light reification as static entity)
Al-Hazen conception of vision by means of light rays	Image Projection Scheme

B. Sample

Our sample incorporated two groups of high school students. The experimental group (innovative instruction) included four 10th grade classes ($N=141$), and the control group (regular instruction) included three 10th grade classes ($N=93$). Students in both groups were chosen from the same schools. All the classes had equivalent populations regarding relevant background aspects. The three types of schools, public urban, regional rural, and boarding comprehensive, made the sample representative of the educational system. The time span of the experiment in both groups covered an entire academic year, with 4 h of instruction weekly.

C. Assessment

Our concern was to create a reliable profile of student's content knowledge, after instruction. The facets-scheme framework provided the instrument to organize alternative knowledge. Scientific knowledge was similarly considered in terms of facets of knowledge. Organized in this manner, students' knowledge, as resulting from the two forms of instruction, was examined for differences of facets and schemes held by students (qualitative comparison), and their frequencies of appearance (quantitative comparison).

The evaluation of both groups was made at the end of the study year by means of an identical conceptually oriented test. To increase reliability and further support the inferences made, an open-ended questionnaire was delivered and interviews carried out with randomly selected students. In addition, the teachers of the experimental classes were interviewed. The quantitative analysis was applied solely to the data of the paper-and-pencil test data. To illustrate the results, some quotes from the interviews will be given.

Questions of the 15-item questionnaire were adopted from previous studies of students' optics knowledge,[28] where their validity and effectiveness was proven. The diverse data obtained by the open-ended questions, though more dependent on interpretation, are indispensable if one aims at revealing facets of knowledge. Students were encouraged to supply reasons for their answers as fully as they could, and support them with drawings, ray diagrams, or sketches to elucidate their ideas.

The questionnaire addressed understanding in three areas:

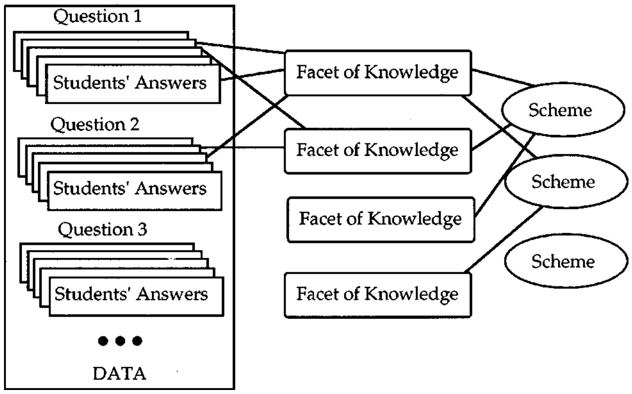

Fig. 1. Process of data categorization into its facets-scheme organization. Connections are only representative.

(i) vision (the role of light, observer, and the object in the process);
(ii) general properties of light (light in space, light emanating from a source);
(iii) optical images in context of reflection and refraction (image formation, location, and observation).

Each topic was probed by more than one question, to enhance the validity and reliability of the test. Such an approach also matches the intention of investigators to reveal facets of knowledge appearing when the same conceptual issue is addressed in a variety of physical settings. Importantly, none of the questions used in the assessment involved any unique content of the experimental instruction. We exclusively addressed the content that is obligatory in the standard optical curriculum. The tests were administered in a regular class environment, during a 45-min period.

One should mention that this study, being focused on the investigation of conceptual knowledge, did not test the students' problem-solving abilities despite the fact that the curriculum of both experimental and control classes included such activities. It is however clear that the control group, conducting the traditional program, spent much more time on quantitative problem solving, whereas the experimental group, which covered a lot of qualitative materials, spent less time on such activity.

1. Qualitative analysis

The accumulated students' answers were processed in several steps. Initially, responses which seemingly presented the same meaning, were grouped together [even if they were expressed in somewhat different wording]. Then, representative categories of explanatory patterns or strategies employed by the students in addressing *particular* situations were identified. These were the *facets of knowledge*, which reflected either conceptual or procedural knowledge of the individuals. Responses to different questions could contribute to the identification of a facet addressing a particular context (Fig. 1). Here, we distinguish between facets representing alternative (naive, scientifically incorrect) conceptions, and those reproducing various aspects of scientifically correct ones. At the next step, the elicited facets of alternative knowledge are grouped around the same explanatory model (as interpreted by the analysists). These models present *schemes of knowledge*. As already stated, a scheme of knowledge presents a sort of theoretical model underpinning for all facets in the cluster. The facet's form, although formulated by researchers, was mainly determined by the students (their wording, elements of their drawings) in making sense of a particular situation, whereas a scheme was formulated and determined solely by the researcher, reflecting his/her intention to generalize and see a common rationale in a number of ''formally'' different patterns of knowledge or behavior. As such, schemes involve a greater degree of interpretation by the researcher and, even though they contradict scientific knowledge, they are normally formulated in the style and language used by science. The elicitation of schemes and their affiliated facets required painstaking analyses of the data. A schematic representation of the data processing is shown in Fig. 1 and is exemplified in the presentation of findings. To increase reliability, the analysis in its different stages was performed by both researchers independently, followed by discussions to reach an agreed result.

This study did not touch on the complex process of facets and schemes formation, such as whether scheme is antecedent in genesis to its facets or vice versa.

2. Quantitative analysis

The frequency of each identified facet was represented by the parameter FA_c for the control group, and FA_e for the experimental group. Quantitatively, the influence of instruction on each facet, is evaluated by the Facet Abundance Difference, FAD, $FA_e - FA_c$. Similarly, the frequency of the evaluated scheme appearance (naive conception), and that of scientific conceptions, were characterized by the parameter SA (Scheme Abundance), and SCA (Scientific Conception Abundance). They were determined by taking into account the contributions of each of the facets associated with the particular scheme or conception. Finally, the Scheme Abundance Difference (SAD) and the parameter SCAD, were used to measure the knowledge difference resulting from a particular instruction in terms of a spread of schemes and scientific conceptions correspondingly, and the statistical evaluation of the differences was computed.[29] The parameters are defined and described in the Appendix.

IV. FINDINGS AND INTERPRETATION OF THE DATA

For brevity's sake, in presenting the findings we focus on the most representative schemes together with their affiliated facets. The appearance of a scientifically correct understanding was indicated by those facets which matched various aspects of scientific knowledge. In our perception, the appearance of a facet associated with the scientific conception should not be taken to indicate a complete acquisition of the correspondent scientific conception, but only of certain fragments or features of the ultimately required knowledge, as would definitely be recognized by a scientist. Although not representing complete knowledge, such a facet does indicate a learning progress and positive gain in knowledge of the learner.

A. Knowledge of vision

With regard to the vision phenomenon, the Spontaneous Vision Scheme, as observed in our study, can represent the most pronounced alternative knowledge of the subject. This information was elicited from the responses of students to

Table II. Student's knowledge of vision. FA—facet abundance, FAD—facet abundance difference ($FAD = FA_e - FA_c$). SA—scheme abundance, SAD—scheme abundance difference ($SAD = SA_e - SA_c$). SCA—scientific conception abundance. SCAD—scientific conception abundance difference ($SCAD = SCA_e - SCA_c$).

#	Nature of knowledge/ Global characteristics	Facets of knowledge	FA_c	FA_e	FAD and statistical significance
I	Spontaneous Vision Scheme	(1) Students being asked to explain vision cannot expand beyond saying: ''To see the object one aims (focuses) his eyes (notice, puts attention, looks) at it,'' ''I look and I see it.'' (Fig. 2-1, 2-9)	43	10	−33 $z = 5.86^c$
		(2) Objects are observed when merely being located in the field of vision (and are not blocked). (Fig. 2-2)	55	0	−55 $z = 9.98^c$
	$SA_c = 26\%$ $SA_e = 2\%$ $SAD = -24\%$ $z = 5.63^c$	(3) In students' written descriptions and sketches describing vision, no reference is made to any physical relation (agent) between the observing eye and the observed object. (Fig. 2-1, 2-2, 2-3, 2-4, 2-9)	41	0	−41 $z = 8.32^c$
		(4) Light moving through an empty space, or being stationary and filling the space, can be seen from the side. (Fig. 2-3)	48	8	−40 $z = 7.03^c$
		(5) Students describing light say: ''Light serves as a medium, helping and improving vision.'' (Fig. 2-4)	20	0	−20 $z = 5.54^c$
II	Scientific conception	(1) Students say that vision can be explained by light reflection from the observed bodies and its refraction inside the eye.	27	22	−5 $z = 0.88$ (ns)^d
		(2) Students say that vision can be explained by light rectilinear expansion and its refraction inside the eye.	17	16	−1 $z = 0.20$ (ns)^d
		(3) Students say that in order to see something, light must ''enter'' the eye. (Fig. 2-5)	0	42	+42 $z = -7.24^c$
		(4) Vision is explained by the fact that light must leave the object and enter the observer's eye. (Fig. 2-6)	0	51	+51 $z = -8.29^c$
	$SCA_c = 6\%$ $SCA_e = 22\%$ $SCAD = 16\%$ $z = 3.3^c$	(5) Students say that vision can be explained by light reflection from the bodies, its rectilinear expansion in space and its refraction within the observer's eye. (Fig. 2-7)	0	32	+32 $z = -6.08^c$
		(6) Students explain vision using beams of light which travel from the object and cause formation of an image on the retina. (Fig. 2-8)	0	10	+10 $z = -5.87^c$

$^a p < 0.05$.
$^b p < 0.01$.
$^c p < 0.001$.
^{d}(ns)—statistically nonsignificant difference ($p > 0.05$).

questions like ''How would you account for the fact that you see objects around you?'' Table II contains five facets in which such understanding manifested itself, and Fig. 2 presents the schematically reproduced sketches by which the students illustrated these answers (facets in Table II include references to the correspondent sketches in Fig. 2). The Spontaneous Vision Scheme implies vision is performed naturally (spontaneously) by a mere presence of eyes, with no mechanism or agent mediating between the eyes and the observed object. Instead of the latter, there might be a recognition by the student of a necessity to turn the face towards the observed object, ''to aim her eyes'' at it, ''to focus on it'' (facet I-1). The mere location of the object in the ''field of vision'' is considered to be a sufficient condition for the object to be seen (facet I-2). The corresponding sketches do not show any physical agent connecting the observing eye with the observed object or image (facet I-3, Fig. 2-1, -2, -3, -4, -9). Light is perceived as a bright object observed by the eyes ''from the side'' (facet I-4), when it is either stationary and filling the space (Fig. 2-3), or travels in empty space (Fig. 3-1). At best, light is recognized in this framework as a necessary medium, helping and improving vision (facet I-5).

All these five manners, in which students elaborated on the vision of objects or images, share the common conception variously displayed: vision is understood as a natural phenomenon, lacking delivery of light (or anything) from the object into the observer's eye. This mode of thinking constitutes the Spontaneous Vision Scheme.

Although facets of the Spontaneous Vision Scheme were registered in both experimental and control groups, only two of them ''remained'' in the list of the facets employed by the experimental group, and at a clearly lower rate. There was a significant overall decrease in the frequency of the scheme in the experimental group ($SAD = -24\%$).

Students also showed a variety of facets fitting the scientifically correct understanding of vision. Facets II-1, -2, -3, -4 reflect the claims elicited from the answers in which students showed fragments of the correct physical model of vision. All such facets manifest the evolving appreciation of the

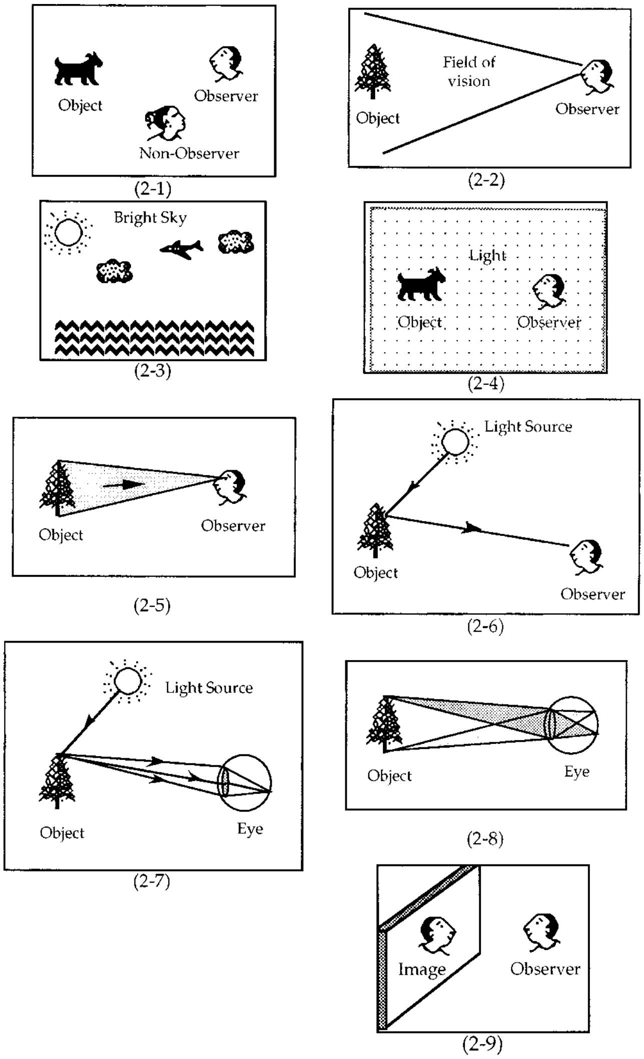

Fig. 2. Schematic reproduction of students' sketches provided to explain their answers with regard to the phenomenon of vision. The corresponding facets of knowledge are shown in Table I.

components of the scientific conception, incompatible with the Spontaneous Vision Scheme. It is specifically in facets II-5, and especially in facet II-6, that we can recognize the required understanding of the subject. The interviews provided further support to this fact:

> *Q: If you want to explain vision to your friend, what would you need?*
>
> S_1: *It depends... if the object is not a source of light I must use the property of reflection to explain how this object is illuminated. But I also need to explain how light arrives from this object to the eye, and for this, I need to use linearity of light. Finally, I must explain how an image is created by the lens, than the law of refraction must be used.*
>
> S_2: *The act of vision must begin by light spreading from the object in all directions as beams of light. One sees the object, when this light enters the eye. Those light beams are focused by the eye-lens, and create a real image on the retina. This is what we need light for. It must enter the eye and it is not enough to only illuminate the body.*

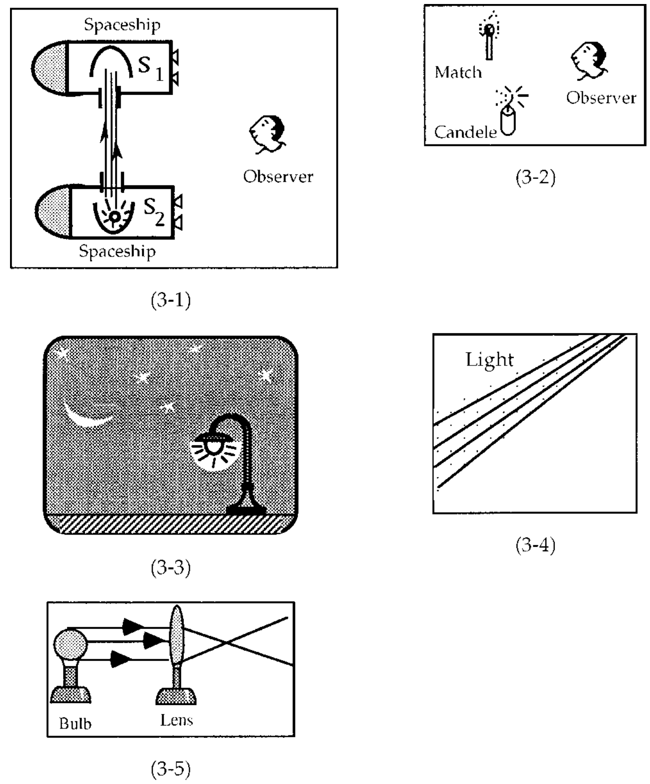

Fig. 3. Schematic reproduction of students' sketches provided to explain their answers with regard to the nature of light. The corresponding facets of knowledge are shown in Table II.

Those facets appeared only in the experimental group, demonstrating that the scientific conception of vision was significantly better entrenched in this group (SCAD $=16\%$).

B. Knowledge of the nature of light

Regarding the nature of light, the strongest scheme is that of light reification, ''Light is Corporeal,'' which was already discussed in the literature see (Ref. 31). Such information was elicited from the responses of students to questions like ''Will the astronaut, floating in the space beside the spaceships, see the light signals passing between the two spaceships?'' (See the space configuration in Fig. 3-1). Within this scheme, students comprehend light as an external material object, a passive subject of observation, not related to the observer. The first five facets in Table III describe such understanding, often supported by the literally taken claim that light is composed of light rays, a frequent expression in many physics textbooks and common instruction. Apparently, the reification of light often coexists with the understanding of vision within the Spontaneous Vision Scheme (Table II). Thus, for example, both schemes share the facet ''Light moving through space or being stationary and filling the space, can be seen from the side'' (facet I-4 and facet III-1), which simultaneously attests to the understanding within both schemes of knowledge, displaying the interdependence of views of vision and the nature of light. Circular references in describing light as that causing vision, and vision, as that caused by light, common in teaching materials, reflect the same conceptual closeness.

Table III. Student's knowledge of the nature of light. FA—facet abundance, FAD—facet abundance difference ($FAD=FA_e-FA_c$). SA—scheme abundance, SAD—scheme abundance difference ($SAD=SA_e-SA_c$). SCA—scientific conception abundance. SCAD—scientific conception abundance difference ($SCAD=SCA_e-SCA_c$).

#	Nature of knowledge/ Global characteristics	Facets of knowledge	FA_c	FA_e	FAD and statistical significance
III	Reified light scheme	(1) Light moving through space, or being stationary and filling the space, can be seen from the side. (Fig. 3-1)	48	8	−40 $z=7.03^c$
	$SA_c=33\%$ $SA_e=4.3\%$	(2) Light remains in a glow around and in a light source (candle, match, bulb, fire). (Fig. 3-2)	42	11	−31 $z=5.50^c$
	$SAD=-29\%$ $z=5.88^c$	(3) Light is brightness (shine) and is better seen in darkness. (Fig. 3-3)	47	0	−47 $z=9.04$
		(4) Light is comprised of (many or an infinite number of) light rays which fill the space. (Fig. 3-4)	61	6	−55 $z=9.20^c$
		(5) Lens break (bend) light rays. (Fig. 3-5)	36	5	−31 $z=6.14^c$
IV	Scientific conception	(1) Light rays are not a real thing but a picture, a geometric description of light which expands straight.	0	47	+47 $z=7.82^c$
	$SCA_c=0$ $SCA_e=22\%$	(2) Light rays are a model by which we solve problems using geometry.	0	12	+12 $z=3.47^c$
	$SCAD=22\%$ $z=4.9^c$	(3) Light is the energy that propagating in space in the form of beams/vibrations/waves.	0	14	+14 $z=3.78^c$
		(4) Light expands in the environment of objects with a decreasing intensity until it strikes opaque objects.	0	80	+80 $z=12.00^c$

[a] $p<0.05$.
[b] $p<0.01$.
[c] $p<0.001$.
[d] (ns)—statistically nonsignificant difference ($p>0.05$).

Common for all five facets of the Light is Corporeal scheme, was their substantially lower frequency in the experimental group. For example, with regard to the strongest facet, representing students' conviction that light is a composition of rays, the difference was most striking: $FAD=-55\%$.

Students' approach to the scientific conception of the nature of light significantly prevailed in the experimental group. The elicited facets seemingly reflect the desired refutation of the naive ideas regarding light rays and preponderance of knowledge closer to scientific. Facet IV-3, which prevailed in the experimental group, contrasted with its opposites, facets III-1, -2, and -3, which were prevalent in the control group. In interviews, students of the experimental group said:

> S_1: *Light rays are not something real or made of some material. They just show which way light goes, and help us to understand that light is traveling in straight lines. Inside light beams there are no rays. Light is some kind of energy.*
>
> S_2: *Light rays are merely a model, a kind of line people invented to describe light traveling. It would be impossible to show light without drawing rays, for light is not seen unless it enters the eye.*

Similarly, the evidence of the stronger refutation of the idea of stationary light in the experimental group might be seen in the lower frequency of facet III-2, whereas the frequency of the contrary facet IV-4 rose impressively there. All together, the experimental group showed significantly superior knowledge in the assimilation of the scientifically correct conception of the nature of light ($SAD=-29\%$, $SCAD=+22\%$, Table III).

C. Knowledge of optical imaging

Optical images present a central topic in all school curricula expanding on the contexts of light reflection, refraction, shadows, and illumination. (The latter two topics are currently rare in optics textbooks.) Students often hold a variety of pronounced naive ideas about images. Such knowledge was elicited from the responses to questions like: ''What will be the effect of covering a half of a converging lens on the image formed by it?'' or ''You are facing a plane mirror on the wall and observe an image of a part of your body. Suggest and explain the way to see a greater part of yourself in the mirror.''

Among the strongest alternative conceptions with regard to this knowledge we found the Image Holistic Scheme. According to Rice and Feher,[30] and Bendall *et al.*[31] this scheme is especially strong in preinstructed students, whereas in postinstructed students, the Image Projection Scheme was found as prevailing and seemingly replacing the holistic scheme.[32] In our data we were able to recognize both image schemes by their facets (Table IV, Fig. 4).

The Image Holistic Scheme interprets the image as an entity which replicates an object and, as a whole, can either move, stay, revolve, or be deformed when passed through an optical device (e.g., a lens). This view commonly lacks further details of image formation and its transfer in space. Seven facets associated with this scheme were elicited in this

Table IV. Students' knowledge of optical imaging. FA—facet abundance, FAD—facet abundance difference ($FAD=FA_e-FA_c$). SA—scheme abundance, SAD—scheme abundance difference ($SAD=SA_e-SA_c$), SCA—scientific conception abundance, SCAD—scientific conception abundance difference ($SCAD=SCA_e-SCA_c$).

#	Nature of knowledge/ Global characteristics	Facets of knowledge	FA_c	FA_e	FAD and statistical significance
V	Image Holistic scheme	(1) Half lens produces a half image. The rest of the image is blocked. (Fig. 4-1)	30	18	−12 $z=2.15$[a]
		(2) If the screen moves towards or away from the lens the image becomes bigger or smaller but remains equally sharp.	48	20	−28 $z=4.53$[c]
	$SA_c=42\%$ $SA_e=9\%$ $SAD=-33\%$ $z=5.96$[c]	(3) When a converging lens is removed, a right-side-up image replaces the previously-observed (on the screen) inverted image. (Fig. 4-2)	20	18	−2 $z=0.38$ (ns)[d]
		(4) Image is always formed and can be obtained on a screen (mirror). There it could be observed (afterwards). (Fig. 4-3)	64	0	−64 $z=11.02$[c]
		(5) Trying to explain the image formed by the lens, students cannot proceed beyond the claim that ''lens turns an image upside-down.'' (Fig. 4-4)	29	0	−29 $z=6.81$[c]
		(6) The image travels to the mirror and bounces off it (is reflected in it). (Fig. 4-5a, 4-5b)	33	0	−33 $z=7.32$[c]
		(7) The image strikes the mirror and is reflected off it at equal angles. (Fig. 4-6)	30	0	−30 $z=6.94$[c]
VI	Image Projection Scheme	(1) When half of a lens is covered, half the light rays from the object are blocked and only half of its image comes through. (Fig. 4-7)	53	18	−35 $z=5.63$[c]
		(2) Converging lens inverses the space ordering of light rays passing through it, thus, an inverted image is obtained. (Fig. 4-8)	47	4	−43 $z=5.63$[c]
	$SA_c=39\%$ $SA_e=10\%$ $SAD=-29\%$ $z=5.29$[c]	(3) Light rays bring an image to a lens. The lens bends the rays and when they pass through its focus, the image becomes inverted. (Fig. 4-9)	33	10	−23 $z=4.38$[c]
		(4) Explaining the image in a lens, students produce a diagram of a point-to-point connection of an object with its image by means of a single ray. (Fig. 4-8, 4-9)	30	18	−12 $z=2.15$[a]
		(5) Light rays bring the image to the mirror. The image is then reflected (bounced off) at equal angles with the rays of light. (Fig. 4-10)	44	0	−44 $z=8.68$[c]
		(6) Explaining the image in the mirror, students produce a diagram of point-to-point connections of an object with its image by means of unique rays.	26	12	−14 $z=2.76$[b]
VII	Scientific conception (lens)	(1) Image is formed by the focusing/shifting/converging of light (flux, beams) passed through the lens. (Fig. 4-11)	0	17	+17 $z=4.20$[c]
		(2) Eye's lens redirects cones of light from the observed object to the retina. (Fig. 2-8)	0	49	+49 $z=8.05$[c]
	$SCA_c=0$ $SSCA_e=70\%$ $CAD=70\%$ $z=10.62$[c]	(3) The material (and shape) of the lens enables it to form images by the deviation of light bemas.	0	43	+43 $z=7.37$[c]
		(4) Each point of the object sends a light beam that forms an image point after passing through the lens. (Fig. 4-11)	0	27	+27 $z=5.48$[c]
		(5) Image is comprised of light spots on a screen (retina). (Fig. 4-12)	0	28	+28 $z=5.60$[c]
		(6) In sketches and explanations, students describe image as a collection of light spots each created by a light flux emanating from an object point.	0	31	+31 $z=5.96$[c]
		(7) Half lens still produces a complete image. (Fig. 4-13)	0	76	+76 $z=11.43$[c]
		(8) When the lens is removed, no image is produced.	0	79	+79 $z=11.86$[c]
	Scientific conception (mirror)	(9) Explaining mirror images, students stipulate its formation by the specular reflection of light although they do not provide any construction procedure.	17	10	−7 $z=1.57$ (ns)[d]
		(10) Students explain that mirror image is created by intersections of light rays extensions, however, no connection to the eye is made. (Fig. 4-14)	33	0	−33 $z=7.33$[c]
	$SCA_c=58\%$ $SCA_e=91\%$ $SCAD=33\%$ $z=5.96$[c]	(11) Explaining mirror images students reproduce the correct path of light and its specular reflection although they do not provide correct construction procedure.	8	25	+17 $z=3.30$[c]

Table IV. (*Continued.*)

#	Nature of knowledge/ Global characteristics	Facets of knowledge	FA_c	FA_e	FAD and statistical significance
		(12) Explaining mirror images students reproduce the correct path of light using the concept of light flux, but do not provide any construction procedure.	0	23	+23 $z+4.99^c$
		(13) Students correctly explain mirror image by using the concept of virtual image formation.	0	33	+33 $z=6.20^c$

[a] $p<0.05$.
[b] $p<0.01$.
[c] $p<0.001$.
[d] (ns)—statistically nonsignificant difference ($p>0.05$).

study. Figure 4 presents some relevant students' drawings attached to the answers classified by us as an expression of the Image Holistic Scheme. The frequency of this scheme in the experimental group was 17% lower than in the control group, with four out of seven facets not observed at all.

Within the Image Projection Scheme,[33] the formation of an image is understood as the one-to-one mapping of an object to its image by means of a single light ray per object point. A light ray, traveling in the ''relevant'' direction, ''carries'' an image point. Though the two schemes, the Image Holistic and Image Projection, reflect essentially different understandings, they look similar and can be distinguished only if the subject provides, verbally or through details in drawing, the mechanism by which he/she comprehends the image transfer takes place from the object point to the location where the image is observed. The adherents of the Image Projection Scheme, as opposed to the adherents of the Image Holistic Scheme, disassemble the image into points, each to be separately transmitted (e.g., Fig. 4-8, 4-9). Thus, for example, facet V-2 can fit both schemes, and the decision of affiliation could not be certain without the aforementioned details. It is then possible that a certain overesti-

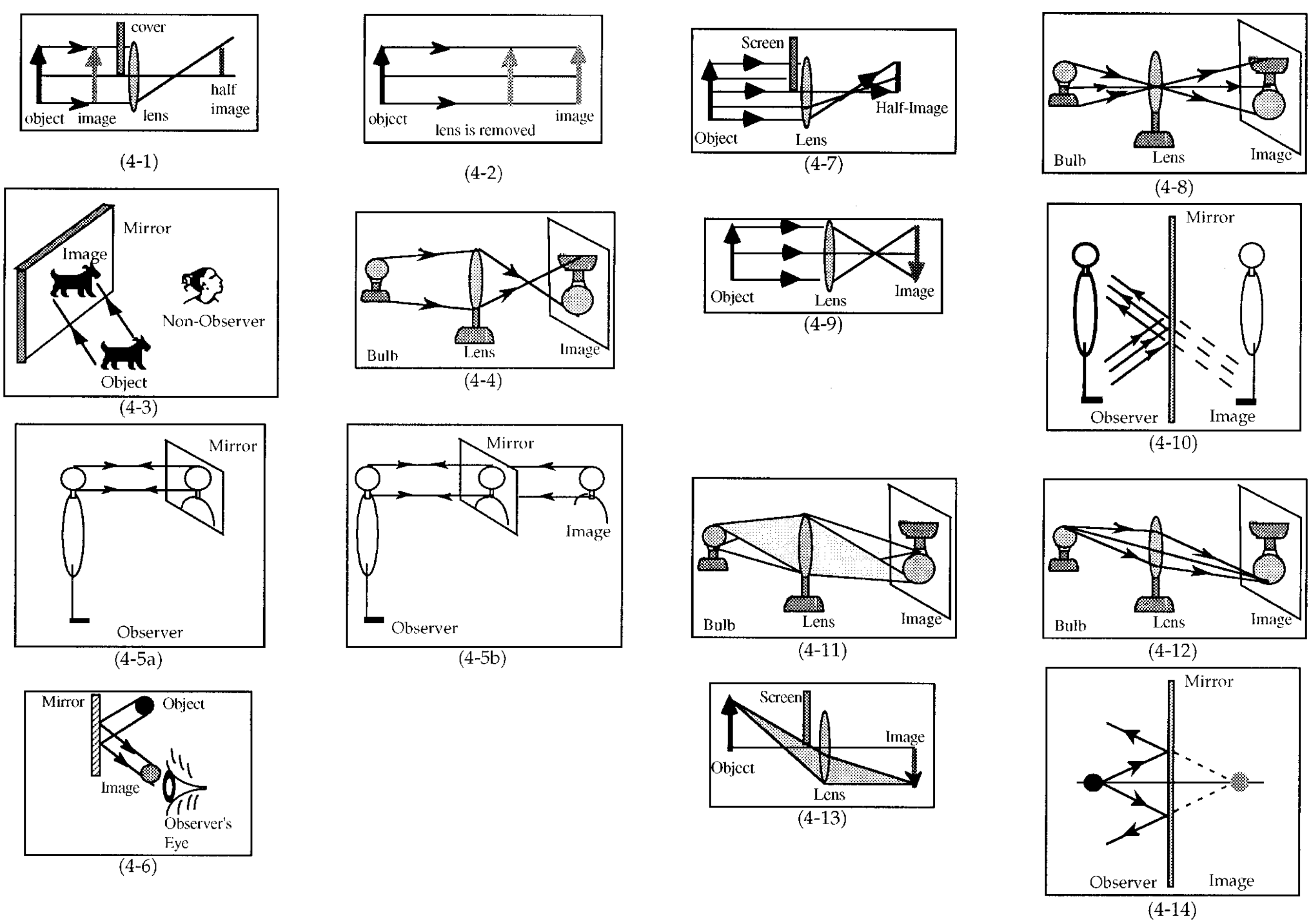

Fig. 4. Schematic reproduction of students' sketches provided to explain their answers with regard to optical images. The corresponding facets of knowledge are shown in Table III.

mation of frequency of the Holistic Scheme was made due to the lack of the details which would cause the identification of the facet as belonging to the Image Projection Scheme. This, however, cannot change the fact that the total frequency of the naive schemes regarding optical images was considerably lower in the experimental group. The Image Holistic Scheme was 17% lower, and the Image Projection Scheme 27% lower in the experimental group. Some of the facets, especially of the Holistic scheme, totally disappeared there.

The scientifically correct conception regarding image formation appeared in a number of facets (Table IV). We grouped them separately with regard to real and virtual images, as the images differ in mechanism of formation. Our results show a clear difference between the groups in the way students expressed their knowledge of light. The ambiguous (in the explanation of image formation) term ''light ray'' used by members of the control group, was replaced in the experimental group by terms such as ''light,'' ''light beam,'' and ''light flux,'' presenting a scientifically superior form of expression. We note that some of the new facets, exclusively observed in the experimental group, presented clear opposites to certain facets widely observed in the control group. For example, facet VII-7 clearly contrasted facets V-1 and VI-1. Similarly, facet VII-8 and facet V-3 are also opposites. Responses such as the following were prevalent in the experimental group:

> *A beam of light that comes from each point on the body is deflected by the eye-lens, which converges it to a light spot. These light spots cover the retina and form an image in the shape of the body*.

The scientific conception of the real image, in contrast with its naive understanding, defines such an image as the reproduction of the object obtained by a collection of light spots, each obtained by a converging of correspondent light flux. This comprehension (facets VII-4, -5, -6) appeared frequently, but only in the experimental group. Thus, one student wrote regarding the image in the eye:

> *Light arriving from the body enters the eye and hits the eye-lens. The role of the lens is to deflect this light toward the retina. Because of the shape of the lens, this deflection is exactly such that an image of the body is formed on the retina*.

Another important difference between the results of the two groups was found in the obtained descriptions of the mirror image, a very difficult topic for many students to understand. A strongly held conception was registered in the control group, where students divided the process of mirror-image observation into two separate processes or stages, image formation and, subsequently and independently, image observation (facet V-4). Although only facet VII-13 actually presented a fairly comprehensive reproduction of the scientific conception of virtual image, other facets (VII-9, -11, and especially VII-12) also showed considerable progress toward the scientific conception, reproducing the understanding of mirror-image formation as a single process. In contrast, many students in the control group reproduced the formally correct ray diagram to account for the mirror image, but often did not complete it by relating the virtual image to the observer's eye, resulting in an ambiguous diagram (facet VII-10). The role of the eye is cardinal in virtual image formation. In fact, facet VII-10, though increasing the score of scientific conception in the control group, left unanswered

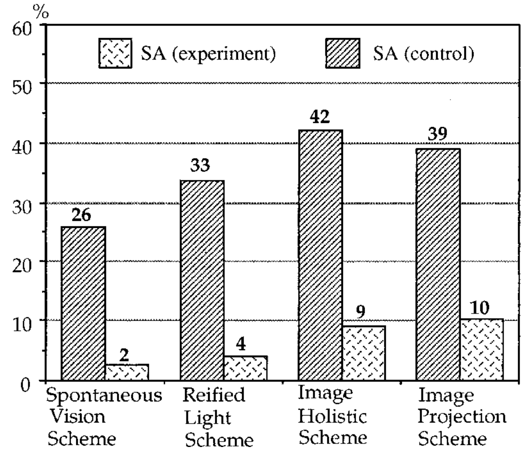

Fig. 5. Frequencies of schemes of alternative knowledge of vision, light and optical imaging.

whether these students genuinely understood the subject. Indeed, it remains unclear what was the status of the light ray ''extensions'' (dashed lines) drawn by the students in their sketches (Fig. 4-14). Even when asked in interviews, the subjects were unable to explain the meaning of these extensions. In contrast, many students of the experimental group showed a more mature and sound knowledge when they defined the mirror image as an optical illusion, and elaborated on its formation within the observer's eye (facet VII-13). Overall, the experimental group exhibited a significant change in the reduction of naive schemes regarding optical images as well as an increase in the mastering of scientific conceptions in the cases of real and virtual images (Table IV).

V. DISCUSSION

The advantage of the experimental instruction was evident in all aspects of the performed assessment. Not only were the frequencies of all schemes of alternative knowledge relatively lower (Fig. 5), and those of the scientifically correct ideas higher (Fig. 6) in the experimental group, but the

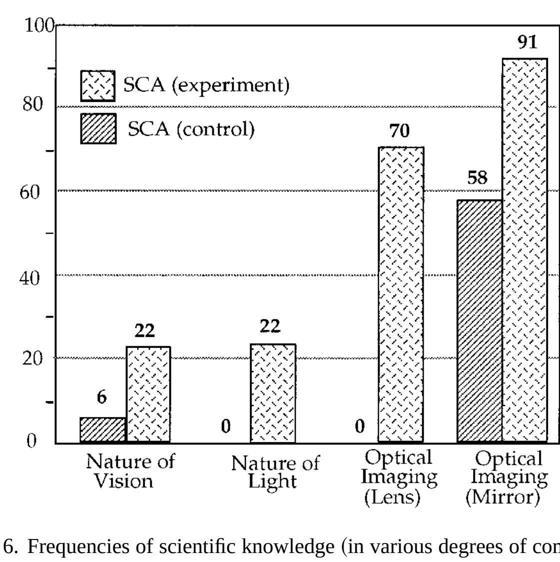

Fig. 6. Frequencies of scientific knowledge (in various degrees of completeness) of vision, light and optical imaging.

knowledge, identified as scientifically correct, was generally of higher quality in the experimental group.

In looking to explain these results, we note that students who learned optics in accord with its historical development became acquainted with a scientific understanding of the subject as it evolved in stages. We cannot but be reminded of Aristotle, who stated that there is no other way to meaningfully comprehend the subject (we may add, scientific), but by following its historical genesis. The expectation that students will exchange their naive conceptions as a result of ''straight to the point'' and ''crystal clear'' instruction, too often showed itself, surprisingly to many, as unrealistic. Instead, when the students are given a chance to gradually develop their ideas, by considering ideas as they evolved from the scientific past, the collision with the scientific conception is softened, and the latter appears as reasonable and superior to the views they had previously considered as plausible. Thus, in our experiment, the exposure, critical discussion, and refutation of the Atomists' theory of Eidola actually addressed the ontologically similar naive conception of vision in the form of the Image Holistic Scheme.

Similar resonant cognitive interaction was encouraged by an intensive discussion on Al-Hazen's medieval theory of image transfer by means of light rays. That theory, normally considered only in books on the history of optics,[34] remarkably coincides with the Image Projection Scheme.[35] When reconstructed in the instruction, the historical refutation of Al-Hazen's theory by Kepler's later understanding of image formation seemingly contributed to the reduction of such alternative knowledge in the experimental group. While the Image Projection Scheme is very often held by students, regular instruction usually does not mention this conception, choosing to focus on numerical problem solving, calculation of image characteristics by employing light-ray diagrams of special rays, and/or using the lens/mirror formula. Given the nontrivial character of optical knowledge, such a formal approach, ignoring alternative ideas of optical images, has a notable chance of leaving the learner with scientifically wrong conceptions, originated and developed in the course of learning.

An advantage of the experimental instruction was the high attention given to the vision process, often insufficiently treated in regular courses. Too often, vision appears as a mere illustrative example of the lens theory. The eye is presented in the same breath with other optical instruments, magnifying glass, camera, etc. In reality, the situation might be even worse. As one of the teachers in the experimental group said:

> *I could see how students' understanding of vision slowly changed from totally naive views to scientific conceptions, experiencing the important breakthroughs in the history of optics. Talking about scientists of the past, students could check and argue their own views on the same subject, sharing with the past similar difficulties of understanding. In a regular class, there is no chance to deal with topics like these...I confess, I myself often even skip over the subject of vision at all, as I have no time to consider applications of the theory, they simply have to master the theory and know to solve problems.*

A heavy accent on intensive and repetitive training of the standard problems comprising final exams often overshadows such issues as the nature of light and vision, which learners are never asked to explain. Teaching of this kind becomes scholastic, and cannot satisfy even simple curiosity. Qualitative explanations to such common reality as ''static'' light on a lit area, bright sky, shining halos around light sources, and twinkling stars are extremely rare in introductory physics textbooks.

Furthermore, the ontological status of ''light rays,'' intensively used as a tool in normal instruction but ignored by many textbooks, often remains an enigma to students. As a result, students' spontaneously perform light ray reification. To appreciate this fact theoretically, the perspective of Chi *et al.*[36] on cognitive development may be helpful. They claim that students typically confuse the ontological status of concepts, naturally intending to refer to the *process-based* concepts as *matter-based* ones, thus failing to grasp scientific conceptions. In optics, we observed students reifying light in general, and light rays in particular (e.g., the Reified Light Scheme, Table III). In contrast with students in a regular class, students of the experimental group explicitly learned about the history of the concepts of ''light ray'' and ''visual ray,'' starting from Euclid. The revived arguments of Al-Hazen against ''visual rays,'' being discussed in the class, encouraged students to reconsider and refute this concept in its naive perception. As to the concept of ''light ray,'' the remedy may come from the study of the historical failure to explain light refraction by means of single rays. Why does the light ray break? This historical question brought students to the necessity to introduce light beam, light flux, and light front concepts to explain the behavior of light. This way, students are exposed to the historical conceptual change in the ontological status of the light ray, from a fundamental concept in the old science to an auxiliary tool in the modern scientific model. This conceptual change could induce a similar one in our subjects, who were apparently much better in understanding light ray status.

Finally, we comment on the identification of the qualitatively positive and statistically significant output of the experiment as evidence in favor of HPS-used materials. Indeed, the experimental course was different from the traditional in more than one dimension. Class discussions on conceptual issues, addressing alternative conceptions, interweaving the topics of light and vision, all these factors presented in the experimental course could by themselves positively contribute to the success of the learners, and seemingly did so. While we recognize that the above-mentioned factors can, and at times are, entered into curricula with the desired results,[37] we believe that HPS is still an important factor by itself. It provides a natural setting in which the mentioned factors can flourish. HPS contents provide students with broad knowledge, expanding on metaphysical issues of scientific method and the nature of science, issues which are also valuable in their own right. Finally, in our experience, discussions of student's misconceptions might be close in spirit to the exposure of historical models, but the former usually lack the richness of content and elaboration of the ideas, available in the history of science. Many educators continue to rediscover the depth of Aristotle's claim; there is seemingly a lot of sense in following the historical genesis of the subject, which brings us to its comprehension.

VI. CONCLUSION

This study probed the effectiveness of teaching high school optics by means of materials heavily loaded with historical contents, which addressed known difficulties of students in understanding optics. The positive evaluations, assessed by means of diagnostics in terms of facets-scheme structure, qualitatively and quantitatively support this approach to teaching optics. The historical approach may be valuable in other fields as well, where the match between historically employed models and naive conceptions of students is strong. The observed merit of the approach for the conceptual knowledge of learners may suggest that we reconsider our attitude that historical models are obscure or too complex for students to learn. This would indicate a need for a corresponding change in curricula that makes physics courses both more effective and attractive to the wider population of high school students, many of whom are disappointed with physics courses as they are often taught, and many who are failing their physics classes.

The approach discussed requires an extensive and intensive research effort to further justify it in terms of the modern theory of learning. This can be done by a more detailed study elaborating essential features of the suggested course. If adopted, such an approach to teaching implies the need for a twofold study to facilitate its application. First, to elicit the structure of students' knowledge (in our terms, identification of schemes of students' knowledge as they appear in students learning of a particular area of physics). Then, such information should guide the selection of the appropriate historical contents. The result of both efforts should determine the design and contents of the new teaching materials. Knowledge of schemes of students' knowledge may also support the follow-up control of the learning progress. We believe that neglecting either of these two dimensions may result in missing the desired remedial effect of the HPS-based materials on students' knowledge.

APPENDIX

The following parameters were introduced to characterize the frequencies of facets and schemes:

FA-Facet abundance parameter. Initially, the researchers listed all responses which correspond to the same facet (in accord with the definition of what is a facet). The accumulated responses could originate either from the same or different test questions. As each respondent contributed only one answer to a given question, the FA was computed by summing the frequencies of all appropriate answers. Responses to the same question contribute as a sum. In case of contributions from responses to different questions, we average contributing frequencies to obtain the resultant FA. For example, our data contained the following four propositions in response to two questions, A and B:

(i) ''The person sees the vase by looking at it'' (16%); (A)
(ii) ''The vase can be seen because the man is aiming his eyes in its direction'' (20%); (A)
(iii) ''In order to see something you must focus your eyes on that something'' (29%); (B)
(iv) ''To see something, you must put your attention at the object you want to see'' (21%). (B)

The numbers shown are frequencies of the particular answer to a particular question. All four propositions were identified as representing the same pattern of understanding—facet of knowledge. Since the first two were given in response to question A, we sum their frequencies and obtain 36%. Similarly, the two other responses provide 50%. To total abundance of the facet (based on responses to A and B), we obtain as an average: $FA=43\%$. The facet was described as:

> *Students being asked to explain vision cannot expand beyond saying: ''To see the object one aims (focuses) her eyes (puts attention, looks) at it,'' ''I look and I see it.'' (Table II, facet I-1).*

FAD—Facet abundance difference parameter is defined in a straight forward manner: $FAD=FA_e-FA_c$, characterizing the difference in facet abundance between the control and experimental groups.

SA—Scheme abundance parameter is determined by the contributions of the facets affiliated with the scheme. Due to the format of our study, focusing on *group* differences, the answers were analyzed per sample. To evaluate the distribution of the scheme, an average over the questions with contributing FAs was taken. Such a step moderated the influence of each facet (context-dependent understanding) on the frequency of the particular scheme (conceptual, context-independent understanding).

SCA—Scientific conception abundance parameter measured the extent to which a scientific conception appeared in students' responses. This parameter was calculated in a manner similar to that described for the SA.

SAD—Scheme abundance difference parameter compared the frequency of the same scheme between the control and experimental groups. Similarly to FAD, it was defined as: $SAD=SA_e-SA_c$.

SCAD—Scientific conception abundance difference parameter is parallel to SAD with respect to scientifically correct knowledge. It was defined as $SCAD=SCA_e-SCA_c$.

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[37]See, e.g., CPU projects in the SDSU: http:/cpuproject.sdsu.edu/CPU/

> The collective judgment of scientists, in so far as there is substantial agreement, constitutes the body of science. The fact that there are very large areas of agreement, in spite of the individualistic, antiauthoritarian nature of science, is partial evidence for the validity of scientific methods. However, there are cases where universal agreement has been attained for an untruth, though this has more often been the case with sweeping generalizations than with the basic observations. Each generation of scientists has to decide for itself what it will believe, using the best available evidence and the most careful methods of interpretation. With the best luck in the world, some of these decisions will later be proved wrong, but there is no other way.
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> E. Bright Wilson, Jr., *An Introduction to Scientific Research*